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Effect of crack opening on the local diffusion of chloride in inert materials

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Abstract

The paper addresses the problem of the effect of crack opening on the ability of chloride ions to diffuse along a crack. Experimental tests are carried out on an inert material (brick) to prevent crack self-healing. A mechanical expansive core is used to generate cracks of constant width across the thickness of the sample. Five cracked specimens with crack openings ranging from 21 to 128 μm were exposed to a chloride solution for 10 h and then removed to determine the total chloride concentration perpendicular to the crack path. The results show that crack opening significantly influences the ability of chloride ions to diffuse along a crack. Indeed, the chloride profiles indicate impediment of chloride-diffusion capacity in cracks less than 53 μm in width. It was found that this crack-opening threshold agrees with the critical crack opening measured in a uniaxial tensile test that characterizes the interaction phenomena between the fracture surfaces.

Keywords: Crack; Diffusion; Chloride; Self-healing; Brick

1. Introduction

Cracks arise during all stages in the life of a concrete structure. They can be induced by load or volumetric charge due to plastic settlement, high curing temperature, various types of shrinkage, creep, and deteriorating mechanisms such as frost and alkali aggregate reaction [1]. These cracks can have negative effects on important parameters such as permeability and rate of chloride ingress, thereby affecting reinforcement-corrosion protection [2] because they can act as preferential channels for the penetration of different types of potentially aggressive agents such as liquids, gases, and ions [1].

The term autogenous healing refers to the ability of cement to heal cracks in fractured concrete. This process commonly occurs in concrete water-storage structures, culverts, and pipes [3]. Various types of crack healing have been reported in the literature. The process can involve a physicochemical process such as ettringite formation or a mechanical one such as the blocking of cracks by rust, corrosion products, or exterior particles. Regardless of origin, self-healing leads to the crack closing, thus improving mechanical, durability, and permeability properties [4]. According to Edvardsen [4], the greatest autogenous-healing effect occurs within the first 3–5 days of water exposure, depending on the crack width and water pressure. This is due to the precipitation of calcium-carbonate crystals ($CaCO_3$) in the crack.

In a study on concretes continuously hydrated for 26 years, Hearn et al. [5] used backscattered electron images that show that they exhibit self-sealing behavior, despite the fact that no unhydrated cement remains in the specimens.

Jacobsen and Sellevold [6] have studied self-healing in high-strength concrete specimens deteriorated by freeze–thaw cycles and stored in water for 2–3 months. The results show that concretes that had lost as much as 50% of their initial relative dynamic modulus during freezing and thawing could almost completely recover during storage in water. Moreover, the compressive strength of high-strength concrete showed reductions of 22–29% on specimens damaged by freeze–thaw compared with only 4–5% recovery on self-healing.

Gagné et al. [7] recently investigated the influence of crack opening and self-healing on the ability of chloride ions to diffuse along a crack path. The total chloride-concentration profiles perpendicular to the crack path indicate no significant chloride penetration for cracks widths

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measuring less than 55 μm. These results suggest that the diffusion process of chloride along the crack path is considerably slower, probably due to self-healing, and appears to be a limiting factor controlling the diffusion process perpendicular to the crack path.

This paper aims at dissociating the combined effects of the crack opening and self-healing on local chloride penetration. For this purpose, an inert material (brick) was chosen in order to avoid potential chemical reactions primarily due to the hydration process in the case of the cement-based materials. A uniaxial tensile test was conducted on notched samples to evaluate the material's fracture response. Comparison between results of diffusion in various crack openings makes it possible to assess the role of the interaction between the fractured surfaces on the reduction in local chloride diffusion. Further experiments investigating chloride diffusion in cracked mortars are still underway to discriminate between the effect of healing and interaction between cracked surfaces.

2. Experimental methods

2.1. Controlled cracking of the brick disks

An experimental procedure developed by Gagné et al. [7] was used to control cracking of the brick disks. The samples were subjected to controlled tensile cracking using a mechanical expansive core and an external confinement steel ring (Figs. 1 and 2). The expansive core, which is inserted into the sample hub, consists of a conical hardened-steel cylinder that slides within a set of six conical hardened-steel petals. A high-strength steel bolt and nut are used to force the conical cylinders against the petals. This process causes the PVC jacket to increase, which induces deformation in the internal diameter of the sample. Controlled cracking is achieved by adjusting the deformation of the expansive core and the confining force applied by the external steel ring. A 3-mm-thick PVC belt is wrapped around the outside of the sample in order to facilitate applying uniform confining pressure around the sample.

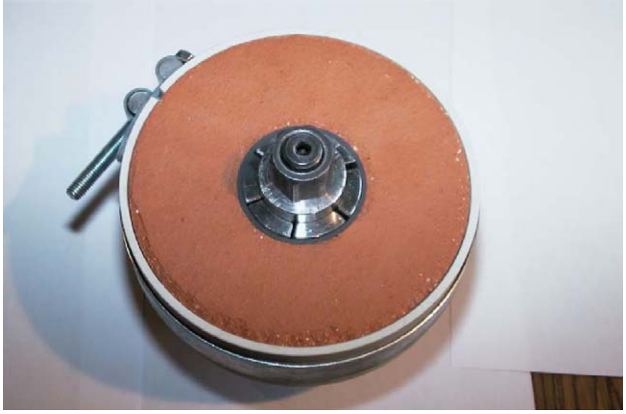

Fig.1. Brick disk in the PVC belt.

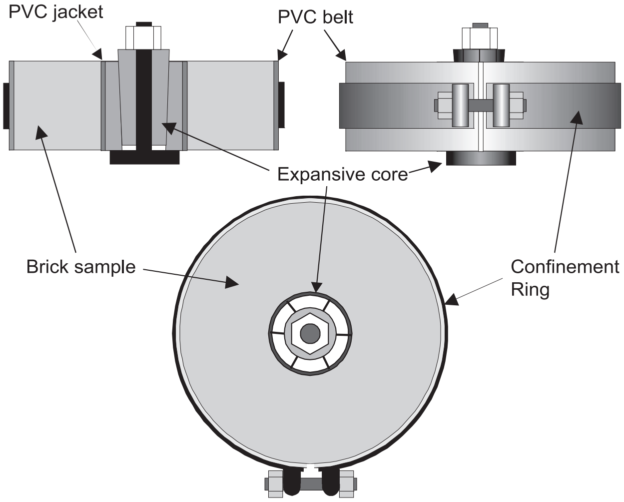

Fig. 2. Schematic view of the sample and the expansive core.

The first step in the cracking process is to firmly tighten the confining ring using the external adjusting bolt. The second step is to tighten the expansive core bolt to induce internal pressure in the sample core. No cracks are generated up to this point. One or two cracks of controlled width can be generated by slowly releasing the confining ring by loosening the ringbolt.

After each step in the loosening process, the sample surfaces (top and bottom) are scanned with a portable videomicroscope to detect the location of the first crack. At this point, crack width can be adjusted by balancing the internal deformation of the expansive core and the external confining force. When the required cracking opening is achieved, the expansive core nut and bolt can be removed since the friction between the conical cylinder and the six conical petals is great enough to firmly hold the assembly in its final position.

2.2. Materials

All the tests were conducted on the brick disks with a thickness of 50 mm, an external diameter of 150 mm, and an internal diameter of 50 mm (Fig. 1). These samples were cores from 400 × 200 × 50 mm blocks.

2.3. Chloride penetration cell

Immediately after being cracked, the samples were saturated with demineralized water for 10 h at 20 °C. Then they were fitted into the 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.

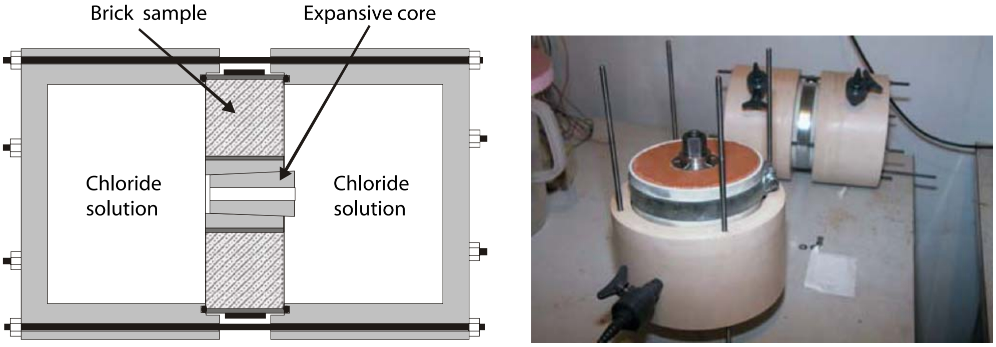

Fig. 3. Chloride penetration cell.

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.

2.4. Determination of chloride concentration profiles

Two types of concentration profiles were determined: perpendicular to the surface and perpendicular to the crack path. Each total chloride profile was determined from powder samples of 1.5–4 g obtained with a Germann Instruments Rapid Chloride Test RCT sampling device.

The device uses a high-speed rotating diamond bit to grind a 30-mm diameter area on the sample profile. All the profiles include data points obtained at depths of 2, 4, 6, 8, 10, 12, and 14 mm. The total chloride content, expressed as a percent weight of the powder, was determined after exposure to diluted HNO_3 at 80 °C for 30 min. After filtration, the total chloride concentration was determined by potentiometric titration using 0.01 N $AgNO_3$.

An initial surface profile was obtained from an intact sample exposed to the chloride solution for 10 h. This profile was used to assess the maximum depth of penetration of chloride in an intact sample. A second surface profile was obtained from a reference sample without exposure 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). The same grinding technique was used for sampling the powders at different depths behind the crack wall. However, 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 exposed surface) to ensure that the powder samples would contain only chloride ions originating from the crack plane and not from the sample surface (Figs. 4 and 5).

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 is estimated at ± 1 mm due to the slightly uneven surface of the crack plane.

3. Results

3.1. Crack characteristics

Five samples were cracked using the expansive core. Table 1 shows the measured crack widths 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 15 μm was measured between the top

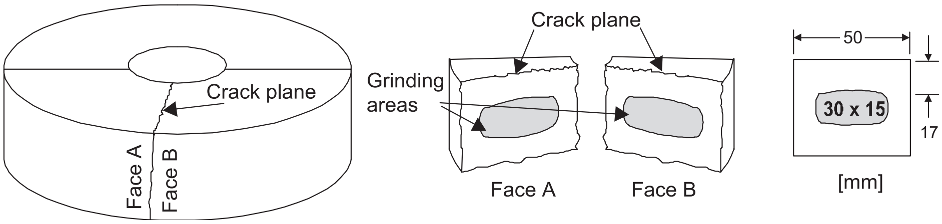

Fig. 4. Grinding areas used for the perpendicular-to-crack profiles.

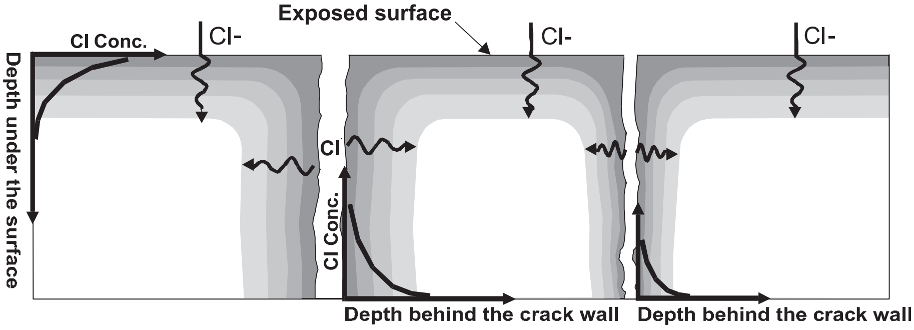

Fig. 5. Location of surface and perpendicular-to-crack concentration profiles.

and bottom surfaces, except for Sample 3, which yielded a difference of 45 μm.

3.2. Chloride penetration profiles

The total chloride penetration profiles, measured both from the sample surface and perpendicular to crack walls, are shown in (Fig. 6). The profile indicated by 'reference' represents the total chloride content supplied by the brick constituents. This profile indicates that the initial chloride content is relatively low, usually less than 0.01% (weight of material). The surface profile shows that after 10 h 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 (the grinding area is located from 17 to 25 mm under the exposed surface), see Fig. 4.

Fig. 6 shows two groups of curves:

For crack widths of 60 μm or more, the perpendicular-to-crack profiles are very similar to the surface profile (the concentration near the surface is between 0.18% and 0.20%; the maximum depth of penetration is 8 mm). These results suggest that for crack widths of 60 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.

For crack widths measuring 53 μm or less, the perpendicular-to-crack profiles show a chloride concentration drop near the surface (0.03–0.07%). This crack opening (53 μm) 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.

Table 1
Crack widths in samples

Sample	Crack opening (μm)		
	Top	Bottom	Average
1	135	121	128
2	66	54	60
3	75	31	53
4	28	40	34
5	23	19	21

3.3. Deformation-controlled uniaxial tensile testing

According to fracture mechanics, most brittle materials like concrete and ceramics exhibit nonlinear behavior due to the stress transfer between the fractured surfaces. The stress-transferring capacity depends on the tortuosity of the crack path; it is generally determined by the relation between crack opening and crack normal stress ($\sigma-w$ relation). From this relation, it is possible to determine an average maximum crack opening (w_c), which is a material property called the critical crack opening. This is the crack opening at which crack surfaces are completely separated and no stress transfer occurs.

The most direct way to obtain the $\sigma-w$ relation remains a deformation-controlled uniaxial tensile test. Since crack opening cannot be measured directly, it must be derived from total deformation. The procedure described in [8] was used. This approach assumes that the

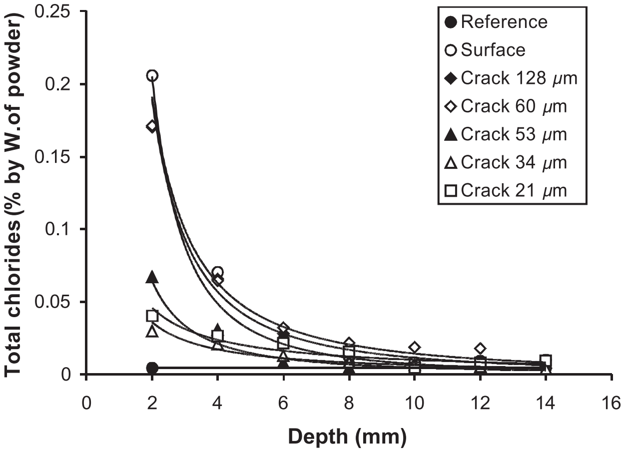

Fig. 6. Reference profile, surface profile, and perpendicular-to-crack penetration profile in the samples after 10 h in chloride solution.

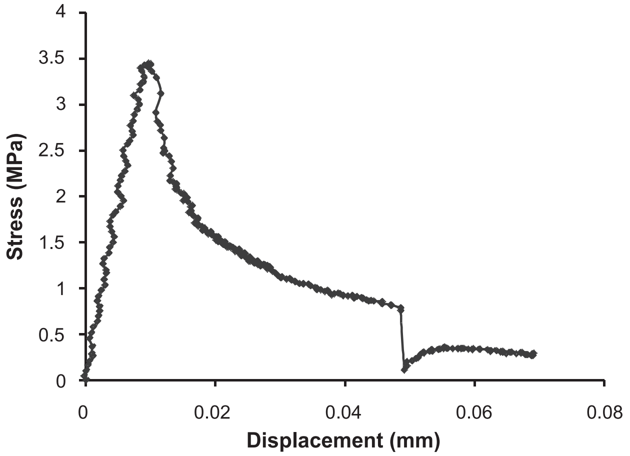

Fig. 7. Stress–displacement curve in uniaxial testing.

crack opening is equal to total deformation minus elastic deformation.

Tensile testing was carried out on a notched cylindrical brick specimen measuring 50 mm in diameter and 100 mm high. A saw cut measuring 5 mm deep and 2.5 mm wide was made in the middle of the specimen to allow cracking to occur at a predetermined place. Three linear variable differential transducers (LVDTs), with a measuring length of 25 mm, were attached to the specimen across the saw cut (120° between each LVDT). The average signal of the three LVDTs is used as a deformation control parameter. An Instron testing machine with a loading rate of 5 μm/min was used for the experiments.

Fig. 7 shows the recorded stress-displacement curve obtained in uniaxial tensile testing; Fig. 8 shows the corresponding $\sigma - w$ relation. The curve in Fig. 8 shows that the critical crack opening is approximately 50 μm. This value is characteristic of the brick tested. Crack widths greater than this critical opening correspond to cracks without mechanical interactions between the fracture surfaces. Due to this interaction, cracks having an opening less than the critical value could expect to have an effect on diffusion.

4. Discussion

The experimental results show that the diffusion processes of chloride perpendicular to the crack wall in relatively large cracks (width >60 μm) is similar to that of the surface. Therefore, in such large cracks, the diffusion of chloride in the solution filling the crack is not a limiting factor controlling the diffusion process perpendicular to the crack wall.

In the case of the fine cracks (width <53 μm), 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. Indeed, the measured critical crack opening was approximately 50 μm, which corresponds to the diffusion threshold in cracks.

These results suggest that in cementitious systems, two mechanisms could account for the reduced chloride diffusion the path of a fine crack path:

1. Mechanical interactions between the fractured surfaces when the crack opening is less than the critical value.
2. Self-healing that leads to deposition of hydration products in the crack path.

5. Conclusion

This paper dealt with the ability of chloride ions to diffuse along a crack in an inert material. The crack openings of 21, 34, 53, 60, and 128 μm were induced and controlled by using a mechanical expansive core and a confining ring. The concentration profiles perpendicular to the crack wall were measured with a chloride penetration cell.

All the perpendicular-to-crack profiles for cracks 60 μm or wider are very similar to that of the surface profile. This suggests that the rate of chloride penetration perpendicular to crack walls is not restricted by the liquid-phase diffusion of chloride along the crack path when this procedure is used. For crack widths measuring 53 μm or less, the perpendicular-to-crack profiles indicate no significant chloride penetration.

The results suggest that the diffusion process of chloride along the crack path is considerably slower, probably due to mechanical interactions between the fracture surfaces, which still exist for values of crack widths less than the critical crack opening (50 μm).

Further experiments on diffusion in cracks in mortars and concrete are currently being conducted to study the coupled effect of mechanical interactions between the fracture surfaces and self-healing, which is often used to explain the reduction of chloride penetration in cracks.

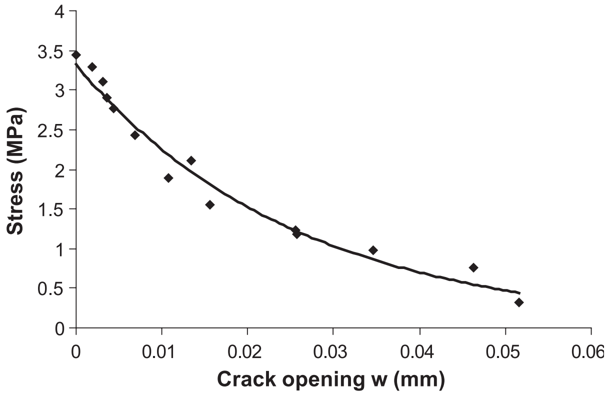

Fig. 8. Stress-crack opening relation.

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