INFLUENCE OF CRACKS ON CHLORIDE PENETRATION IN CONCRETE

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Abstract: Chloride initiated reinforcement corrosion is the main durability problem for concrete structures in a marine environment. If the chlorides reach the reinforcement steel, it will depassivate and start to corrode in presence of air and water. Since the corrosion products have a larger volume than the initial products, concrete stresses are induced, leading to spalling and degradation of the concrete structures. If cracks, caused by early drying, thermal effects, shrinkage movements or overstress, are present in the concrete, the penetration of chlorides is much faster than in uncracked concrete. In this way, the corrosion process is initiated earlier and the service life is decreased drastically.

In order to investigate the influence of existing cracks in concrete structures on the penetration of chlorides and the resulting service life, a test program was set up at the Magnel Laboratory for Concrete Research of Ghent University, Belgium in cooperation with the "Politehnica" University of Timisoara, Romania. Part of the testing program was carried out on concrete specimens with artificial cracks. These artificial cracks were manufactured using thin copper plates with a thickness of 0.2mm or 0.3mm. The copper plates were positioned inside the fresh concrete for a depth of 5, 10, 15 or 20mm and removed after approximately 4 hours. In order to study the influence of the amount of cement, two types of concrete were considered with a different amount of cement and a constant W/C ratio. From the age of 28 days, diffusion test were carried...
out in a 3.5% NaCl solution. Each month, during 10 months, the chloride penetration depth was measured on 2 concrete specimens. The specimens were split and on each of the freshly split sections, a 0.1 M AgNO$_3$ solution was sprayed. The chloride penetration depth is measured at 19 points, visually checking the presence of white silver chloride precipitation.

With these penetration profiles, the influence of the cracks on chloride penetration was quantified by comparing the cracked zone of the specimens with the uncracked zone. The ratio of the chloride diffusion coefficient of the cracked concrete zone to the chloride diffusion coefficient of the uncracked zone was called the crack influence factor $\eta$, depending on the crack depth. The crack width was not taken into account because for crack widths of 0.2 mm and 0.3 mm no influence was found of the crack width.

With this crack influence factor, the influence of a crack on the expected service life is illustrated in Figure 1. In this figure, the time needed for the reinforcement to start to corrode, with a concrete cover thickness of 50 mm and a diffusion coefficient of 2.5, 5 or 7.5 $10^{-12}$ m$^2$/s is given for different crack depths.

![Figure 1: Relation between service life, diffusion coefficient and crack depth](image)

From this figure it is very clear that the influence of cracks is enormous. A crack halves the expected service life if the crack depth equals 10 mm. For crack depths of 20 mm, the expected service life is only 25% of the expected service life of uncracked concrete.
1. INTRODUCTION

The penetration of chlorides and the resulting corrosion of the reinforcement steel are a major durability issue for concrete structures in a marine environment. If cracks, caused by early drying, thermal effects, shrinkage movements or overstress, are present in the concrete, the penetration of chlorides is much faster than in uncracked concrete. In this way, the corrosion process is initiated earlier and the service life is decreased drastically.

In order to study the influence of existing cracks in concrete structures on the penetration of chlorides a test program was set up at the Magnel Laboratory for Concrete Research of Ghent University, Belgium in cooperation with the “Politehnica” University of Timisoara, Romania. The first part of the test program consists of concrete specimens with artificial cracks. In the next step, concrete with real cracks will be studied.

In this paper, the influence of different crack widths and crack depths of artificial cracks on the chloride diffusion is investigated. In order to study the influence of the amount of cement, two types of concrete were considered with a different amount of cement and a constant W/C ratio. The chloride penetration into the concrete was realised by immersing the concrete specimens in a 3.5% NaCl solution at the age of 28 days. Each month, during 10 months, the chloride penetration depth was measured with a colorimetric method on 2 specimens. From these penetration profiles, the influence of the cracks on the maximum penetration depth, the end of the initiation period and thus, the service life is investigated in function of the cement content, the crack width and the crack depth.

2. EXPERIMENTAL PROGRAM

2.1 Concrete composition

Two types of concrete with the same W/C ratio and based on ordinary Portland cement (CEM I 52.5 N) were investigated. T1 and T2 have a cement content of 300 kg/m³ and 400 kg/m³ respectively. The concrete composition is given in Table 1. For each concrete composition, eight concrete batches have been produced, one for each notch configuration (see 2.2). For these mixes, the slump and density were measured in fresh condition. The compressive strength (on 3 cubes with side length 150mm) and density of the hardened concrete were measured at the age of 28 days. For these properties, the mean values are given in Table 1. For each mix, 20 specimens for the determination of the chloride penetration were cast. The concrete specimens were stored in a climate room at 20 °C ± 2 °C and more than 90 % R.H. until the testing age.
<table>
<thead>
<tr>
<th>Composition</th>
<th>T1</th>
<th>T2</th>
</tr>
</thead>
<tbody>
<tr>
<td>CEM I 52.5 N [kg/m³]</td>
<td>300</td>
<td>400</td>
</tr>
<tr>
<td>sand 0/4 [kg/m³]</td>
<td>670</td>
<td>585</td>
</tr>
<tr>
<td>gravel 2/8 [kg/m³]</td>
<td>490</td>
<td>430</td>
</tr>
<tr>
<td>gravel 8/16 [kg/m³]</td>
<td>790</td>
<td>690</td>
</tr>
<tr>
<td>water [kg/m³]</td>
<td>150</td>
<td>200</td>
</tr>
<tr>
<td>Fresh properties</td>
<td></td>
<td></td>
</tr>
<tr>
<td>slump [mm]</td>
<td>19</td>
<td>224</td>
</tr>
<tr>
<td>density [kg/m³]</td>
<td>2415</td>
<td>2375</td>
</tr>
<tr>
<td>Hardened properties</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( f_{\text{cub},28d} ) [N/mm²]</td>
<td>57.4</td>
<td>49.6</td>
</tr>
<tr>
<td>density [kg/m³]</td>
<td>2390</td>
<td>2365</td>
</tr>
</tbody>
</table>

Table 1: Concrete composition, fresh and hardened properties

2.2 Crack configuration

Concrete specimens were made with artificial cracks by means of the positioning and removal after approximately 4 hours of thin copper sheets inside the specimen. These copper sheets had a thickness of 0.2mm or 0.3mm. The copper plates were placed at a depth in the concrete of 5mm, 10mm, 15mm or 20mm. As a result, the surface of the artificial cracks or notches contained more cement than the surface of a real crack in a concrete element.

2.3 Chloride penetration

The ingress of chloride ions into concrete occurs in different ways: capillary suction, diffusion, migration, ... or combinations of these transport mechanisms. In this research, the non-steady state migration test and diffusion tests are used for the chloride penetration. In this paper, only the obtained results of the diffusion tests will be analysed. In a next step, both methods will be compared. The diffusion test were performed by immersing the specimens in a 3.5% NaCl solution at the age of 28 days. Each month, during 10 months, the chloride penetration depth was measured on 2 specimens. These specimens were split, perpendicular to the notch. On each of the freshly split sections, a 0.1 M AgNO₃ solution was sprayed and the chloride penetration depth is measured at 19 points, visually checking the presence of white silver chloride precipitation. This colorimetric method is described in Otsuki et al.¹. For each concrete specimen, two penetration profiles were obtained. In this way, 4 penetration profiles are obtained for each composition, notch configuration and test duration. The mean penetration profile for crack width 0.2mm and crack depth 20mm for T1 is given in Figure 2. On the horizontal axis, the distance to the crack (or notch) is given. Distance 0 indicates the crack location. In this figure, only the chloride penetration depths after 1, 5, 7 and 10 months of immersion are shown.
2.4 Discussion on test results

The chloride penetration profile is strongly influenced by the test duration (see Figure 2) for all tests: the longer the test duration, the higher the penetration depth. This was to be expected, but what is most interesting, is the changing of the chloride penetration front: for the small test durations, the chloride penetration front is very steep in the crack region. For the larger test durations, the chloride penetration front has flattened. The influence of the crack width is less pronounced. In earlier research\(^5\), studying the chloride penetration by non steady state migration, smaller crack widths lead to smaller penetration depths until a crack width of approximately 0.1mm. For larger crack widths, no influence was found. Also for the results of this study, no significant influence of the crack width (0.2 -0.3mm) is distinguished. For that reason, the further analysis will be carried out without taking into account the crack width.

Both for T1 and T2 and for both crack widths, a higher chloride penetration depth is noted for a higher crack depth. This is more pronounced for longer test durations.

By increasing the amount of cement from 300 kg/m\(^3\) for T1 to 400kg/m\(^3\) for T2 at a constant W/C ratio, the penetration depth is decreasing. This is explained by the higher amount of chlorides that is bound to the cement matrix.

2.5 Modelling of test results

The diffusion of chlorides is usually described by Fick's second law and its solution for a 1D problem where C is the total chloride content, t the time, D the diffusion coefficient, \(C_0\) the constant surface concentration and \(\text{erf}(\ )\) represents the error function:
\[ C = C_0 \left[ 1 - \text{erf} \left( \frac{x}{2\sqrt{D_0 t}} \right) \right] \]  

(1)

It is crucial to take into account the time dependency of the chloride diffusion coefficient. This diffusion coefficient decreases in time due to ongoing hydration and refining of the pore structure. This leads to a slower penetration of chlorides into the concrete. This time dependency is taken into account by substituting \( D \) in equation (1) by the apparent diffusion coefficient \( D_a \):

\[ D_a = \frac{D_0}{1-n} \left[ \left( 1 + \frac{t_{ex}}{\Delta t} \right)^{1-n} \left( \frac{t_{ex}}{\Delta t} \right)^{1-n} \left( \frac{t_{ex}}{t} \right)^n \right] \]  

(2)

With \( D_0 \) and \( t_0 \) a pair of known diffusion coefficient and age of the concrete, \( t_{ex} \) the age of the concrete at the start of exposure to chlorides, \( \Delta t \) the exposure duration and \( n \) the age factor.

With equation (1) and (2), the corresponding diffusion coefficient for the maximum penetration depths is calculated for each notch configuration and exposure duration. For this calculation, the values for \( n \) were respectively 0.33 and 0.26 for T1 and T2. At the colour change and the surface, a chloride content of respectively 0.15 wt.-%/cement and 2.10 wt.-%/cement is present.

The influence of the cracks on chloride penetration was quantified by comparing the cracked zone of the specimens with the uncracked zone. The ratio of the chloride diffusion coefficient of the cracked concrete zone to the chloride diffusion coefficient of the uncracked zone was called the crack influence factor \( \eta \), depending on the crack depth. The crack width was not taken into account because for crack widths of 0.2 mm and 0.3 mm no influence was found of the crack width. Based on other research, the following equation is proposed:

\[ \eta = \exp \left[ a \left( \frac{d}{d_0} \right)^b \right] \]  

(3)

With \( d \) = crack depth (mm) and \( d_0 = 1 \) mm. The constants \( a \) and \( b \) are determined with a numerical regression analysis, based on the least square analysis method. For T1 a and b are respectively 0.0669 and 1.053 with a \( R^2 \) of 0.97, for T2 respectively 0.1525 and 0.6136 with a \( R^2 \) of 0.82.
3. SERVICE LIFE PREDICTION

As illustration of the influence of cracks in concrete, Figure 3 is given. In this figure, T2 is considered in a marine environment with a chloride concentration $C_0$ of 2.1 wt.-%/cement. The critical chloride concentration is considered $C_{cr} = 0.6$ wt.-%/cement. The concrete has a W/C ratio of 0.5, a cement content of 400 kg/m³ and a diffusion coefficient of $5 \times 10^{-12}$ m²/s at 28 days. The concrete is exposed to chlorides at 28 days. In Figure 3, the critical chloride penetration depth is given in function of time for different crack depths from 0 to 20 mm. From Figure 3 it is clear that in an uncracked concrete with a concrete cover thickness of 50 mm, it takes 36 years for the chlorides to reach the critical concentration at the reinforcement, which will start to corrode. In cracked concrete, with a crack depth of 20 mm, the corrosion process will start after only 9 years.

![Figure 3: Influence of crack depth on critical chloride penetration depth in function of time](image)

In Figure 1, the time needed for the reinforcement to start to corrode, with a concrete cover thickness of 50 mm and a diffusion coefficient of $2.5, 5$ or $7.5 \times 10^{-12}$ m²/s is given for different crack depths. From this figure it is very clear that the influence of cracks is enormous. A crack halves the expected service life if the crack depth equals 10 mm. For crack depths of 20 mm, the expected service life is only 25% of the expected service life of uncracked concrete.
4. CONCLUSION

In this paper, the influence of artificial cracks, so-called notches, with different crack widths (0.2mm and 0.3mm) and crack depths (5 to 20 mm) on the chloride penetration is experimentally studied and related to the service life. Some general conclusions could be made:

- A higher penetration of chlorides is obtained at the notch tip than in the ‘uncracked’ part of the test specimens. The penetration depth is increasing with an increasing notch depth. This effect is more pronounced for longer test durations.
- The total chloride distribution is not influenced by the notch width (in the range 0.2-0.3mm).
- A crack influencing factor was reduced, which is used to illustrate the influence of cracks on the service life of a concrete structure in a marine environment, leading to the conclusion that the presence of cracks easily halves the service life duration.

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REFERENCES