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Chloride penetration in cracked mortar and the influence of autogenous crack healing

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HIGHLIGHTS

- Autogenous crack healing of mortar exposed to marine environments is investigated.
- Mortars are able to autogenously heal or seal crack widths up to 100 μm.
- Crack sealing is also obtained by formation of a brucite layer at the surface.
- The resistance against chloride penetration improves due to the healing process.
- 10 μm is the critical crack width for chloride penetration.

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ABSTRACT

Cracks in cementitious materials have a negative influence on the durability in aggressive environments, especially in marine environments since chlorides and sulphates are able to penetrate faster. Since constructions in marine environments mostly have an important social function with a high economic impact, repair of the cracks is of utmost importance.

In this paper, the ability of the material to heal 100 μm and 300 μm cracks autogenously in marine environments is investigated. To do so, some Ordinary Portland Cement mortar samples and Blast-furnace Slag blended mortar samples were permanently immersed in chloride solutions as well as in combined chloride and sulphate solutions. Another part of the samples were exposed to wet-dry cycles in water and in chloride solutions. Autogenous crack healing was evaluated by means of microscopic measurements. The resistance against chloride penetration was measured by means of colorimetric measurements and chloride profiles.

It was shown that cementitious materials, exposed to a simulated marine environment, are able to heal or seal crack widths up to 100 μm. Autogenous healing is obtained by ongoing hydration, calcium carbonate precipitation as well as by formation of a layer of magnesium and sulphate reaction products (brucite) at the surface. Furthermore, the resistance against chloride penetration improves due to the healing process. However, the efficiency depends on the initial crack width.

1. Introduction

A commonly used building material for marine structures is reinforced concrete. However, chlorides affect the durability of reinforced concrete by initiating corrosion of the reinforcing steel. In addition, when cracks appear in the concrete structure, chlorides will penetrate faster. Nevertheless, cracks in cementitious materials have the ability to heal autogenously. However, the influence of marine environments hereon is not exactly known.

1.1. Chloride penetration in cracked concrete

Conform to the standard NBN EN 1992-1-1 (2010), the allowable crack width in reinforced concrete structures depends on the environmental class and is in the range of 300–400 μm. However, according to Ismail et al. [1] crack widths of 200 μm and wider allow unlimited chloride diffusion perpendicular to the crack wall.

Furthermore, Win et al. [2] found that the chloride penetration depth at the crack tip of a 100 μm wide crack was already slightly higher than the chloride penetration from the surface Van den Heede et al. [3] suggest to consider a crack width lower than

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50 μm in order to avoid chloride penetration via the crack. So, it seems that in marine environments, the crack widths should be limited more in order to maintain or increase the durability of the structures.

The most commonly used methods to test chloride penetration in cracked concrete are: chloride diffusion (by means of immersion) and chloride migration (migration cell or rapid chloride migration). Afterwards chloride penetration depths are measured by means of the colorimetric method, and chloride diffusion or chloride migration coefficients are calculated.

Djerbi et al. [4] found a bilinear relation between the chloride migration coefficient, obtained by migration cell tests, and the crack width. Cracks were created by means of a controlled splitting test which means that the cracks were throughgoing. For crack widths between 0 μm and 100 μm, the migration coefficient increased with increasing crack width, and for crack widths between 100 μm and 200 μm this increase was less clear and the migration was rather constant.

Similarly, Audenaert et al. [5] found a bilinear relationship between the chloride penetration depth measured after rapid chloride migration tests and the crack width for artificial cracks obtained by use of embedded thin metal plates. They also found a bilinear relationship. However, the fit is not as good as it is for the data obtained by Djerbi et al. [4]. The second part, where a constant penetration depth is suggested, does not appear for the measured data. So, this relationship should be reconsidered.

Ye et al. [6] investigated chloride profiles after chloride diffusion tests for specimens with realistic cracks ranging from 50 μm to 200 μm at the crack mouth, obtained by 3-point bending tests, from which it was clear that the chloride concentrations increase at certain depths from the exposed surface, when the crack width increases. Comparable to this, Park and Kwon [7] found an increasing colour change depth when crack widths increased up to 400 μm. In addition, they found the chloride penetration increasing faster for crack widths above 200 μm. Furthermore, Kwon et al. [8] found for on-site drilled cores that chloride diffusion coefficients kept increasing with crack widths up to 300 μm. This is different from what Djerbi et al. [4] and Audenaert et al. [5] concluded.

In accordance, Jang et al. [9] found an increasing linear relationship between crack widths up to 206 μm and the chloride migration coefficient, by performing migration cell tests. They used realistic through-going cracks obtained after performing a splitting test. Furthermore, Sahmaran [10] concluded that when the crack width increases, the diffusion coefficient increases as well, and this effect was more distinct when the crack width was larger than 135 μm. However, the relative increase seems not of the same order of magnitude as in the data obtained by Kwon et al. [8].

Apparent diffusion coefficient calculations performed by Mu [11] show rising values with crack widths ranging from 0 μm to 450 μm. As the crack width exceeds 450 μm, the diffusion coefficient remains constant. So this could be defined as the upper boundary for crack widths influencing the chloride diffusion.

In addition, Jang et al. [9] also found that the chloride migration coefficient, does not increase with increasing crack widths up to the critical crack width, approximately 55 μm. Yoon et al. [12] define the critical crack width as a threshold crack width above which chloride penetration from the surface is faster than in sound concrete. They concluded, based on rapid chloride migration tests, that the critical crack width is about 12 μm. In their experiments, they created realistic not through going cracks by applying tensile stresses on metals plates attached at the surface of the specimen. According to the chloride diffusion profiles obtained by Ismail et al. [1], the critical crack width is maintained at 30 μm. They created cracks using the expansive core method. Next [10], found that the effect of realistic crack widths below 135 μm on the chloride diffusion coefficient is marginal, however, this is not a critical crack width.

1.2. Crack healing/sealing

From the literature it seems that quite some research has been done on chloride penetration in cracked concrete. However, the conclusions are somehow contradictory. Nevertheless, it is clear that cracks promote the chloride ingress and thus impair the durability of cementitious materials. In practice, repair interventions upon crack formation are needed in order to reduce chloride induced corrosion. Instead of applying manual repair, one could decide to rely on the autogenous self-healing capacity of concrete. Alternatively, a smart self-healing mechanism could be embedded to create an autonomous self-healing concrete.

Autogenous self-healing materials, exhibits self-healing properties due to the composition of the cementitious matrix. To achieve this so-called autogenous healing the presence of water is crucial for ongoing hydration of unhydrated cement particles and in addition, also CO_2 is needed to obtain calcium carbonate precipitation [13–17]. Huang [13] found that the air permeability of Ordinary Portland Cement (OPC) paste with w/c ratio of 0.3 decreases by about 65% when the filling fraction of a micro crack (10–30 μm) with reaction products is about 28% after curing in water for 200 h. This demonstrates that self-healing of cracks can reduce the ingress of harmful agents through cracks significantly and thus prolong the service life of concrete structures, even if the cracks are not completely filled with reaction products. Furthermore, according to Jacobsen et al. [18], after three months storage in water, autogenous healing of cracks in OPC concrete leads to a reduction in the rate of chloride migration. The reduction amounts to 28–35% compared to migration in freshly cracked specimens. This effect is in accordance with the findings of Sahmaran [10], who observed a significant amount of autogenous crack healing, with initial crack widths less than 50 μm, resulting in a reduced chloride diffusion coefficient and a slower chloride penetration rate.

Very little research has been done on the efficiency of autogenous self-healing of concrete in chloride containing environments. Nevertheless, research by Palin et al. [19] focusses on this topic. They have quantified the autogenous healing capacity of OPC and BFS cement mortar specimens submerged in fresh- and sea-water. According to them, OPC specimens submerged in sea-water display the greater healing capacity, considerably less were the OPC and BFS cement specimens in fresh-water, while the lowest were BFS cement specimens in sea-water. After 56 days, BFS cement specimens in sea-water healed 100% of cracks up to 104 μm, for OPC specimens it was 592 μm. In fresh-water, BFS cement specimens healed 100% of cracks up to 408 μm, while OPC specimens healed 100% of cracks up to 168 μm. The difference in performance is attributed to the amount of calcium hydroxide present in these mortars and specific ions present in sea-water.

Although, autogenous crack healing seems to have a beneficial influence on chloride penetration, it is a rather slow healing mechanism which is only suitable for small cracks in humid environments [17,20,21]. In case of possible chloride ingress, fast healing is required and autonomous crack healing seems more appropriate since the healing mechanism is triggered by crack formation and cracks are filled up almost immediately. In previous research by the authors, this mechanism has proven to be able to reduce chloride penetration in marine environments [22].

Cracks in cementitious materials have the ability to close themselves, nevertheless, the crack closing is limited due to several factors related to the environment and the material characteristics. In this paper, the influence of marine environments on autogenous crack healing in cementitious materials is investigated. To do so, cracked mortar specimens are immersed in chloride and sulphate