Chloride Transport under Compressive Load in Bacteria-based Self-healing Concrete

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ABSTRACT

An experiment was carried out in this study to investigate the effect of compressive load on chloride penetration in self-healing concrete containing bacterial-based healing agent. Bacteria-based healing agent with the fraction of 2 mm – 4 mm of particles sizes were used in this contribution. ESEM was applied to study samples which were taken by cutting the area of prisms in contact with the chloride solution and together with LIBS method to measure the total chloride content of bacterial concrete. Three load parameters of the compressive load are proposed to describe the phenomena of chloride transportation in bacterial concrete by which the results in prediction analysis of concrete performance within service life were much affected by different percentage of mechanical damage. It was found that the particles sizes of healing agent used leads to more porous-structure of concrete, subsequently affect the transport rate of chloride in concrete. Nevertheless, this investigation indicates that bacteria-based healing agent can still be considered as a measure of protection to concrete under combined action.

1. INTRODUCTION

It is a challenging task to design for a service life of concrete since it is usually interacts with loads and environmental actions which involve many affecting factors and complexities. However, only few studies had taken this into account until recently it has significant attention in investigation the degradation of concrete performance due to this coupled effects. Flow through cracks could be one of the main reasons for not considering cracks effect on chloride penetration due to the difficulty to obtain its accurate measurement. However, the reality of cracks in concrete is undeniably and the penetration of harmful substances through cracks must be considered.

As cracks generated by mechanical loading serve an additional pathway to deteriorating materials into concrete, it is important to get these cracks healed. Some years ago, a novel type of self-healing concrete in which bacteria mediate the production of crack-filling material has shown positive remarks on improving the liquid-tightness problem of concrete due to cracks [1,2]. The next challenge is to increase the resistance of concrete to the attack of harmful solutions under the load-induced cracks. In this study, therefore, an experiment was carried out to evaluate the durability of bacteria-based self-healing concrete under service loading of different compressive stress level. Apart from chloride transport analysis, morphology of bacterially produced mineral precipitates was investigated by environmental scanning electron microscopy (ESEM).

2. MATERIALS

Healing agent

The healing agent used in this study is mainly consisting of bacterial spores and calcium lactate as mineral precursor compound. They were coated with polymer-based coating materials and crushed in form of flakes ranging from 1 to 4 mm in size. However, the particle size used in this study is limited from 2 to 4 mm. This type of healing agent is incorporated in concrete to fill the cracks generated by compression load. Precipitation of calcium carbonate on the crack surface is expected to delay the process of chloride transportation in concrete, hence prolong service life of concrete structures. Further details on microbial healing concept are discussed in [5].

Preparation of materials

Table 1 shows a self-healing concrete mix proportion that was investigated in this study. The self-healing concrete prisms with a size of 100 mm x 100 mm x 400 mm were manufactured using Ordinary Portland Cement type I, 42.5, sand and crushed gravel with nominal maximum size 16 mm. The water/cement ratio of 0.45 was used with a small amount of super-plasticizer to achieve higher workability. The whole materials were mixed using tap water. The fresh concrete was poured and compacted on a vibration table.

Table 1. Mix proportion of fresh concrete (kg/m^3)

w/c	Portland cement	Sand	Coarse aggregates	Tap water	Super-plasticizer	Healing agent
0.45	360	840	1028	165	2.6	15

3. METHODS

Environmental conditioning

After casting, the specimens were covered with plastic sheets. All mixing and casting were carried out in a standard laboratory condition at 23 ± 2°C and 50 ± 5% RH. The specimens were removed from the mould on the following day and submersed in water for 28 days. Prior to the load and chloride ingress test, the specimens were saturated with a saturated calcium hydroxide, $Ca(OH)_2$ solution under vacuum conditions for two hours. All surfaces were then sealed with self-adhesive aluminium foil except an area from the moulded surface that is exposed to the chloride solution.

Specimen under combined load

The specimens were subjected to 30 % and 60 % of applied compressive load and also without applied compressive load as a control. Then all prisms were exposed to chloride solution containing 3% of sodium chloride, NaCl on the opening area of 80 mm x 160 mm positioned at the mid height of the prism. The chloride solution was circulated using a small capacity pump and recycled from 4 litres capacity basin in every setup. The specimens were left under combined environmental mechanical loads at different exposure time of 2 and 18 weeks.

RESULTS

Chloride ingress

Chloride profile by percentage of concrete of loaded and unloaded specimens after 2 and 18 weeks exposure duration are given in Figure 1. It can be seen that chloride-penetration depth in 2 weeks differ slightly than in 18 weeks specimens. This observation is not commonly found in normal type of concrete. In 2 weeks specimen, further hydration is expected to still occur and lead to the lower amount of penetrated chloride. However, it is generally thought that further exposure duration will significantly increase the chloride penetration depth. In this case, it may be assumed, as function of time a dense layer of calcium carbonate is produced due to metabolic conversion of calcium lactate, thus blocking the pathways of chloride transport. Fatigue load may cause multiple micro-cracks in concrete [3], but if the micro-cracks are not interconnected it also contributed to the delayed of ingress.

As can be seen from Figure 1 the content of chloride penetration into concrete at load level of 30% is marginally decreased, anticipated that at low compressive stress the penetration of chloride ions was reduced due to densification of the concrete porous structure by elastic deformation of the pore space [4]. Further increase to 60% load level not indicates any remarkable changes of chloride profile with the one observed in 30% load level samples. Although cracks should be evident at stress level of 60%, the precipitation of calcium carbonates on crack surface facilitated cracks sealing. Thus, lead to impermeable concrete matrix and reduce accessible to chloride. In addition, the chloride profile obtained at 18 weeks exposure time was a bit scattered. The observed trend can be explained by the fact of peak measurement areas were close to the healing agent region which is normally more porous than intact matrix.

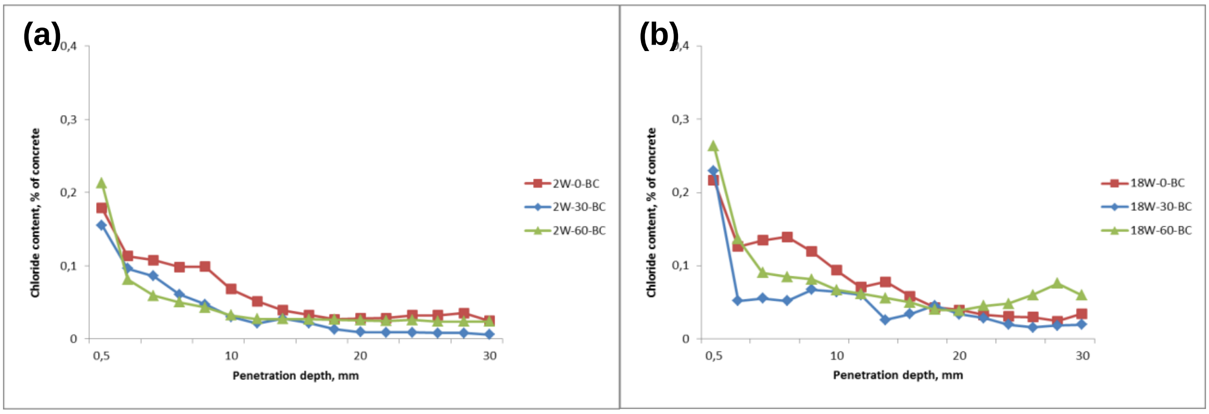

Figure 1: Total chloride profiles at (a) 2 weeks and (b) 18 weeks

ESEM Observation and assumptions

It is impossible to get cracks information from a two-dimensional polished section impregnated with fluorescent epoxy from the three-dimensional structure as they vary substantially. Therefore, only morphological difference of bacterially produced mineral precipitates was investigated in this paper. Figure 2 shows the microscopic morphology of bacterial-based self-healing concrete specimen using an environmental scanning electron microscope (ESEM). It indicates precipitation of crystalline calcium carbonate on the crack surface blocking the crack and making the crack nearly disconnected. The minerals produced were further confirmed by EDAX analysis in which the intensity of elements present show higher peak size of calcium, carbon and oxygen. It can be concluded that the potential of the bacteria to enhance calcium carbonate precipitation to seal the crack is convincing.

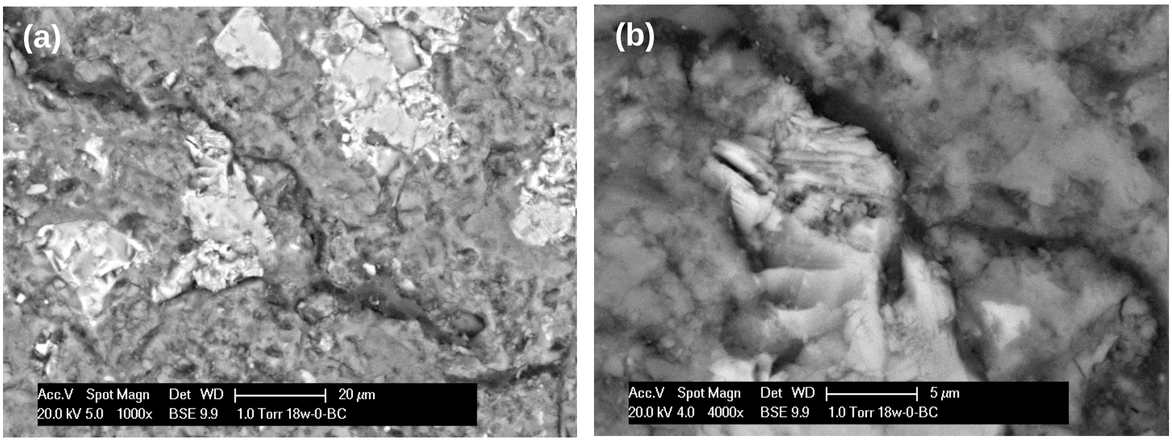

Figure 2: Mineral formation on the crack surface of a bacteria-based specimen. (a) ESEM image 1000xmagnification. (b) ESEM image 4000xmagnification.

4. CONCLUSIONS

Bacterial activity leads to impermeable concrete matrix and reduces ingress of chloride. Although it is still necessary to establish the efficiency of bacteria-based healing agent as protective measure to chloride penetration into concrete under mechanical loading, the process shows positive influences as ESEM analysis indicates the potential of the bacteria to enhance calcium carbonate precipitates to seal the crack.

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