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Effect of crack opening on the local diffusion of chloride in cracked mortar samples

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ABSTRACT

The paper presents an experimental study on chloride penetration in cracked mortar specimens. A mechanical expansive core was used to generate cracks of constant width across the thickness of the sample. Sixteen specimens with crack openings ranging from 6 to 325 µm were subjected to a test designed to allow chloride diffusion along the crack path for a period of 14 days. Chloride penetration tests were carried out on mortars at 28 days and 2 years. Relationships between crack opening and chloride–ion diffusion along a crack are presented and discussed. The results show that crack opening significantly affects chloride–ion diffusion along a crack. Overall, chloride diffusion along a crack decreases with crack opening. On the other hand, no chloride diffusion occurs in cracks with an opening of 30 µm or less. This crack-opening threshold agrees with the critical crack opening obtained from a stress-displacement curve of a mortar sample subjected to uniaxial tension. At crack openings greater than the threshold value, chloride diffusion along the crack path depends on mortar age. This result suggests that self-healing could reduce chloride diffusion in cracks.

1. Introduction

Concrete structures are frequently cracked by the action of different types of physico-chemical mechanisms (external loads, restrain shrinkage, internal expansion). Cracks could impair the durability of concrete structures by creating preferential paths for the penetration of various types of potentially aggressive agents (liquids, gases, and ions) [1]. Chloride ions are among the most common and aggressive agents for reinforced concrete structures. Recent experimental data indicates that chloride ion penetration is faster in cracked reinforced concrete beams [2]. Crack opening was found to be a key parameter controlling the local diffusion of chloride ions in a crack [3]. However, results indicate that no significant chloride diffusion occurs in crack having an opening below a critical value [4]. It was also found that self-healing can significantly reduce the rate of chloride migration in cracked concretes [5].

Self-healing (autogenous healing) refers to the cement's capability of healing cracks in fractured concrete [6]. Self-healing can involve physicochemical processes, such as ettringite and brucite formation and precipitation of calcium carbonate, or mechanical processes, such as the blocking of cracks by corrosion products or external particles [1,6,7]. Formation of hydration products (C–S–H, ettringite, portlandite) and calcium carbonates in cracks has been experimentally confirmed by SEM observation and XRD analysis [8].

It is important to discriminate between self-healing and self-sealing. Self-sealing is the phenomenon of time-dependent reduction of flow under saturated permeability conditions. Two major differences between self-healing and self-sealing are: a) major cracks are not a prerequisite for self-sealing and b) self-sealing is observed in closed systems where carbonation of dissolved $Ca(OH)_2$ is not possible [9].

Ismail et al. investigated the influence of crack opening on an inert material (brick) in order to avoid self-healing during the diffusion process along the crack path [4]. Deformation-controlled tensile tests were conducted to measure the mechanical critical crack opening of the brick. The mechanical critical crack opening represents the opening for which no stress transfer occurs between crack surfaces (cracks are considered completely separated). Experimental results show that the mechanical critical crack opening was approximately 50 µm and that the diffusion process along the crack path was strongly reduced with fine cracks (crack opening <53 µm). The authors concluded that the reduced diffusion capacity of chloride ions along such fine cracks could be explained by mechanical interaction between the fracture surfaces, tending to impede chloride diffusion.

2. Research significance and test program

The aim of this paper is to discriminate the effects of self-healing and mechanical interaction between crack surfaces on the local diffusion of chloride ions along a crack path. Testing to determine the diffusion of chloride ions along crack paths were performed on mortar samples with a constant water/cement ratio of 0.48. A mechanical expansive core was used to induce controlled cracking in doughnut-

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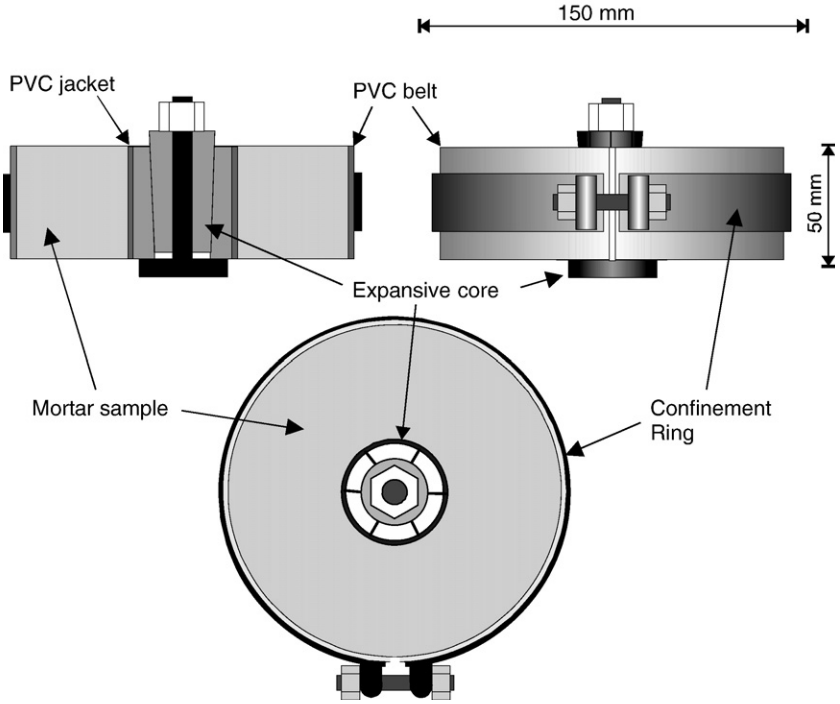

Fig. 1. Schematic view of the sample and the expansive core.

shaped mortar specimens. Twenty cracks, with openings ranging from 6 to 325 µm, were produced in 16 mortar samples. Two simulated cracks (81 and 225 µm) with flat fracture surfaces were also produced by cutting two samples with a thin precision circular saw. Simulated cracks were used to evaluate the effect of surface roughness on the local diffusion of chloride along the crack path. Cracks were induced in mortar samples at 28 days and 2 years in order to vary the self-healing potential of the cementitious matrix. Chloride penetration profiles obtained from mortar samples were compared to those previously obtained with an inert material (brick) using the same experimental approach [4]. The critical mechanical crack opening of the mortar was determined using a deformation-controlled tensile test.

3. Experimental methods

3.1. Materials

All the mortar samples were fabricated with a French cement CPA (CEMI 52.5R) having C_3S, C_2S, C_3A and C_4AF contents of, 65%, 5%, 11%, and 7% respectively (Bogue composition). The fine aggregate was a standard siliceous sand of 2 mm maximum size (CEN EN 196-1). Three 9.23-kg batches of mortar were produced in a 5-L mortar mixer. All the mortar mixtures were made with a water/cement of 0.48 and a sand/cement of 2.72. Each mortar mixture was made with 1.052 kg of water, 2.198 kg of cement, and 5.989 kg of sand.

The three mortar batches were used to produce seven disk-shaped samples with precision-machined PVC moulds with a thickness of 50 mm and an external diameter of 150 mm. A 50-mm-diameter Teflon insert was set into the central area of the mould in order to produce a doughnut-shaped sample after unmoulding [3]. The mould was filled in one step and vibrated for 30 s on a vibrating table. The fresh mortar surface was levelled and the moulds covered with a Plexiglas plate and wet burlap. After 24 h, the samples were carefully unmoulded to avoid any cracking, and stored in lime-saturated water until the age of 28 days. Observation with a portable video-microscope confirms the absence of surface cracking after the demoulding of samples. During the curing period, both annular faces of the samples

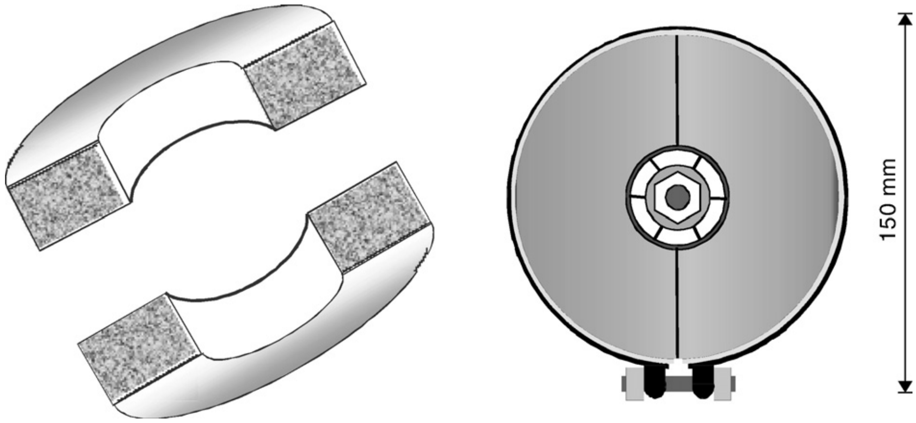

Fig. 2. Schematic view of the procedure used to produce simulated cracks.

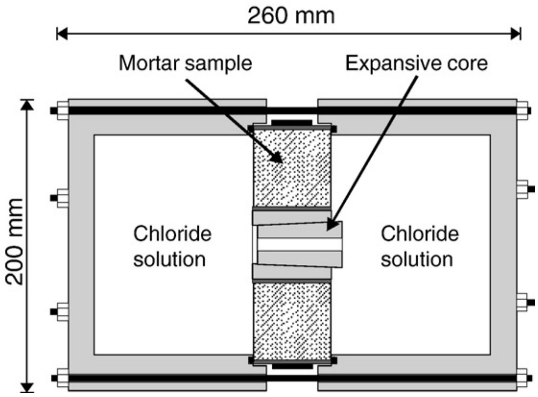

Fig. 3. Chloride penetration cell.

Table 1
Crack widths in samples cracked at 28 days

Sample	Crack Opening (μm)		
	Top	Bottom	Average
1	5	7	6
2	40	50	45
	50	60	55
3	14	22	18
	122	128	125
4	192	217	205
5	320	330	325
6	103	88	96
7	85	73	79
8	106	92	99
9	24	16	20
10	92	75	84

were polished with several grinding powders to obtain flat and smooth surfaces. A set of samples was kept in controlled environment (100% RH −20 °C) for 2 years.

3.2. Controlled cracking of the samples

Controlled cracking of the samples was performed with an experimental procedure used by Gagné et al. [3] and Ismail et al. [4]. The samples were subjected to controlled tensile cracking with a mechanical expansive core and an external confinement steel ring (Fig. 1). Simulated cracks were produced but saw-cutting samples in two identical pieces (Fig. 2). Both pieces were confined around the expansive core using an external confinement steel ring. The deformation of the expansive core and of the confinement pressure applied by the external steel ring were adjusted to produce simulated cracks with selected crack openings.

3.3. Chloride penetration cell

Immediately after being cracked, the samples were fitted into a chloride penetration cell (Fig. 3) along with the expansive core and the confinement ring. The cell consists of the two cylindrical PVC containers approximately 1-L in capacity. Six threaded metal rods with tightening nuts hold the two containers firmly against the sides of the sample.

An O-ring provides a watertight seal between the flat surface of the sample and the container's edges. The cell (both sides of the sample) is filled with a chloride solution comprised of 1 g/L of NaOH, 4.65 g/L of KOH and 32.99 g/L of NaCl in demineralized water.

3.4. Determination of chloride concentration profiles

Two types of concentration profiles were determined: perpendicular to the surface and perpendicular to the crack path. All the profiles include data points obtained at depths of 1, 3, 5, 7, 9, 11, and 13 mm, according to a procedure used by Gagné et al. [3].

An initial surface profile was obtained from an intact sample exposed to the chloride solution for 14 days. This profile was used to assess the maximum depth of chloride penetration of chloride in an intact sample. A second surface profile was obtained from a reference sample not exposed to the chloride solution. This profile was used to establish the baseline chloride concentration in the reference sample.

The perpendicular-to-crack profiles were determined by breaking the sample in order to split the crack plane and expose the two crack walls (Fig. 4). A grinding technique was used for sampling the powders at different depths behind the crack wall [3,4]. The grinding areas, measuring 30 × 15 mm, were located in the center of the crack plane to allow at least 17 mm between the boundary of the grinding zone and the two exposed surfaces (Fig. 4). The location of the perpendicular-to-crack penetration profiles was set sufficiently high (17 mm below the exposed surface) to ensure that the powder samples would contain only chloride ions originating from the crack plane and not from the sample surface (Fig. 4).

Each data point in the perpendicular-to-crack profile comes from one powder sample obtained by mixing both powder samples from each face of the crack plane. The measurement error in the depth of the data points in the perpendicular-to-crack profiles was estimated at ±1 mm, due to the slightly uneven surface of the crack plane.

4. Results

4.1. Crack characteristics

Cracks were created in samples divided in two age groups. The first group contains the 28-day samples; the second contains the 2-year samples.

Ten samples were cracked at 28 days with the expansive core. The cracking process usually generates one or two random cracks. One crack was created in Samples 1, 4, 5, 6, 7, 8, 9, and 10. Two cracks were created in Samples 2 and 3. Table 1 shows the crack width measured on the top and bottom annular surfaces of each sample and their average widths. Each crack width on the top and bottom is the average of 10 measurements taken along the crack path using a portable video-microscope. The video-microscope includes measurement software with maximum enlargement of 175X. A difference of less than

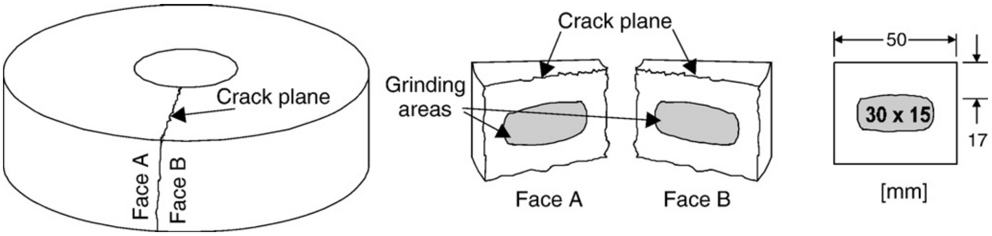

Fig. 4. Grinding areas used for the perpendicular-to-crack profiles.

20 μm was measured between the top and bottom surfaces, except in the case of Sample 4, which yielded a difference of 25 μm.

Six samples were cracked at 2 years using the expansive core. One crack was induced in Samples 2, 3, 4, and 5; two cracks were induced in Samples 1 and 6. Table 2 shows the crack width measured on the top and bottom annular surfaces of each sample and their average widths. Each crack width on the top and bottom is the average of 10 measurements taken along the crack path. A difference of less than 20 μm was measured between the top and bottom surfaces, except in the case of Sample 6, which yielded a difference of 25 μm.

4.2. Chloride penetration profiles

The total chloride penetration profiles, measured both from the sample surface and perpendicular to crack walls, are shown in Fig. 5 for samples at 28 days and in Fig. 6 for samples at 2 years. The reference profile indicates that the total chloride content supplied by the mortar constituents (water, cement, and sand) is relatively low and usually under 0.01% (weight of mortar).

The surface profile shows that, after 14 days of exposure, the chloride penetration depth is approximately 8 mm. This confirms that the chloride concentration in the grinding area used to measure the perpendicular-to-crack profiles was only affected by chloride ions entering via the crack plane and not from the exposed surface.

Fig. 5 shows three groups of chloride penetration profiles obtained from mortars cracked at 28 days. The first group includes crack widths of 125 μm or more. The perpendicular-to-crack profiles are very similar to the surface profile, since all the near-surface concentrations range from 0.20% to 0.25% and the maximum depth of penetration is 8 mm for all these cracks. These results suggest that, for crack widths of 125 μm or more, the rate of chloride penetration perpendicular to crack walls is not restricted by the liquid-phase diffusion of chloride along the crack path.

The second group includes crack widths of 55 μm or less. The perpendicular-to-crack profiles are very similar to the base profile of the reference mortar. A slight concentration drop is observed between 1 mm and 7 mm behind the crack wall. The concentration gradient is very small (<0.02%) and can probably be considered trivial compared to the precision of the sampling and the chloride concentration procedures. The results suggest that a crack opening in the 55–79 μm range marks the threshold below which the diffusion process of chloride along the crack path appears to be a limiting factor controlling the diffusion process perpendicular to crack wall.

The last group of curves includes crack widths ranging from 79 μm to 99 μm. Although the chloride profiles in this case differ from the surface profiles, diffusion still occurs along the crack path. Restriction, however, was observed in the diffusion process along the crack path.

Fig. 6 shows four groups of chloride penetration profiles obtained from mortars cracked at 2 years. The first includes a crack width of 322 μm. The perpendicular-to-crack profile is very similar to the surface profile. The second group includes a single crack of 29 μm. The perpendicular-to-crack profile is similar to the base profile of the reference mortar except for the first millimeter. A slight concentration drop is observed between 1 mm and 3 mm behind the crack wall. Again, the concentration gradient is very small (<0.04%) and can be considered trivial compared to the precision of the sampling and chloride concentration procedures.

Table 2
Crack widths in samples cracked at 2 years

Sample	Crack Opening (μm)		
	Top	Bottom	Average
1	20	37	29
	97	81	89
2	53	43	48
3	75	93	84
4	104	84	94
5	138	119	129
6	181	175	178
	334	309	322

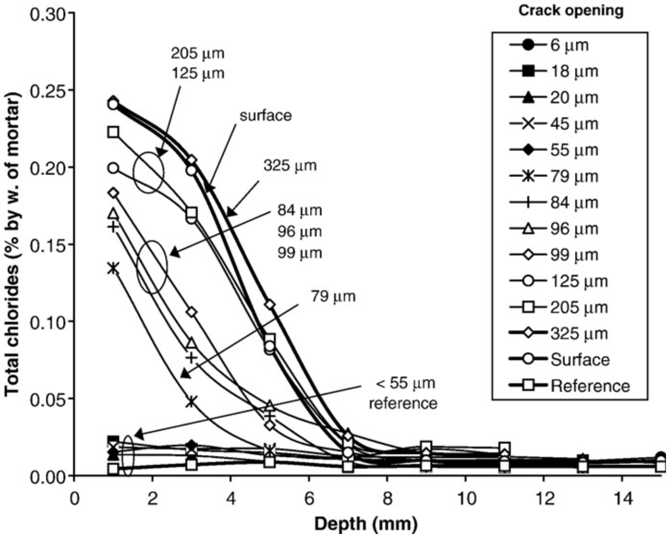

Fig. 5. Perpendicular-to-crack chloride penetration profiles, surface profile and reference profile in samples cracked at the age of 28 days.

The third group includes cracks widths ranging from 84 μm to 178 μm. The chloride profiles are different than the surface profile, but diffusion still occurs along the crack path. The fourth group includes a single crack of 48 μm. Chloride concentration values are among the lowest, but the values are too high to be included in the second group of curves (baseline concentration).

4.3. Deformation-controlled uniaxial tensile testing

According to fracture mechanics, most brittle materials like concrete exhibit nonlinear behavior due to the stress transfer between the fractured surfaces. The stress transferring capacity depends on the tortuosity of the crack path and is generally determined by the relationship between crack opening and crack normal stress (σ–w relationship). This relation makes it possible to determine an average maximum

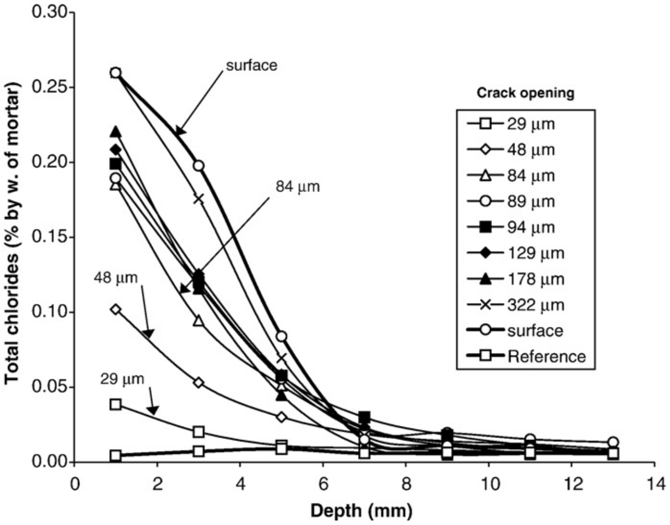

Fig. 6. Perpendicular-to-crack chloride penetration profiles, surface profile and reference profile in samples cracked at the age of 2 years.

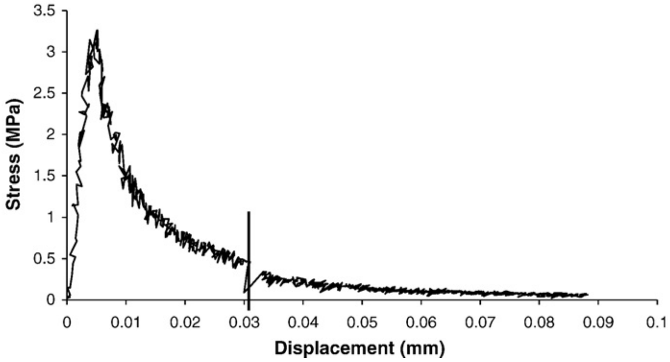

Fig. 7. Stress-displacement curve in uniaxial testing.

crack opening (w_c), which is a material property, called the mechanical critical crack opening. This is the crack opening at which crack surfaces are completely separated and no stress transfer occurs. Deformation-controlled uniaxial tensile test is the most direct way of obtaining the σ–w relationship. Since crack opening cannot be measured directly, it must be derived from total deformation [10]. This approach assumes that the crack opening is equal to the total deformation minus elastic deformation. A detailed experimental procedure used to asses the mechanical critical crack opening can be found elsewhere [4].

Fig. 7 shows the stress-displacement curve obtained under uniaxial tensile testing. The σ–w relationship in Fig. 8 indicates that the critical crack opening is approximately 30 µm. This value is a material property of the concrete and is not significantly affected by concrete maturity. No mechanical interactions occur between the fracture surfaces when the crack openings are greater that the critical value. Therefore, crack path can be considered continuous. Mechanical interactions between fracture surfaces can still occur for crack opening below the critical value. The crack path is segmented by hydrates bridges impeding the local diffusion of chlorides along the crack.

5. Discussion

Fig. 9 shows some selected chlorides penetration profiles obtained from 28-day mortars (Fig. 5) and from 2-year mortars (Fig. 6). Two additional profiles obtained with simulated cracks are also provided. The chloride concentration profile for a 60 µm crack in an inert material is given as a reference [4]. The total chloride concentrations are indicated as percentages of the total chloride concentration measured at 1 mm under the surface (surface profile) of samples tested at the same age (28 days and 2 years).

The curves in Fig. 9 indicate that the chloride diffusion perpendicular to the crack wall in large cracks (width ≥205 µm) is similar to that for the surface. In such large cracks, the chloride diffusion in the solution filling the crack is not a limiting factor controlling the diffusion process perpendicular to the crack wall, regardless of the age at which the mortar was cracked. These results suggest that the lower diffusion profiles could be due to the restriction of chloride ions diffusion in the liquid phase within the cracks. In fact, the diffusion coefficient does not change because the materiel remains the same. However, the profiles change because the boundary conditions are modified. When the crack opening decreases, the chloride concentration on the surface of cracks also decreases.

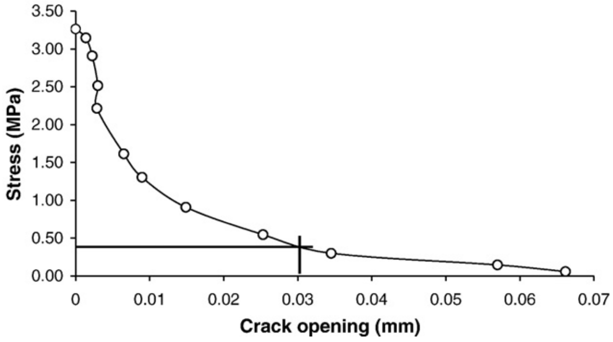

Fig. 8. Stress-crack opening relationship.

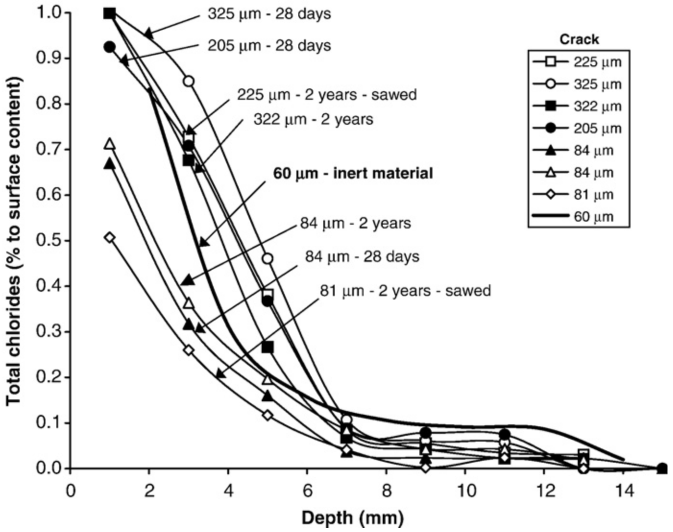

Fig. 9. Selected chlorides penetration profiles obtained from mortars at 28 days and 2 years.

The penetration profile obtained from a simulated crack of 225 µm agrees with those obtained from other large cracks This indicates that the tortuosity of the crack path is not a key parameter controlling chloride diffusion in such large cracks.

The chloride concentration profiles obtained with 80–100 µm cracks indicate that the diffusion process still occurs in such fine cracks, but at a significantly lower level (Figs. 5 and 6). Experimental results indicate that diffusion is reduced by a factor of about 2, regardless of the age at which the mortar was cracked. The concentration profile obtained from a simulated crack of 81 µm confirms the results obtained from normal cracks of similar width. Again, the similitude between the

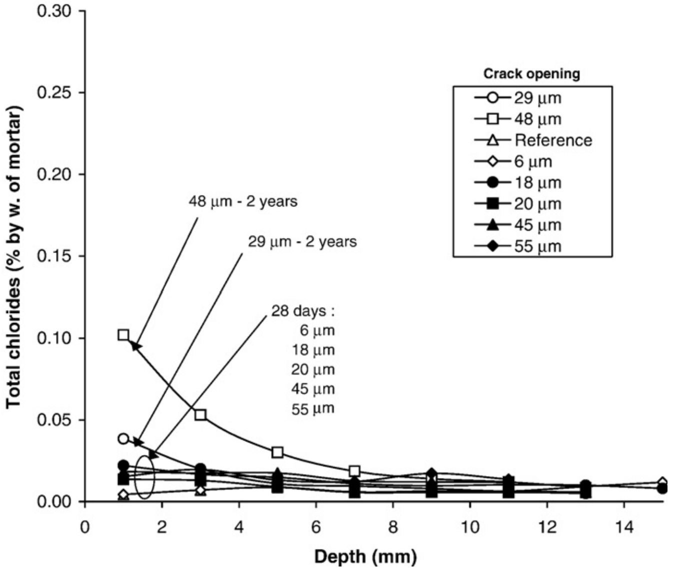

Fig. 10. Perpendicular-to-crack chloride penetration profiles in fine cracks (mortars at 28 days and 2 years).

chloride concentration profiles obtained for both the natural and simulated cracks indicates the tortuosity of the crack path is not a key parameter controlling chloride diffusion.

Comparison between the chloride penetration profile obtained with a 60 µm crack in an inert material and those obtained with 84 µm cracks (at 28 days and 2 years) in mortar samples give additional information on the effect of material type on the local diffusion of chlorides along a crack path. The results produced by Ismail et al. [4] for an inert material, such as brick, indicate that chloride diffusion along a crack path is not restricted for cracks as fine as 60 µm (Fig. 9). In the case of mortar samples, the results indicate that chloride diffusion had been significantly impeded in cracks of about 81 to 84 µm, regardless of the age at which the cracks were formed (Fig. 9). These results suggest that the self-healing potential of the mortar matrix can impede the chloride diffusion along a crack path. In the case of large cracks (>60 µm), however, the age at which the crack is formed appears to have no significant effect on the ability of self-healing to impede chloride diffusion along a crack path.

Chloride concentration profiles obtained with crack openings of 55 µm or less are shown in Fig. 10. In mortar samples in which the cracks were formed at 28 days, chloride diffusion along the crack path is totally blocked when the crack opening is 55 µm or less. In mortar samples in which the cracks were induced at 2 years, chloride diffusion along the crack path still occurs in 29 µm and 48 µm cracks. These results confirm that the self-healing potential of mortar matrixes can impede chloride diffusion along a crack path. The effect of self-healing on the reduction of chloride diffusion in fine cracks (<60 µm) is stronger when the cracks are induced in young mortars (28-d). However, for crack opening lower than the critical mechanical opening (30 µm), no chloride diffusion occurs along the crack path, regardless the age at which the crack was induced.

6. Conclusion

The following conclusions can be drawn from the results of this research:

- The diffusion of chloride in the solution filling cracks with an opening greater than 200 µm is not a limiting factor controlling the diffusion process perpendicular to the crack wall, regardless of the age at which the mortar was cracked.
- The results obtained with 80–100-µm cracks indicate that the diffusion process still occurs, but at a much slower rate. Experimental results indicate that diffusion is reduced by a factor of about 2, regardless of the age at which when the mortar was cracked.
- The self-healing potential of the mortar matrix can impede the chloride diffusion along a crack path. When the crack openings are 60 µm or more, the age at which the crack is induced appears to have no significant effect on the ability of self-healing to impede chloride diffusion along a crack path.
- 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. The effect of self-healing on reducing chloride diffusion in fine cracks is greater in young mortars (28-d).
- For crack opening lower than the critical mechanical opening (30 µm), no chloride diffusion occurs along the crack path, regardless the age at which the crack was induced.

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