Autogeneous healing and chloride ingress in cracked concrete

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An experimental study of the influence of autogeneous healing on chloride ingress in cracked concrete is presented. In the study, two concrete mixtures (a Portland cement mix and a blast furnace slag mix), two healing regimes (submerged and fog room regime), two cracking ages (14 and 28 days), and multiple crack widths are used as parameters. An adapted Rapid Chloride Migration testing procedure is used after the healing period to assess the effectiveness of healing. It was found that small bending-type (i.e. tapered) cracks can heal fully, and larger cracks partially under tested conditions. The obtained results provide a good starting point for further study of the influence of autogeneous or self-healing on concrete durability.

Key words: Concrete, cracking, autogeneous healing, durability, marine environment

1 Introduction

Reinforced concrete structures are, typically, cracked. Cracks may occur due to many reasons, for example mechanical loading or restrained shrinkage. Even though cracking is usually not an issue of immediate safety, the durability of a reinforced concrete structure may be jeopardized if wide cracks are present in the concrete cover. Most codes of practice consider cracks smaller than 0.30 mm acceptable for aggressive environmental conditions [CEB_FIP model code, 1990; Eurocode 2, 1992; BS 8110 -1, 1997]. Cracks in the concrete cover present preferential routes for ingress of deleterious ions, such as chloride [Šavija et al., 2014a; Šavija, 2014c] or CO_2 [De Schutter, 1999], and could have an influence on the initiation and the propagation phase of reinforcement corrosion [Pacheco and Polder, 2012].

It has been long known that concrete cracks have a certain capability to heal under favourable conditions. This mechanism is called autogeneous (self) healing, sometimes referred to as self-closing, when no significant recovery in mechanical characteristics is achieved. Several mechanisms are thought to govern self-healing (Figure 1) [de Rooij et al., 2013]:

- *Physical causes*: The main physical cause is swelling of hydrated cement paste (HCP) near the crack surfaces. This is a minor cause contributing to self-closing of cracks.
- *Chemical processes*: There are three possible chemical processes which can contribute to autogeneous healing. The first one is the hydration of unhydrated cement particles. This might be a significant contribution when crack widths are small (less than 0.1 mm) and concrete is young. The second chemical process is the formation of calcium carbonate and the growth of crystals on the crack faces. Calcium ions originating from the concrete pore solution react with carbonate ions in the water and form CaCO3, which precipitates in the crack. This mechanism has been thoroughly examined by [Edvardsen, 1999], and is considered to be the most important mechanism leading to autogeneous healing of cracks. In seawater, a third process occurs: due to the presence of Mg(SO)4 in sea water, ettringite and brucite form in the crack [Mohammed et al., 2003].
- *Mechanical causes*: It is considered that mechanical causes, such as clogging of the cracks by fine particles originally present in water, or by particles broken off from fracture surface, constitute a minor mechanism in autogeneous closing of cracks. Under high hydrostatic pressure, however, the importance of this mechanism might increase [Kermani, 1991].

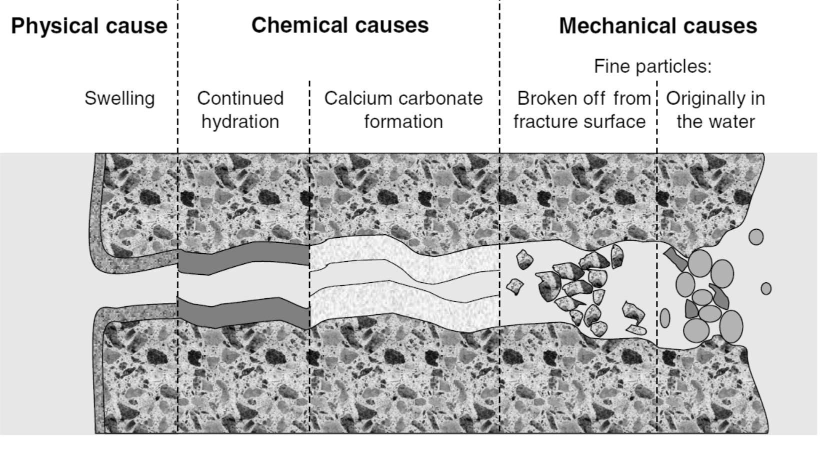

Figure 1: Possible causes of autogeneous crack healing in concrete [de Rooij et al., 2013]

Autogeneous healing was first noticed to occur in water retaining structures and pipes. Leakage of water through small cracks was shown to stop due to crack healing. Accordingly, multiple studies have dealt with the relation between autogeneous healing of cracks and water permeability: [Ramm and Biscoping, 1998] studied autogeneous healing of cracks and reinforcement corrosion in deionized and acidic water; [Edvardsen, 1999] performed a systematic study on healing of cracks under hydraulic pressure; [Reinhardt and Jooss, 2003] studied the influence of temperature on healing. Although these studies show somewhat contradictory results on the influence of some parameters, all of them agree that autogeneous healing can significantly reduce the water permeability of cracked specimens. The findings are of importance for design of water retaining structures and reservoirs.

Apart from water permeability, other techniques have been used to characterize and quantify effects of crack healing [de Rooij et al., 2013]: air permeability, optical and electron microscopy, capillary water absorption, ultrasonic measurements, computed tomography, and others. These techniques are a good way to characterize and quantify the extent of crack healing, but cannot be directly used to assess the effect that crack healing has on durability of reinforced concrete.

It is expected that autogeneous healing can reduce chloride ingress in cracks. Several studies have dealt with the issue: [Jacobsen et al., 1996] found a 28-35 % reduction in rate of chloride migration in specimens which were stored in lime water for 4 months, compared to newly cracked specimens; [Şahmaran, 2007] observed autogeneous healing of small cracks in specimens subjected to a NaCl ponding test; [Ismail et al., 2008] found that autogeneous healing reduced chloride ingress along the crack path in specimens cracked after 28 days compared to those cracked after 2 years; [Yoon and Schlangen, 2014] found a significant difference between chloride ingress in cracks in a short term (rapid) and long term test, and attributed it to crack healing. Even though most studies suggest that a submerged condition is needed for autogeneous healing (e.g. [ter Heide, 2005]), [Yang et al., 2009] showed that cracks in engineered cementitious composites can heal also under wetting and drying cycles. Similar findings were reported by [Ferrara et al., 2014]. Apparently, crack healing could have an important impact on chloride ingress in cracked concrete. With that in mind, a research program was designed to try to quantify the extent of autogeneous healing on chloride ingress in cracks. Concrete specimens were prepared, cracked, exposed to promote healing, and tested using a modification of the Rapid Chloride Migration test [NT Build 492, 1999]. The results reflect an influence of different healing regimes on chloride ingress in cracks, and can be used when assessing the influence of cracks on the long term durability of concrete structures. It has to be noted that the aim was not to study the mechanisms of autogeneous healing (see, for example, [Van Tittelboom, 2012; Huang et al., 2013; Huang et al. 2014a; Huang, 2014b]), but rather its effect on the chloride transport.

2 Materials and methods

2.1 *Materials*

Two concrete mixes with w/c ratio of 0.45 were used in this study: a mix prepared with CEM I 52.5 R cement (designated OPC mix), and a mix prepared with CEM III/B 42.5 N cement (designated slag mix). Mix proportions for both mixes are given in table 1.

Table 1: Concrete mixes used in the study

Mix	Water (kg/m3)	Cement (kg/m3)	Sand (kg/m3)	Gravel (kg/m3)	Superplasticizer (% cement)
OPC	166	366	842	1027	1.4
Slag	157	350	1055	844	1.4

The mixing procedure was as follows: first, fine aggregate was mixed for one minute. Then, cement was added, and mixing was continued for one more minute. After that, water (with superplasticizer) was added and mixed for four minutes. The mixing was then stopped for one minute. Finally, coarse aggregate was added and mixed for three minutes. The total mixing time was about ten minutes. The specimens were then cast and compacted using a vibrating table. Three standard cube specimens (150·150·150 mm3) per mix were tested to determine the compressive strength at 28 days. The average concrete strength at 28 days was 55.4 MPa for the OPC mix and 46.9 MPa for the slag mix.

2.2 *Specimen preparation, cracking, and exposure*

For the specimen preparation, cubic moulds of 150·150·150 mm^3 are used. Prior to casting the specimens, a PVC profile with a cross section of 40·40 mm^2 is mounted onto the mould, in order to create a recess in the sample (Figure 2). The alternative procedure would be to cut the cubical specimen in order to obtain the target shape. The PVC profile is removed after one day, when the specimens were demoulded. One day before cracking of the specimens, a notch (5 mm thick) is sawn in the specimen using a water cooled saw (Figure

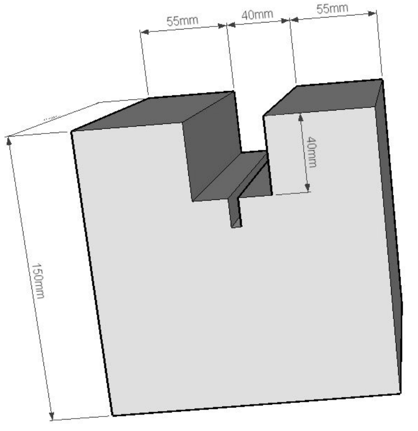

Figure 2: Specimen geometry used in the study

2). The purpose of the notch is to guide the fracture process; namely, the crack should typically start from the notch.

The specimen geometry was adopted according to the wedge splitting test [Brühwiler and Wittmann, 1990]. The wedge splitting test has long been used in fracture mechanics of concrete. The test is schematically presented in Figure 3. A specimen is prepared by casting or sawing a groove and a notch. In the testing machine, the specimen is placed on a linear support. Two rollers and a wedge are used to convert the vertical load (i.e. machine movement) into horizontal load. Two LVDTs are placed at the bottom of the notch, and their average is used as a feed-back signal to the machine. This way, the average crack width is controlled. After the unloading, the crack partially closes (Figure 4). For all tested

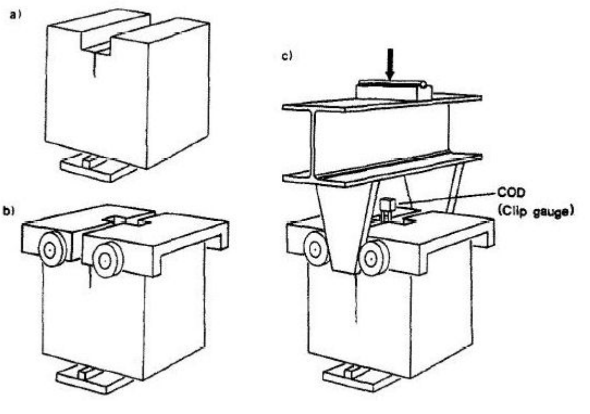

Figure 3: The wedge splitting test used for controlled cracking [Brühwiler and Wittmann, 1990]

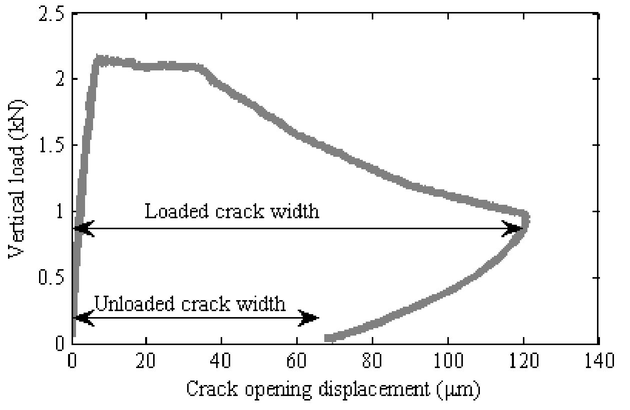

Figure 4: A typical load-displacement curve for wedge-splitting test (WST)

specimens, an approximately linear relation between the loaded and the unloaded crack width was found (Figure 5).

In total, five series of specimens were tested per concrete mixture. The series had different curing regimes: series 1 was cracked at 14 days and cured afterwards in a fog room (20 °C and 95% relative humidity), series 2 was cracked at 28 days and cured in a fog room, series 3 was cracked at 14 days and cured in water, series 4 was cracked at 28 days and cured in water, and series 5 was cracked only prior to chloride testing to prevent any healing. The nomenclature used for different series is given in Table 2. For each series, slump, air void content, and non-steady-state migration coefficient at 28 days (DRCM) according to [NT Build 492, 1999] were measured (Table 2). Note that the slump and the air void content are measured once per batch, while the DRCM value of each concrete batch is an average of

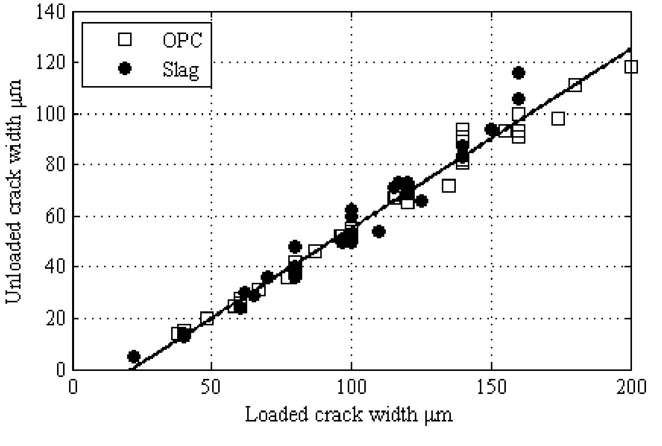

Figure 5: Loaded vs. unloaded crack width for all tested specimens

three measurements, compliant with [NT Build 492, 1999]. All series (except series 5) were cured after cracking as stated for more than 70 days prior to chloride exposure, making them around 3 months old at the age of testing (including the curing period). This was done to minimize the influence of concrete age on the results, since not all of them could be tested at the same time due to the limited number of RCM test setups. As previously stated, series 5 was tested shortly after cracking.

Prior to chloride testing, a 100 mm diameter core was drilled from each specimen (Figure 6). The cores were further cut in such a way that cylindrical specimens with about 90 mm thickness are obtained for chloride exposure.

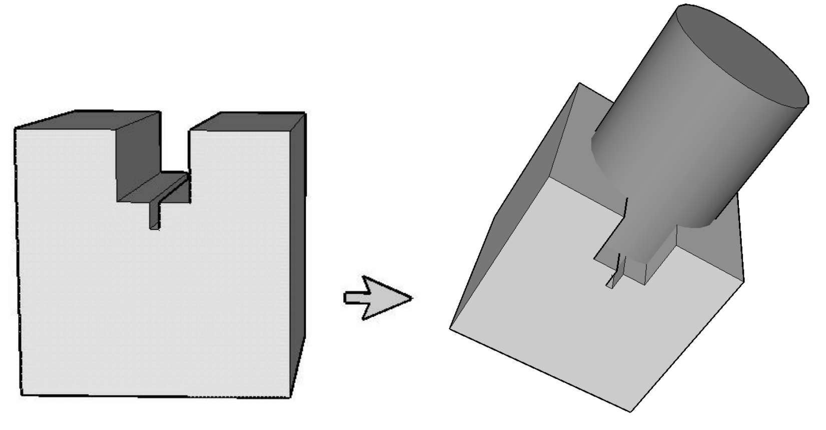

Figure 6: The coring procedure prior to the chloride exposure

Table 2: Properties of different mixes used in the study

Series	Slump (cm)	Air void content (%)	28 days D_{RCM} ($\cdot 10^{-12}$ m²/s)
14DaysFogOPC	8	3.1	9.76
28DaysFogOPC	7	2.75	12.54
14DaysWaterOPC	6	3	9.84
28DaysWaterOPC	5.5	1.35	12.03
NoHealingOPC	6	1.7	12.80
14DaysFogSlag	22	2.5	3.51
28DaysFogSlag	18	2.5	4.83
14DaysWaterSlag	21.5	1.9	3.68
28DaysWaterSlag	22	2.5	3.23
NoHealingSlag	19	3	4.25

The cracked specimens were tested in a modified Rapid Chloride Migration test [NT Build 492, 1999]. The modifications were the test duration and the specimen thickness, which is 50 mm in the standard test. A trial-and-error procedure was employed to obtain a reasonable test duration and voltage for each concrete mixture. The OPC specimens were tested using a voltage of 25 V for 12 hours, while the slag specimens were tested using a voltage of 50 V for 4 hours. After the chloride exposure, the specimens were split in the direction perpendicular to the crack, and then sprayed with $AgNO_3$ (silver nitrate) solution. The penetration depth was measured. The maximum penetration depth (penetration through the crack) was designated as P_{max}, and the average penetration depth (average of five measurements) in the uncracked part as P_0 (Figure 9). Their ratio was used to quantify the autogeneous healing.

3 Results and discussion

It is expected that cracks will exhibit either partial or full healing, depending on their width and the healing conditions (Figure 7). In Figure 8, a relationship between the loaded crack width and the maximum penetration depth (P_{max}), and the average penetration depth in the uncracked part of the specimen (P_0) is given for OPC and slag series, respectively. The relationship with the loaded crack width is shown first since there are indications that, after unloading, damage that has occurred may still have influence on the chloride ingress [Pease, 2009, Blagojević, 2016]. On the other hand, the unloaded crack width is the actual value which would be observed e.g. when inspecting a structure. As the crack partially closes upon unloading (see Figure 5), it might

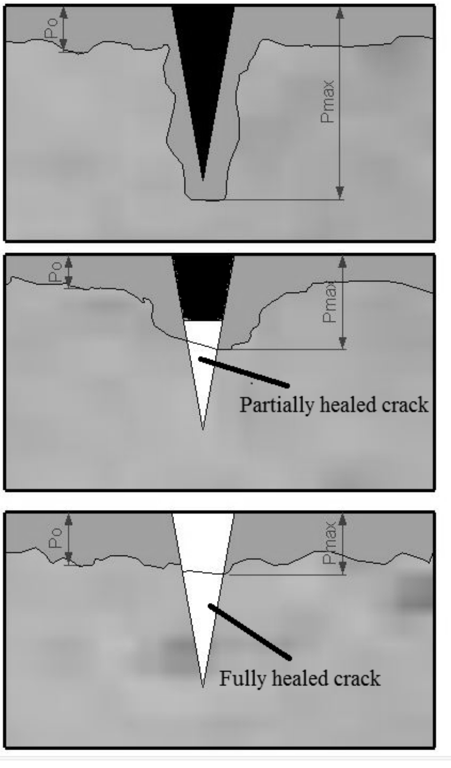

Figure 7: Schematic representation of partial and full healing of tapered cracks

be more important to see how the unloaded crack width influences the penetration depth. This relationship is shown in Figure 9. The NoHealing series of both mixtures exhibit the expected behavior: the penetration depth increases with the increase in crack width. This has to do with both the crack width and the crack depth (which was not measured): as the crack becomes wider, it also becomes deeper in the present setup. The obtained cracks are V shaped, similar to bending cracks. It is therefore expected that this trend would also increase for cracks larger than those studied. This would not be the case for parallel-walled

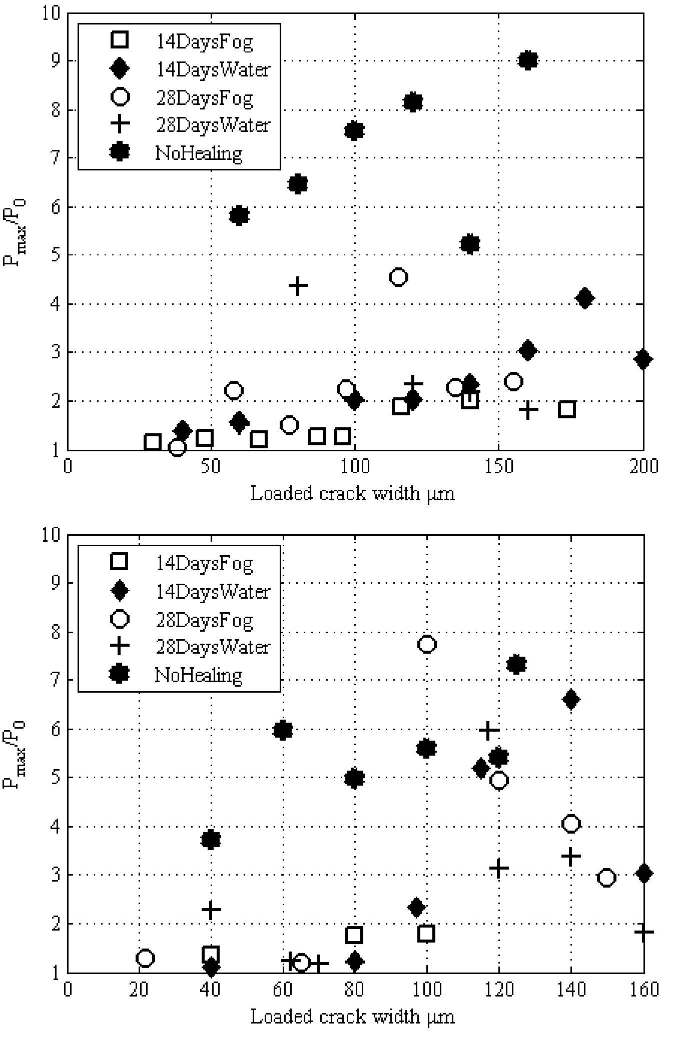

Figure 8: Influence of crack width on autogeneous healing (crack width before unloading) for OPC (top) and slag (bottom) mixtures

cracks, e.g. obtained by Brazilian splitting.

There is a marked difference between the NoHealing series and all others: namely, the maximum penetration depth is significantly lower in other series. This can probably be attributed to autogeneous healing of cracks.

From Figures 8 and 9, the maximum crack width which seems to have healed is about 60µm in the unloaded state (about 100µm in the loaded state) for all series subjected to healing. Chloride penetration in these cracks seems to be of the same order of magnitude

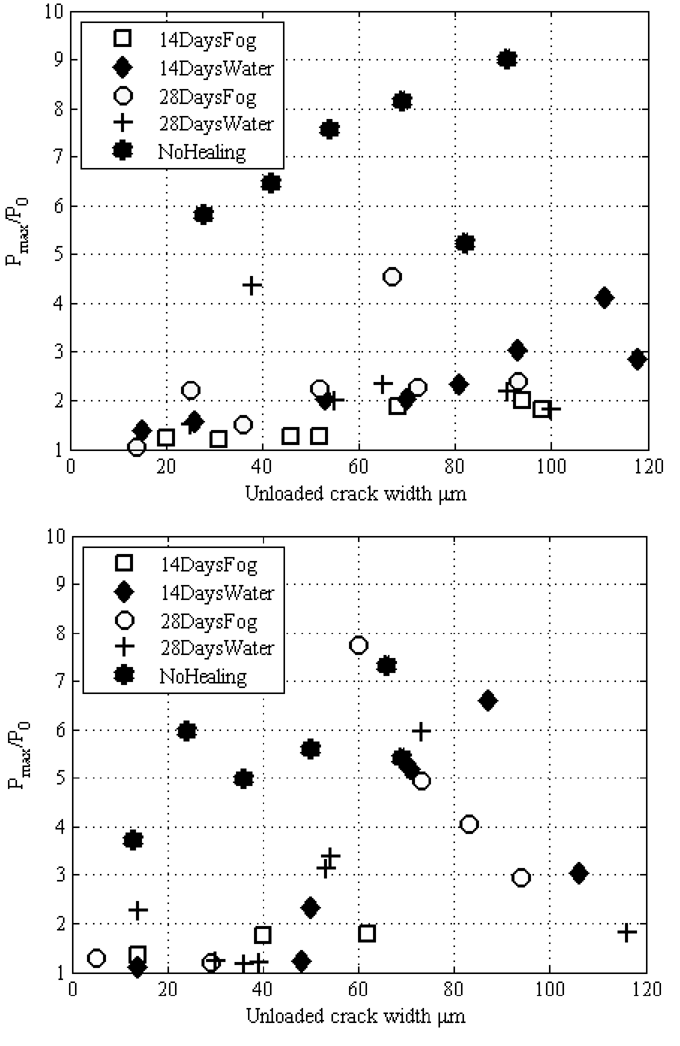

Figure 9: Influence of crack width on autogeneous healing (crack width after unloading) for OPC (top) and slag (bottom) mixtures

as in the uncracked material. Similar was observed by [Ismail et al., 2008]: they found that "in the case of fine cracks (<60 µm), the age at which the crack is induced influences the ability of self-healing to impede chloride diffusion - when the crack openings are 60 µm or more, the age at which the cracks were induced appears to have no significant effect on the ability of self-healing to impede chloride diffusion along the crack path". In the same study, larger cracks showed no autogeneous healing, due to their parallel walled shape. In the current study, it can be seen that larger cracks have partially recovered the resistance to chloride ingress, due to their tapered shape, which enabled the narrow part to heal (see Figure 7). Also, it seems that the resistance to chloride ingress of small cracks has recovered not only when cured under water, which was expected [Jacobsen et al., 1996], but also when specimens were cured in the fog room. This means that autogeneous healing of these cracks could be possible in real structures in humid climate, and not only in submerged conditions.

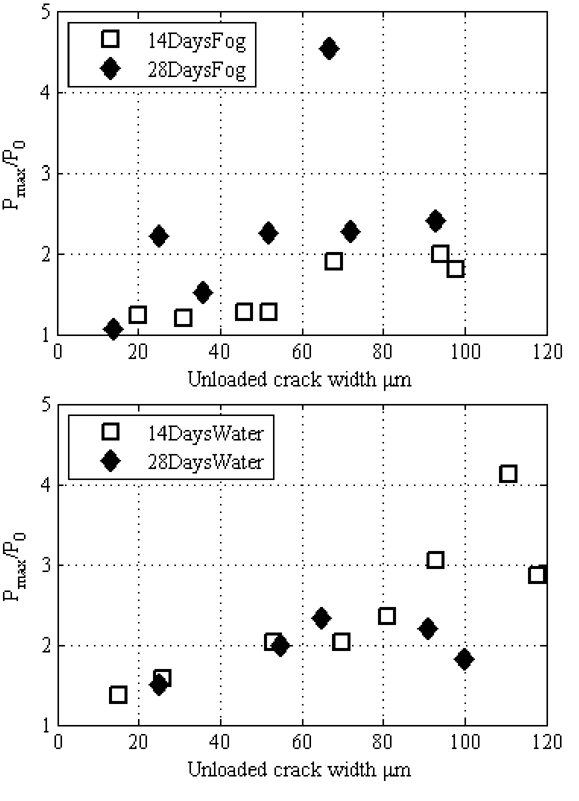

Figure 10: Influence of cracking age on autogeneous healing (OPC mixture) for specimens cured in fog room (top) and water (bottom)

The age at which concrete cracks could also potentially have an influence on the extent of autogeneous healing. [Ter Heide, 2005] studied crack healing in young concrete, and found that cracking age is a significant contributing factor. In her study, strength recovery of specimens cracked between 20 and 72 hours was studied. In the current study, two cracking ages were compared for both mixtures and healing conditions. The effect of cracking age on the P_{max}/P_0 ratio is given in Figure 10 for the OPC mix and in Figure 11 for the slag mix.

There is not much difference between specimens cracked at 14 and at 28 days in terms of autogeneous recovery of chloride resistance properties, judging by Figures 10 and 11. A slight difference can be observed for specimens cured in the fog room, where it seems that specimens cracked at 14 days show somewhat lower relative chloride penetration in the crack compared to those cracked at 28 days. This is possibly due to higher autogeneous healing capacity of the specimens cracked at an earlier age. [Ter Heide, 2005] observed a

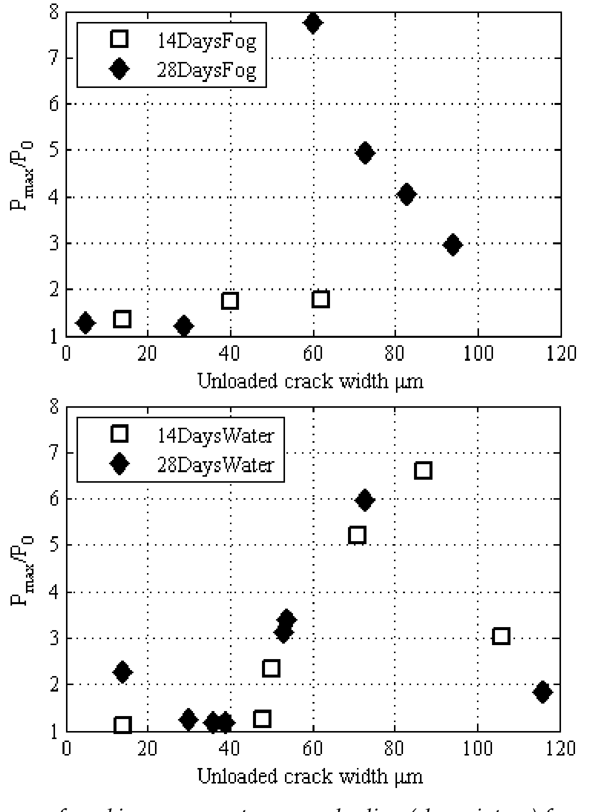

Figure 11: Influence of cracking age on autogeneous healing (slag mixture) for specimens cured in fog room (top) and water (bottom)

recovery in mechanical properties in specimens cracked at a very early age (3 days), but not in older specimens. Note, however, that the same trend was not observed for specimens cured under water. It is possible that the difference between 14 and 28 day series (for both curing conditions) exists but is not very significant due to the fact that the difference in degree of hydration between 14 and 28 day old specimens is not that high. Curing/healing conditions are another important factor. [Ter Heide, 2005] found that healing only occurred in specimens stored under water. [Yang et al., 2009] observed crack healing in ECC also under wet-dry cycles. In these studies, autogeneous healing was defined as recovery of mechanical properties. In the current study, however, recovery of resistance to chloride ingress is studied. The comparison is given in Figures 12 and 13 for OPC and slag mixtures, respectively.

No clear trends are observable here. It seems that there is no significant difference between

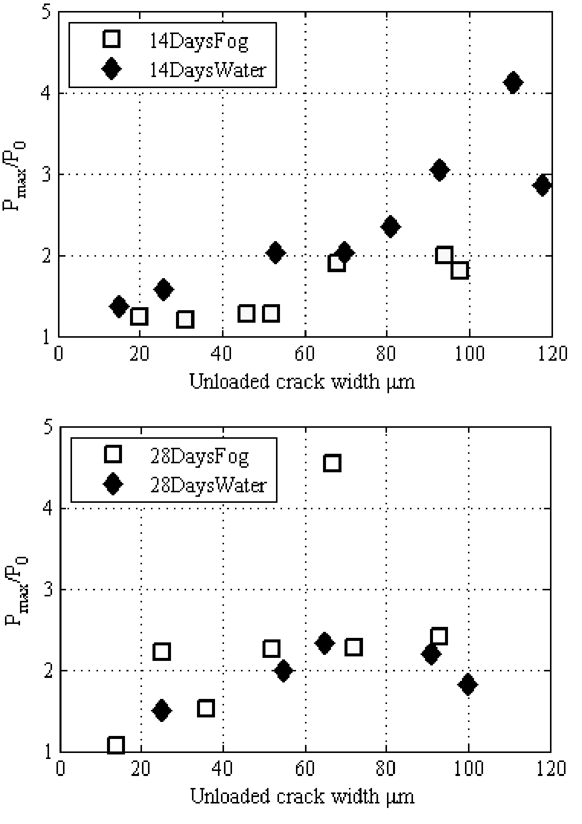

Figure 12: Influence of curing/healing conditions on autogeneous healing (OPC mixture) for specimens cracked after 14 (top) and 28 days (bottom)

specimens cured under water and those cured in the fog room. This seems to be the case for both specimens cracked at 14 days, and those cracked at 28 days. It seems that curing in the fog room provides a sufficiently moist environment for crack healing with respect to chloride transport. Prolonged curing under water is, therefore, not necessary. This may have some practical implications: in countries with high relative humidity environments and a lot of rainfall, such as the Netherlands, it is possible that small cracks heal without intervention by the contractor due to this mechanism.

It has to be noted that the observed absolute values for P_{max}/P_0 ratio are *specific* for tested mixtures, crack geometries and testing conditions (applied voltage and exposure duration). Studies by [Marsavina et al., 2009] and [Yoon and Schlangen, 2014] yielded somewhat different ratios, due to different experimental conditions. This is a limitation of the adopted accelerated setup, and one which limits its direct use in practice. This same was observed

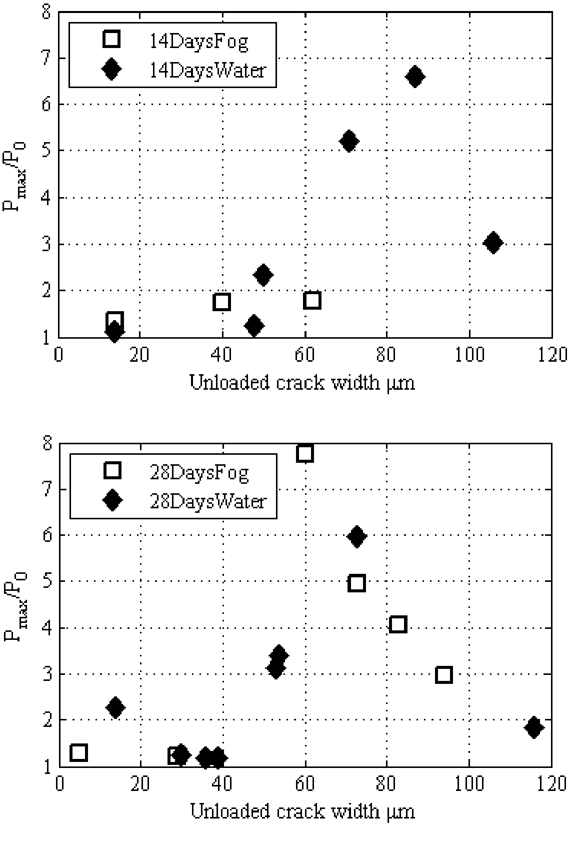

Figure 13: Influence of curing/healing conditions on autogeneous healing (slag mixture) for specimens cracked after 14 (top) and 28 days (bottom)

by numerical modeling of the Rapid Chloride Migration test [Šavija et al., 2014b]. Consequently, diffusion coefficients of cracked zones are not calculated here according to [NT Build 492, 1999]. Also, since different testing parameters were used for two tested mixtures (due to a significant difference in their transport properties), the results cannot be directly compared. The proposed test is, however, useful for comparative purposes. Its short duration enables it to discriminate between the autogeneous healing, which occurs prior to the chloride exposure, and its effect on the chloride ingress. In a long term (diffusion) experiment, these two would be coupled, since crack healing would occur during the chloride exposure (e.g. [Şahmaran, 2007; Ismail et al., 2008]). The diffusion test thus simulates well the conditions in submerged structures. The proposed test, however, mimics a case when a structure is built and loaded (cracked), and only after a certain period of time exposed to chloride load, such as de-icing salt exposure.

4 Conclusions

In this paper, an experimental study dealing with the relation between chloride ingress in cracks and autogeneous crack healing is presented. The study considered two concrete mixtures, two different cracking ages, two different curing/healing regimes (and a control mixture), and a range of crack widths. Based on the results presented, several conclusions can be drawn:

- For the NoHealing (control) series of both concrete mixtures, a nearly linear relation exists between the crack width (loaded or unloaded) and the relative maximum chloride penetration (i.e. P_{max}/P_0 ratio). This probably has to do with the increase of crack depth which follows the increase of crack width.
- For all series subjected to conditions suitable for autogeneous crack healing, a decrease in P_{max}/P_0 ratio is observed, compared to the control series. For cracks smaller than 60 μm (in the unloaded state), this ratio is close to unity, meaning that the cracks have fully recovered their resistance to chloride ingress (full crack healing, Figure 9) . For wider cracks, this ratio is higher, but still lower than that of the NoHealing series. This implies that wider cracks have partially recovered their ability to resist chloride ingress (partial crack healing, Figure 9).
- Cracking age in the tested range (14 and 28 days) does not seems to influence the ability of cracked specimens for autogeneous healing of their chloride resistance. A larger influence of cracking age could be expected for very early age (e.g. 3-7 days) and for very mature concrete. However, such ages were not studied.

- Both healing/curing regimes tested in this study (i.e. submerged and fog room conditions) enabled similar recovery of chloride resistance.

In this study, a potential of ordinary concrete mixes (i.e. mixes not engineered for self-healing) for autogeneous recovery of chloride resistance properties of cracks is proven. In the future, a wider range of healing/curing conditions should be studied, in order to determine which are the minimum conditions needed for crack healing (e.g. relative humidity and temperature and duration of curing). Also, a wider range of concrete mixtures could be studied (e.g. different w/c ratios and cement types). Furthermore, this study deals only with consequences of autogeneous healing (i.e. decrease in chloride ingress), and not with the mechanisms of autogeneous healing itself. This is beyond the scope of the current project.

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