THE INFLUENCE OF CRACKS ON CHLORIDE PENETRATION IN CONCRETE STRUCTURES – PART I: EXPERIMENTAL EVALUATION

Katrien Audenaert (1), Geert De Schutter (1) and Liviu Marsavina (2)

(1) Magnel Laboratory for Concrete Research, Ghent University, Belgium

(2) University "Politehnica" Timisoara, Department Strength of Materials, Romania

Abstract

A good durability of concrete structures greatly depends on the quality of the cover concrete. Preliminary damage of this protective concrete skin due to e.g. thermal or shrinkage cracking can lead to a considerable reduction in service life of the concrete structure. Although a consensus exists about the fact that a cracked concrete cover zone is harmful to the durability of reinforced concrete structures, the quantification of this phenomenon is still not well known.

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. The influences of different crack widths and crack depths are investigated. The chloride penetration into the concrete was realised with the non-steady state migration test, using an electrical field, developed by Tang (1996) [1] and described in NT BUILD 492 [2].

The experiments and the discussion of the obtained results are presented in this paper, Part 1, the numerical modelling of part of these tests is discussed in Part 2 [3].

1. INTRODUCTION

The durability of concrete is a very important issue in actual concrete research. The service life of concrete structures can severely be reduced by the influence of cracks, caused by early-age thermal cracking due to heat of hydration, or cracking due to shrinkage, impact or overloading in combination with subsequent acceleration of degradation owing to, for example, chloride penetration.

At the Magnel Laboratory for Concrete Research, Ghent University, Belgium several research programmes have been conducted concerning the influences of cracks on the durability behaviour [4,5]. Together with the "Politehnica" University of Timisoara, Romania a project is going on concerning the numerical simulation of the influence of crack formation on chloride penetration in reinforced concrete. In a first step, the chloride penetration in unreinforced concrete specimens with artificial cracks is considered. The experiments are carried out at Ghent University, the modelling of the test results is performed at the "Politehnica" University of Timisoara.

2. DESCRIPTION OF THE TESTING PROGRAM

2.1 Concrete composition

Two different concrete compositions are studied and given in table 1, together with the compressive strength and the density at 28 days. It should be noted that the concrete T3 is 5 years old and completely carbonated. The concrete T2 is 'new' concrete and not carbonated. From these concrete mixtures, concrete specimens were made with dimensions 158 x 158 x 70mm³ and stored in a climate room at 20 °C ± 2 °C and more than 90 % R.H. From each specimen, a concrete core with a diameter of 100mm and a height of 50 was taken to determine the chloride penetration. Afterwards the concrete cores were replaced in the climate room until the testing date.

Table 1: Concrete compositions

	T2	T3
Sand 0/4 (kg/m³)	670	670
River gravel 2/8 (kg/m³)	490	
River gravel 8/16 (kg/m³)	790	
River gravel 4/14 (kg/m³)		1280
Water (kg/m³)	150	150
CEM I 52.5 N (kg/m³)	300	
CEM III/ B 32,5 HSR LA (kg/m³)		300
$f_{cube150,28days}$ (MPa)	55.1	30.4
ρ_{28days} (kg/m³)	2390	2375

2.2 Notch configuration

In order to simulate cracked concrete, specimens with artificial cracks were manufactured using thin copper plates with a thickness of 0.2 mm, 0.3 mm or 0.5 mm. These copper plates were positioned inside the fresh concrete for a depth of maximum 20mm and removed after approximately 4 hours. As a result, the surface of the notches contained more cement than the surface of a real crack in a concrete element.

The number of test specimens for the different combinations of crack width and crack depth for both concrete compositions, is given in table 2 and 3. Also specimens without notch were made in order to determine the chloride penetration behaviour in uncracked concrete.

Table 2: Number of test specimens in function of crack width and crack depth for concrete T2

		WIDTH (mm)	
		0.2	0.3
DEPTH (mm)	5	20	20
	10	20	20
	15	20	20
	20	20	20

Table 3: Number of test specimens in function of crack width and crack depth for concrete T3

		WIDTH (mm)		
		0.2	0.3	0.5
DEPTH (mm)	5	1	2	
	10		1	
	20			2

2.3 Description of test method

The non steady state migration test (CTH) was performed following the method of Tang et al. [6]. Firstly the specimens are vacuum saturated with a saturated $Ca(OH)_2$ solution. Afterwards an external electrical potential (for concrete T2 25 V, for T3 35V or 40V) is applied across the specimen that forces the chloride ions to migrate into the specimens. Afterwards the specimen is axially split and a silver nitrate solution is sprayed on to the freshly split sections. The chloride penetration depth can then be measured on each section at several points from the visible white silver chloride precipitation in order to describe accurately the chloride penetration depth.

For the concrete composition T2, 20 specimens are available for each notch configuration. For this reason, the test duration was varied from 2 to 4, 6, 8 and 10 hours. For each duration, 3 specimens were tested. In this way, the proceeding of the penetration front can be visualized.

For the concrete composition T3, only few specimens are available. For this reason, a test duration of 4 or 6 hours was chosen and specimens with different notch configurations were tested simultaneously.

2.4 Influence of testing age

As written in literature [7,8,9], the diffusion and also the migration coefficient of concrete is decreasing with age. This has a significant influence on the measured penetration depth. As the CTH tests were not carried out on a constant concrete age, a correction is needed in order to compare the penetration depths. A reference concrete age of 28 days was chosen. The equation mostly used for the influence of age on the migration coefficient in literature [8,10,11,12] is:

$$D(t) = D_1 \, t^{-m} \tag{1}$$

with D_1 the value at an age of 1 year and m a constant. Based on test results from earlier testing programmes carried out at the Magnel Laboratory for Concrete Research on pure

Portland cement concrete [7,13], a value of 0.27 for m is used. This value is corresponding very well with values in literature [8,9].

From equation (1), the following equation for the calculation of the migration coefficient on 28 days could be derived:

$$\frac{D_{28}}{D_t} = \left(\frac{28}{t}\right)^{-0.27} \tag{2}$$

The relation describing the chloride concentration in function of the distance from the concrete surface is given by the so-called error function equation:

$$C = C_0\left(1 - \mathrm{erf}\left(\frac{x}{2\sqrt{Dt}}\right)\right) \tag{3}$$

After transforming this equation, the relation between the penetration depth of the chlorides and time is given:

$$x = 2\sqrt{D}\ \mathrm{erf}^{-1}\left(1 - \frac{C_x}{C_0}\right)\sqrt{t} = A\sqrt{Dt} \tag{4}$$

with A a constant and C_X the chloride concentration which leads to a colour change at the determination of the chloride penetration depth with the silver nitrate solution method.

From this equation, the following equation is obtained, giving the penetration depth at a concrete reference age of 28 days in function of the measured penetration depth at a concrete age t:

$$x_{28} = x_t\sqrt{\frac{D_{28}}{D_t}} = x_t\sqrt{\left(\frac{28}{t}\right)^{-0.27}} = x_t\left(\frac{28}{t}\right)^{-0.135} \tag{5}$$

With this formula, the chloride penetration depths at the reference age of 28 days are calculated from the measured chloride penetration depths.

This method is not applied for the concrete T3 because there is no value for m available. T3 is not a pure Portland cement based concrete and moreover it is completely carbonated concrete.

3. TEST RESULTS

These chloride profiles are given in figures 1 to 4 for the concrete T2 with a notch width of 0.2 mm. The depth of the notch is indicated in the figures. The penetration depths are drawn for half a specimen.

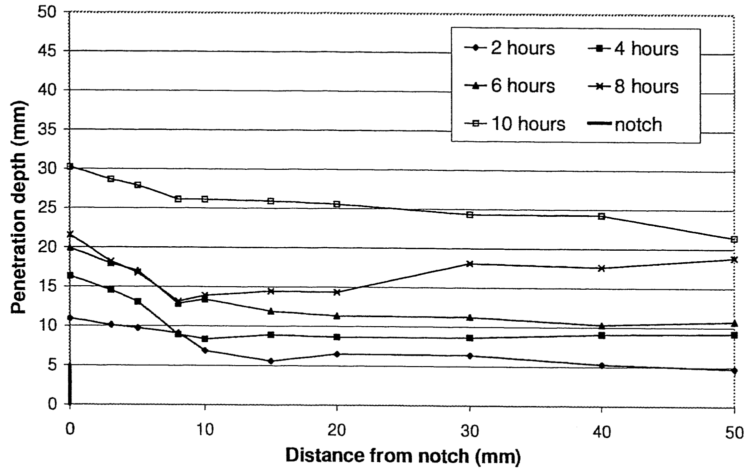

Figure 1: Penetration depth in function of distance from notch for T2-0.2x5

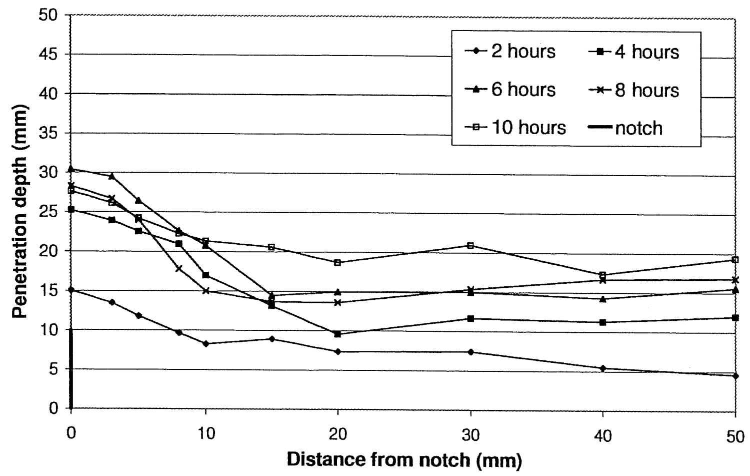

Figure 2: Penetration depth in function of distance from notch for T2-0.2x10

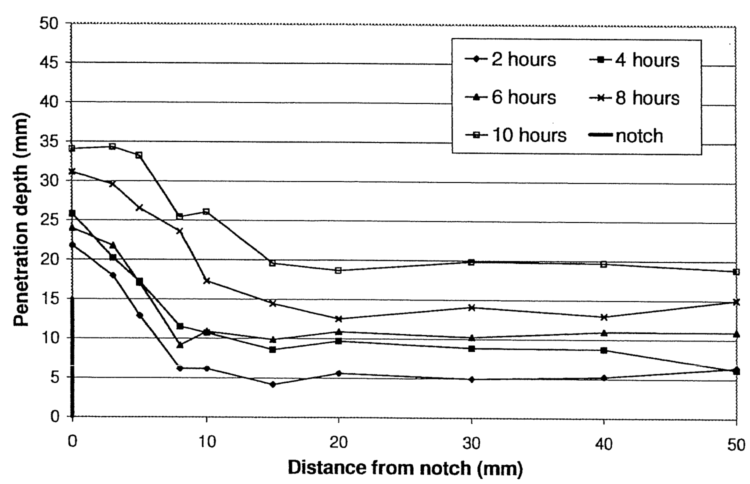

Figure 3: Penetration depth in function of distance from notch for T2-0.2x15

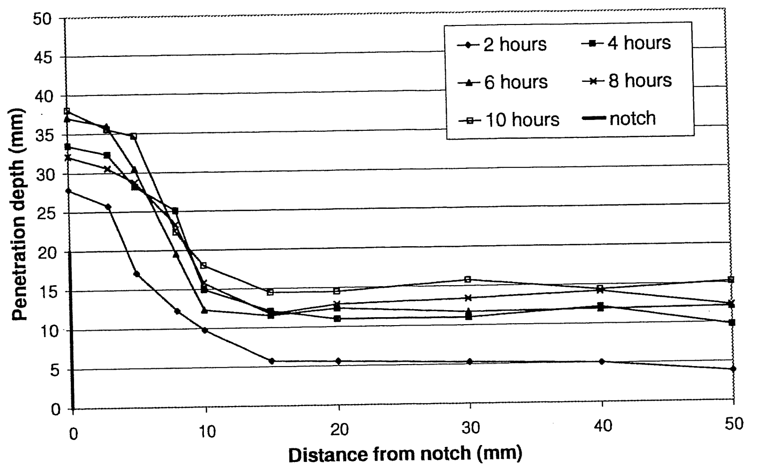

Figure 4: Penetration depth in function of distance from notch for T2-0.2x20

In Table 4 to 6, the test results of concrete composition T2 are given. In table 4, the mean penetration depth of the crack zone is given. For the calculation of this value, the mean value of the penetration depths 0mm (at the notch) and 3 mm distance from the notch, is determined. In table 5, the mean of the whole penetration front is determined. The mean value in the end zones (from -50mm to -30mm), which are supposed not to be influenced by the notch, is given in table 6.

The values of T3 are not corrected for the concrete age and are consisting of a very limited number of chloride profiles. Also the voltage applied is differing with T2 (see section: Description of test method). For this reason, no direct comparison between T2 and T3 is possible.

Table 4: Maximum penetration depth

	Crack width (mm)	Crack depth (mm)	Duration of test (h)					
			2	4	5	6	8	10
T2	0.3	5	10.4	13.4		17.2	16.6	16.7
	0.3	10	10.0		12.2		20.8	30.6
	0.3	15	12.4	25.0		25.1	27.6	35.3
	0.3	20	26.0	29.8		35.1	31.8	33.5
	0.2	5	10.4	15.2		18.6	19.3	29.2
	0.2	10	14.0	24.4		29.8	27.3	26.7
	0.2	15	19.2	22.1		22.5	30.1	34.2
	0.2	20	26.4	32.7		36.3	31.1	36.4
T3*	0.5	20		48.2		43.5		
	0.3	5		46.0		35.5		
	0.3	10		46.8				
	0.2	5				39.5		

*: 35V was applied for the test of 4 hours and 40V for the test of 6 hours

Table 5: Mean penetration depth

	Crack width (mm)	Crack depth (mm)	Duration of test (h)					
			2	4	5	6	8	10
T2	0.3	5	6.2	9.6		13.9	13.6	14.8
	0.3	10	5.3		8.7		15.6	23.8
	0.3	15	6.7	10.7		14.8	17.9	25.6
	0.3	20	11.5	13.1		19.4	18.0	19.9
	0.2	5	7.3	10.4		13.4	16.7	25.8
	0.2	10	8.9	16.2		20.0	18.6	21.6
	0.2	15	8.9	12.3		13.4	19.1	24.7
	0.2	20	11.2	18.2		18.9	19.0	21.8
T3*	0.5	20		43.8		37.0		
	0.3	5		45.3		35.4		
	0.3	10		43.8				
	0.2	5				36.1		

*: 35V was applied for the test of 4 hours and 40V for the test of 6 hours

Table 6: Mean value end zones

	Crack width (mm)	Crack depth (mm)	Duration of test (h)					
			2	4	5	6	8	10
T2	0.3	5	3.2	6.3		11.2	12.8	13.6
	0.3	10	2.8		5.9		11.7	15.0
	0.3	15	4.3	5.5		8.5	11.6	16.1
	0.3	20	4.9	4.4		10.5	10.4	13.4
	0.2	5	5.5	9.0		10.8	18.2	23.3
	0.2	10	5.8	11.7		15.0	16.3	19.2
	0.2	15	5.5	7.9		10.7	14.0	19.5
	0.2	20	4.7	11.0		11.9	13.3	15.1
T3*	0.5	20		40.6		33.1		
	0.3	5		45.7		36.1		
	0.3	10		42.1				
	0.2	5				35.1		

*: 35V was applied for the test of 4 hours and 40V for the test of 6 hours

4. DISCUSSION

From the figures 1 to 4 it is clear that a higher penetration depth is obtained at the notch. This is also found by comparing the values of table 4 and 6. This is explained by two reasons: firstly, the chloride ions are present at the notch tip and start migrating in the concrete from that point. Secondly, a higher potential drop is present in the notch zone, leading to a higher chloride transport.

Generally, the maximum penetration depth is increasing with an increasing test duration and with an increasing notch depth, which is conform the expectations. The increased penetration depth for an increasing notch depth is more pronounced for longer test durations. This could be attributed to variations inherently to the test method, such as the accuracy of the measurement of the penetration depth.

The influence of the crack width is less pronounced. By studying tables 4 to 6, it even seems that a smaller crack width leads to a higher penetration depth. In earlier research [4,5], studying the chloride penetration by immersion in mortar prisms with notches, this phenomenon is not noticed.

This behaviour could be possibly explained by microcracking at the notch tip. These microcracks are originating in stress concentrations at the notch tip by the hydration and shrinkage of the concrete. It is known that stress concentrations are higher for smaller notch widths. Also further numerical modelling is planned in order to verify the influence of the electrical field on the transport of ions.

5. CONCLUSIONS

In this paper, the influence of artificial cracks, so-called notches, with different crack widths and crack depths on the chloride penetration is experimentally studied. The chloride penetration is realized by the CTH test [2] using an electrical field. 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 influence of the notch width is not clear. Further research is needed to clarify the influence of the notch width.

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