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Influence of Cracks on the Efficiency of Surface Impregnation of Concrete

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Abstract

Surface impregnation with liquid silanes, if properly carried out, is a reliable protective measure for extending the service life of reinforced concrete structures. However, the question as to whether surface impregnation will also extend service life if the surface is cracked has as yet not been clearly answered. Results of a comparative study are presented in this paper. Three groups of concrete samples were prepared. The first was cracked at the centre by three-point bending. This group served as reference. The second group received first surface impregnation, was then cracked at the centre, and finally the third group was cracked first and subsequently surface impregnated with liquid silane. It could be shown that chloride penetrates quickly and deeply into untreated and cracked reinforced concrete elements. This is a serious risk for corrosion of reinforced concrete in aggressive environment. Surface impregnation with silanes generally reduces the ingress of chlorides if applied prior or after cracks are formed. Therefore it can be concluded that service life of cracked and uncracked reinforced concrete structures in a marine environment or under similar aggressive conditions can be significantly extended by surface impregnation with silanes.

Keywords: surface impregnation, silane, water repellent concrete, protective measure, cracks.

1 Introduction

Surface impregnation with silanes has become a well established technology to protect reinforced concrete structures from ingress of water by capillary suction. This implies that ions dissolved in water, directly in contact with the surface of a concrete structure, will not penetrate into the porous structure of cement based materials [1-4]. Water flow has proved to be a most efficient mechanism for transport of dissolved ions. Hence surface impregnation of concrete can be considered to be an efficient protective measure for concrete structures in aggressive environment. Typical examples of potential applications of this protective measure are harbour constructions and bridges exposed to de-icing salts.

In most recommendations for design and application of water repellent agents in practice a minimum penetration depth of the water repellent agent is required (see for example [5]). This requirement is essentially justified by the observation that the efficiency of surface impregnation strongly depends on the penetration depth of silane, which is equivalent to the thickness of the water repellent surface near zone. Crack formation, however, is hardly taken into consideration although most concrete structural elements in practice are cracked by mechanical or environmental loads or a combination of both.

Penetration of liquids into cracks has been studied by a number of authors either theoretically or experimentally [6-12]. From results available in the literature it is known that water penetrates quickly into untreated cracks of concrete while penetration is hindered in water repellent cracks up to a critical crack width, which depends on the external pressure. For an estimation of service life of cracked concrete structures in marine environment it is of major interest to know the chloride penetration into cracks under given climatic conditions. Therefore the question is whether chloride penetration into cracks can be suppressed, or at least reduced significantly, by surface impregnation with a water repellent agent. In this contribution new experimental results of a comparative study shall be presented. It is hoped that these results finally will allow us to estimate the efficiency of surface impregnation as a protective measure for cracked concrete elements. The final aim is to quantify the influence of surface impregnation with silanes on service life of uncracked and cracked reinforced concrete structures if placed in an aggressive environment.

2 Preparation of samples

For all test series the same type of concrete was prepared (standard concrete type B of our laboratory). In this case the water-cement ratio is fixed at 0.5. River sand with a maximum diameter of 5 mm and crushed natural granitic aggregates with a maximum diameter of 20 mm, both from the area around Qingdao, China, were used. The fresh mix was produced in the laboratory with ordinary Portland cement type 32.5 from the

Shanshui plant. In order to obtain good workability 2 %, related to the mass of cement, super-plasticizer (naphthalene) was added. The composition of the concrete is given in Table 1.

Table 1: Concrete composition, related mass is expressed in kg/m^3

W/C	Cement	Sand	Gravel	Water	Super-plasticizer
0.5	320	653	1267	160	2%

Prismatic specimens, with the following dimensions 100 x 100 x 300 mm^3, were produced in steel forms. In order to be able to introduce well defined cracks into the concrete samples, two steel bars with a diameter of 8 mm were placed in the forms at a height of 25 mm above the bottom. All prisms were demolded after two days and then cured in a humid chamber (T = 20 °C, RH > 90 %) for 28 days. Then all specimens were dried in a ventilated oven at 50 °C for three days. After cooling down to room temperature the side surfaces were sealed with wax, leaving the bottom surface and the upper finished surface untreated.

After this pre-conditioning the concrete prisms could be loaded under controlled three-point bending conditions in order to induce well-defined cracks in the centre. Once a crack became visible, the width was measured at eight positions along the crack mouth and from these individual readings an average crack width was calculated. The applied force was then increased until an average crack width of 0.1 ± 0.01 mm, 0.2 ± 0.02 mm and 0.4 ± 0.03 mm, respectively, had been reached. The crack width was always controlled after unloading the beam.

The specimens were subdivided into three groups. The first group had been cracked by bending only. The bottom surface of the second group had been impregnated by direct contact of the surface with liquid silane (Wacker BS 1701, isooctyltriethoxysilane) for one hour before cracks were induced. And the third had been cracked first and then the bottom surface was impregnated with liquid silane by direct contact of the surface for one hour. The average penetration depth of the silane was measured to be 8.9 mm. This value corresponds to the requirements for deep impregnation in practice [5]. Deep impregnation was carried out, as this surface treatment is recommended for the establishment of a reliable and durable chloride barrier in practice.

The bottom surface of all the specimens from the three groups were then placed in contact with an aqueous 3 % NaCl solution for 28 days. The arrangement was essentially the same as proposed for the usual test of capillary suction [2].

After exposure to NaCl solution for 28 days, slices of the pre-cracked centre part were cut by means of a diamond saw. The centre slice with the artificial crack in the middle had a thickness of approximately 22 mm. On the two opposite sides of the crack, two additional slices with an approximate thickness of 13 mm were also cut. Finally, the slices were cut again to obtain prisms from different height with respect to the bottom surface. The height of the prisms varied between 10 and 15 mm. The cutting sequence and the geometry of the specimens obtained for analysis are shown in Fig.1.

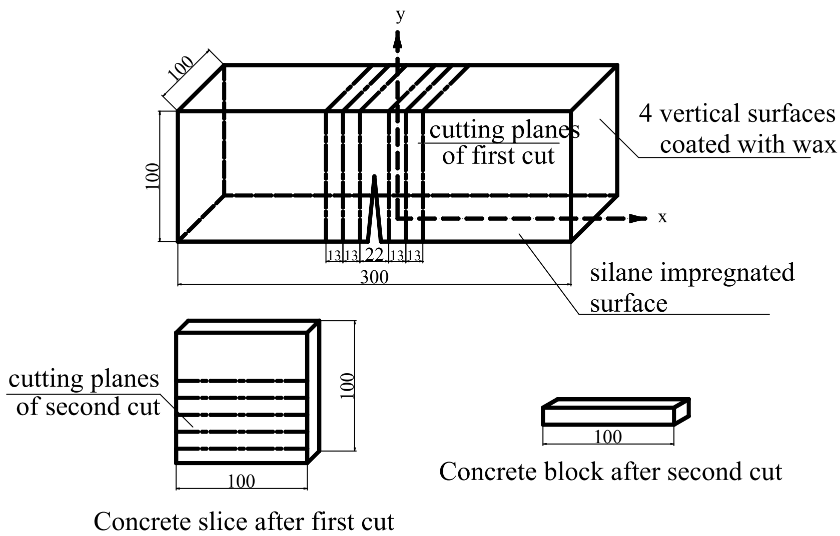

Figure 1: Schematic representation of the cutting sequence and geometry of slices and blocks.

The prismatic blocks obtained after the second cut, represent a volume element in the test prisms at a given distance from the impregnated surface (bottom) and from the induced crack. Because of symmetry reasons the values obtained right and left of the crack at the same distance could be averaged. By analyzing the chloride content of these prismatic blocks, it was possible to determine the three-dimensional distribution of chlorides in the concrete specimens. For that, after drying at 50 °C for one day, all small prisms were ground to powder and suspended in water in order to extract the chlorides. After filtering the suspension, the water soluble chloride content was measured by means of a calibrated ion-selective electrode.

3 Results and discussion

In order to represent the obtained results graphically two coordinates were introduced. The distance from the impregnated surface (vertical) is called depth (d) in accordance with the penetration depth of capillary suction in uncracked specimens, and the distance from the crack surface (horizontal) is called (x).

The chloride profiles at three different distances from the crack (x) and as function of the depth for untreated samples are shown in Fig. 2. The symbols B-1, B-2, and B-4 refer to a crack width of 0.1 mm, of 0.2 mm and of 0.4 mm respectively. The chloride content indicated by three lines is the average value measured in concrete situated at a distance between 0 and 11 mm; between 11 and 25 mm; and, finally a distance between 25 and 38 mm, as function of depth. For reasons of symmetry average values from corresponding volume elements from the two opposite sides of the crack are shown.

Chloride ingress into cracked concrete is obviously a two-dimensional process. Far from the crack chloride penetrates normal to the surface into the porous material. Chloride profiles in these areas are identical with chloride profiles as measured in uncracked concrete elements. Cracks are instantaneously filled with aqueous NaCl solution followed by migration parallel to the exposed surface into the concrete [8, 9]. As a first approximation, it may be assumed that the chloride profile, which will develop with time far from a crack tip and parallel to the exposed surface, will be similar to the chloride profile, which will develop in the uncracked zone normal to the exposed surface. This hypothesis is based on the assumption that the chloride diffusion in concrete is an isotropic process. This also means that the well-known skin effect is neglected. Close to the crack tip there is overlap of horizontal and vertical chloride penetration. This process needs to be further studied and quantified both theoretically and experimentally.

The chloride profile shown in Fig. 2 for the range close to the crack surface ($0 < x \pm 11$ mm) shows high chloride content even at distances from the surface above 70 mm. Under three-point bending in this range no real crack is being formed but a fracture process zone develops due to the imposed strain. This is a clear indication that chloride migration is enhanced by mechanically induced damage. This is just another example

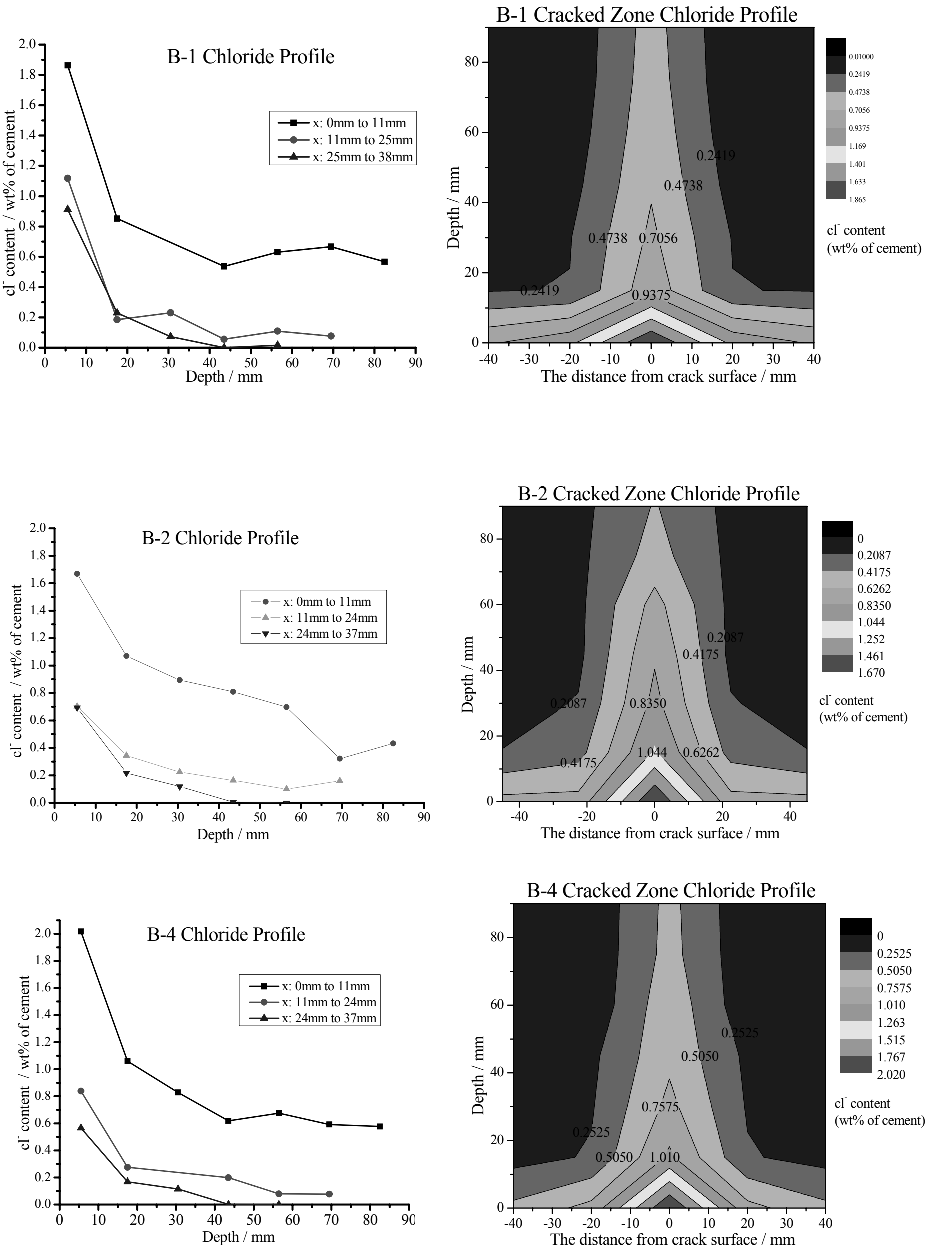

Figure 2: Chloride profiles as measured at three different distances from the crack surface (left) and contour diagrams for a plane normal to the crack surface (right) as measured on cracked untreated samples (first group)

for reduced durability of reinforced concrete structures under combined mechanical and environmental loads.

In Fig. 3 results obtained from the second group are graphically represented. The surface of concrete in this case had been first impregnated with liquid silane and then cracks were induced. From the contour diagrams it is evident immediately that through a fine crack in the surface of the water repellent concrete (crack width ≤ 0.1 mm) a small amount of chloride enters the zone near the surface. If the crack becomes wider than 0.2 mm, chloride penetrates deeper into the crack. It seems, however, that there is not enough salt solution in the crack in the water repellent concrete with a width of 0.1 mm to initiate horizontal chloride diffusion away from the crack. We conclude from this observation that very little chloride is transported through the crack. In surface impregnated concrete with crack width of 0.2mm and higher, however, a certain amount of chloride containing water is penetrating the crack. Most probably a water droplet forms a bridge between the outer solution and the untreated concrete surface in the crack. Under these conditions chloride migrates horizontally into the concrete from the crack surface. Again, this observation is of practical relevance with respect to service life of reinforced concrete structures and requires further studies.

Finally, results obtained on specimens from the third group (first crack induced then surface impregnation) are shown in Fig. 4. It can be seen, that very little chloride has entered these cracks, independent of the crack width. When the crack is formed after surface impregnation, a small amount of chloride can migrate into the crack as shown in Fig. 3. However, if surface impregnation is carried out after the crack was formed, chloride ingress is practically negligible. In addition we can see from Fig. 3 that the fracture process zone cannot be penetrated by chloride solution. Due to the imposed strain during crack formation, the structure of concrete ahead of a crack is weakened by micro-crack formation (compare with Fig. 2), but silane impregnation hinders chloride penetration into the damaged zone. This means that the capillary action of the process zone is totally suppressed. This finding may turn out to be of special interest when the originally designed service life of mechanically damaged (probably including frost damage) concrete structures is to be restored.

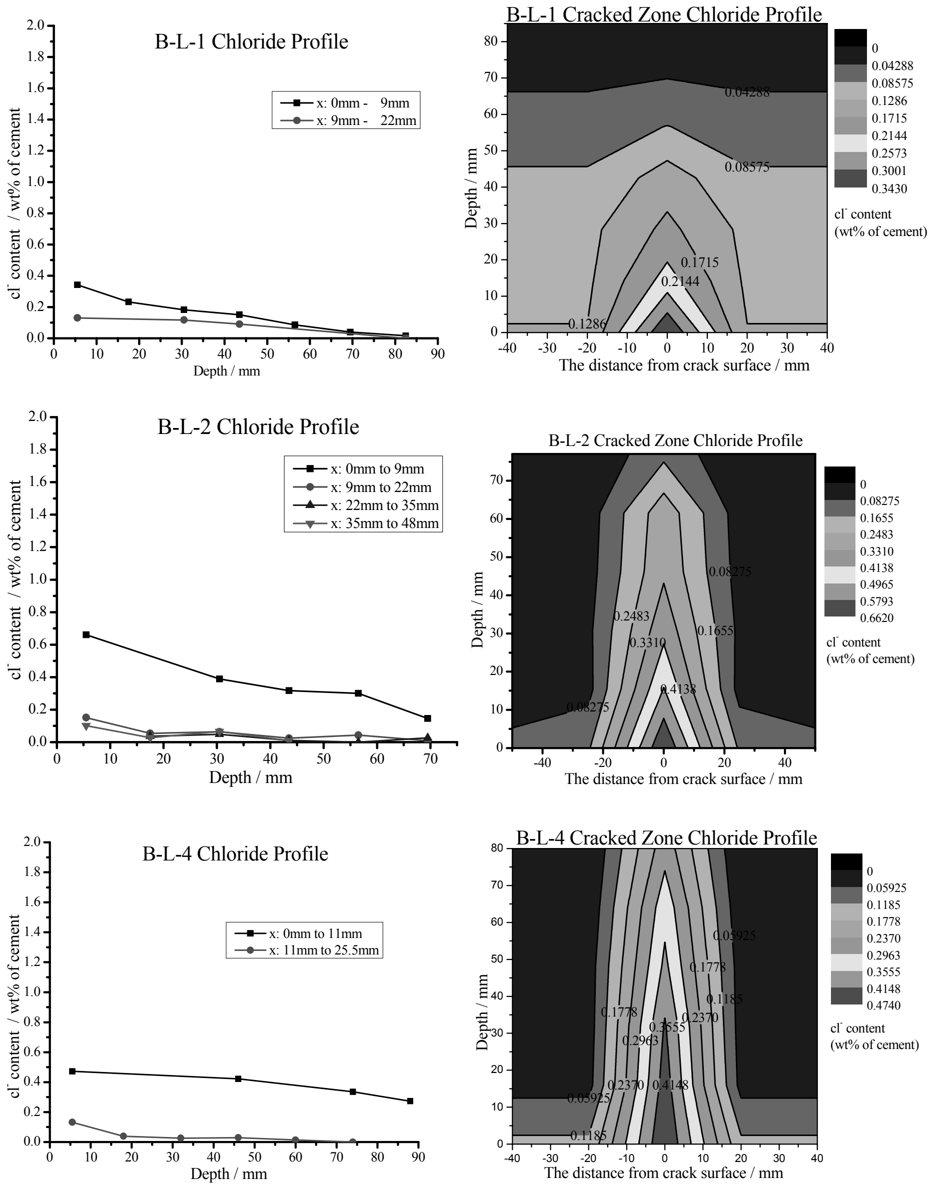

Figure 3: Chloride profiles as measured at three different distances from the crack surface (left) and contour diagrams for a plane normal to the crack surface (right) for the second group; first surface impregnation and then crack formation.

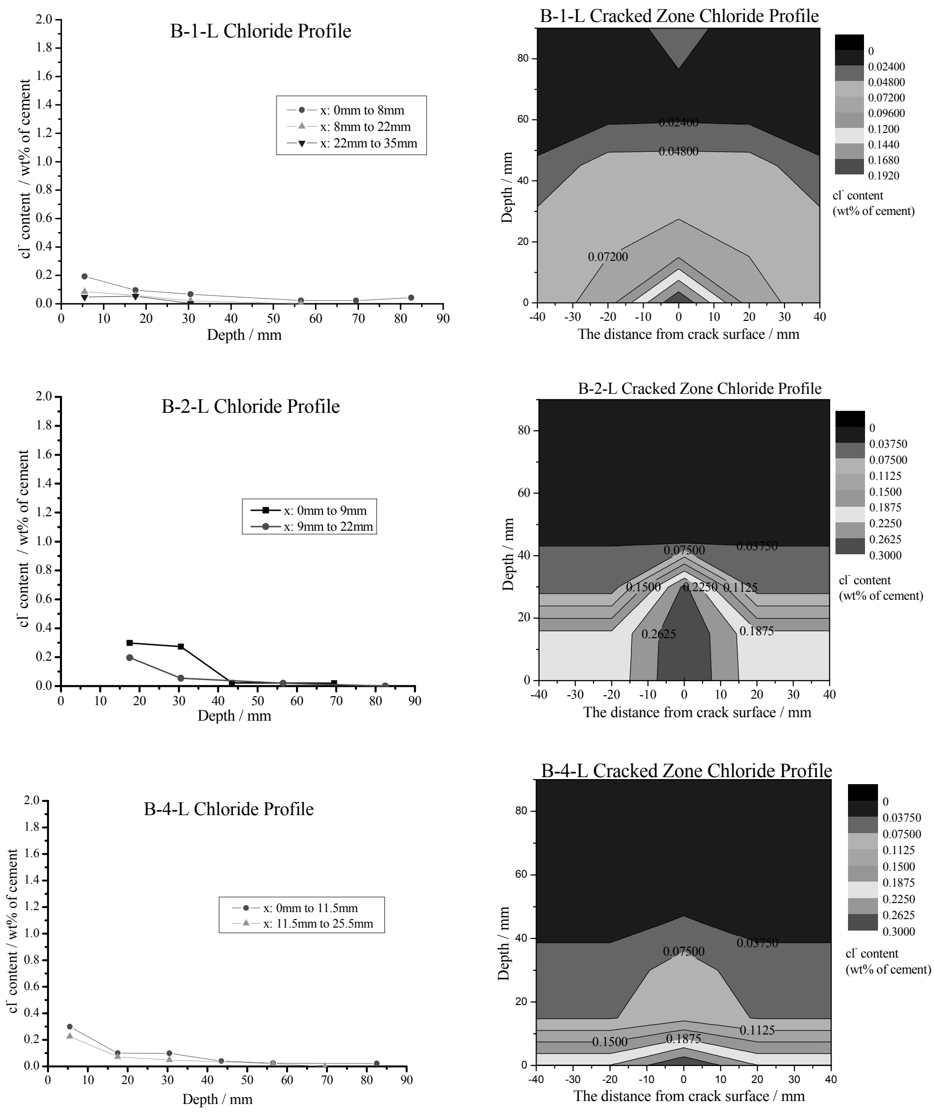

Figure 4: Chloride profiles as measured at three different distances from the crack surface (left) and contour diagrams for a plane normal to the crack surface (right) for the third group; first crack formation then surface impregnation.

4 Conclusions

From the results presented in this contribution we can conclude that:

(1) In case of untreated concrete samples, cracks are quickly filled with water or salt solution if the cracked surface is in direct contact with the liquid. From this moment onwards the solution is absorbed by capillary action out of the cracks, normal to the crack surface. The chloride content in the zone near the crack surface increases. This is a serious risk for initiation of corrosion in reinforced concrete structures.

(2) Ahead of a crack there exists a fracture process zone. The material in this zone is weakened by micro-cracks and hence capillary action is enhanced. Chloride can easily penetrate the fracture process zone in case of untreated concrete. Chloride can penetrate much deeper than the actual crack length. This migration mechanism is an example for the origin of reduced service life under combined mechanical and environmental loads.

(3) If cracks are formed in a structural element, which has been surface impregnated with silane according to practical recommendations (deep impregnation) [5], the penetration of chlorides is significantly slowed down in comparison with untreated concrete.

(4) If cracked structural elements are surface impregnated, the inner crack surface and the fracture process zone ahead of a crack will be water repellent as well. As a consequence cracks and in particular fine cracks will not absorb salt solutions. As wider cracks absorb some salt solution the crack surface will not transport the chlorides into the porous material facing the crack, and therefore chloride penetration into concrete is significantly reduced.

(5) Surface impregnation after crack formation prevents chloride penetration into the fracture process zone. Mechanically induced damage and its influence on service life of reinforced concrete structures can be significantly reduced by surface impregnation.

(6) Service life of cracked and uncracked reinforced concrete structures can be extended significantly by surface impregnation with silane.

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