Influence of cracks and crack width on penetration depth of chlorides in concrete

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Abstract

Chloride induced reinforcement corrosion is the main durability problem for concrete structures in a marine environment. If the chlorides reach the reinforcement steel, the latter 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 are present in 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 decreasing drastically.
In order to investigate the effect of cracks on the chloride penetration, a testing program was carried out. Firstly, a method was developed to create cracks in concrete. Afterwards, chloride penetration tests with the non-steady state migration test described in NT BUILD 492 were carried out. From the penetration profiles, the influence of the crack width on the maximum penetration depth and the extent of the crack influencing zone were investigated. This leads to the conclusion that for increasing crack width, the maximum penetration depth is increasing and that the extent of the crack influencing zone is depending on the crack width.

Keywords: Chloride penetration, crack, crack width

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.

This paper describes the first test results of a research programme dedicated to the influence of cracks on the penetration of chlorides and the resulting service life. In a first step, the non-steady state migration test is used for the chloride penetration, leading in a few hours to results. Chloride diffusion tests are also started, but it will take months and probably years to obtain experimental results. In order to simplify the modelling of the test results, two types of cracks will be studied: artificial cracks, made by the placement of thin copper sheets in the fresh concrete, and natural cracks.

In this paper, the developed method to create natural cracks is described, followed by a short explanation of the used non-steady state chloride migration test. Crack widths between 0.02mm and 0.2mm were obtained. From the chloride penetration profiles on 117 concrete cores, the influence of the crack width, measured on the concrete surface exposed to chlorides, on the maximum penetration depth of chlorides is investigated as well as the extent of the crack influencing zone.

2. Comparison of crack formation test methods

2.1 Introduction

The first step in the testing programme was the development of an experimental test set-up to create cracks in concrete. Some limiting conditions were present: in order to obtain test results in a rather short time period, the use of the non-steady state migration test for the chloride penetration was considered to be used. This method is using an electrical field to force the chlorides into the concrete, excluding the use of steel reinforcement in the test specimens. Secondly, concrete cores with a diameter of 100mm and a height of 50mm with diametrical cracks have to be used in the non-steady state migration test. Finally, the test set-up was to be as easy as possible, making use of the available test equipment.

Several methods from literature were compared. Two methods were experimentally examined: three-point bending tests on reinforced concrete prisms 150mm x 150mm x 600m and Brazilian splitting tests on drilled concrete cores with a diameter of 100mm and 150mm height. After the comparison of both methods, the Brazilian splitting test was selected for the following tests. Crack widths between 0.02 and 0.20 mm were obtained with this method.

2.2 Literature review

A literature review is carried out in order to evaluate the different test set-ups for the formation of cracks. The aim is to study the influence of 'large cracks' with a crack width up to 0.2 mm, as accepted in most concrete design codes and standards. Microcracking is not studied here for two reasons: other test methods are used to create them and they behave differently with regard to the penetration of potentially aggressive substances.

Roughly four different groups of test methods are distinguished: firstly, the Brazilian splitting test, creating tensile cracks in a concrete core or disk subjected to diametral compression, as described by Wang et al. (1997), Aldea et al. (1999), Chen et al. (2004) and Song et al. (2006). For this type of test, linear variable displacement tranducers (LVDT's) are used, together with a feedback displacement controlled test machine. Secondly, the wedge splitting test, used in many researches in the field of fracture mechanics because of the rather easy analytical description of the crack formation (Brühwiler (1990)). This type of test is also used in concrete research (Leite et al. (2004), Karihaloo et al. (2006), Pease et al. (2007), Reinhardt (2007)). The third group are the 3- or 4-point bending tests on concrete prisms as investigated by Mohammed et al. (2001), Win et al. (2004), Granju et al. (2005), Kato et al. (2005). For the study of long term processes, such as the penetration of chlorides into cracked concrete, groups of 2 or 3 prisms loaded in 3- or 4- point bending are used: Gowripalan et al. (2000), Mohammed et al. (2001) and Mu et al. (2002). The last group makes use of ring shaped discs with an expansive core (Ismail et al. (2004). Of course, many variations are possible on each of the four types of tests.

After the evaluation of these test methods, two methods were considered for experimental tests: the three point bending tests on reinforced concrete prisms and the Brazilian splitting test.

2.3 Experimental comparison of two test methods

2.3.1 Concrete composition

One concrete composition is used for the tests: 300 kg/m³ CEM I 52.5 N, 670 kg/m³ river sand 0/4, 1280 kg/m³ river gravel 2/16 and 150 kg/m³ of water. Concrete cubes with side length 150mm for determination of the compressive strength and (un)reinforced concrete prisms 150mm x 150mm x 600m were manufactured. The unreinforced prisms were used for the splitting and bending tensile strength determination, as well as for the drilling of concrete cores with a diameter of 100mm and a height of 150mm, drilled from the levelled face. The reinforced prisms were used for the 3-point bending tests in order to create cracks. The reinforcement consisted of two steel bars with a diameter of 6mm, placed at the bottom side in the corners at 15mm of the concrete surface.

The concrete specimens were stored in a climate room at 20 ℃ ± 2 ℃ and more than 90 % R.H. until the testing age (approximately 6 months). A the age of 28 days, the compressive strength and bending and splitting tensile strength were determined, resulting in 55.6 MPa, 5.3 MPa and

3.6 MPa respectively. In a further stage of the research program, other concrete compositions will be investigated to identify the influence of e.g. W/C ratio, type of coarse aggregate, etc.

2.3.2 Three-point bending test

The three-point bending test was carried out on reinforced concrete prisms with dimensions 150mm x 150mm x 600m. The load was applied until bending cracks appeared. After that, the specimens were unloaded and the cracks were closed. Next, a concrete core with diameter 100mm and a height of 50mm was drilled between the reinforcement, containing the crack. The main advantage of this test method is that 'real' bending cracks are created. The disadvantages of this test procedure were that a rather large amount of concrete is needed to have one test specimen and that it was very difficult to create resulting cracks with a crack width larger than 0.1 mm.

2.3.3 Brazilian splitting test

The Brazilian splitting test was performed on cylindrical samples with a diameter of 100mm and a height of 150mm. In order to prevent the concrete core of brittle failure, reinforcement has to be applied. However, steel can not be used because of the non steady-state migration test. Therefore, the concrete cores were externally wrapped with two layers of glass fibre reinforced polymers (FRP). Before the application of the FRP, a layer of adhesive tape is applied on the concrete in order to prevent bonding between the FRP and the concrete. In this way, the concrete is confined and brittle failure is prevented.
The test was carried out on the wrapped cylindrical samples, tested on their side in diametral compression. The load was applied through plywood strips (15mm wide and 4mm thick), interposed between the cylinder and the platens of the testing machine. A small area of glass fibre and concrete in contact with the plywood strips is subjected to vertical compression stresses and horizontal tensile stress. The load was increased until a visible crack was distinguished on one of both sides of the concrete cylinder. Stress distribution shows very high compressive stresses near the ends of the diameter and almost uniformly distributed tensile stress over the middle two-thirds of the specimen. Since concrete is much weaker in tension than in compression, failure occurs in splitting tension in the middle zone. After the splitting test, the concrete sample is sawn in three cylindrical specimens with a height of 50mm. Afterwards the FRP reinforcement is removed even as the adhesive tape. By this manipulation, a minor fraction of specimens collapsed.
The result is concrete specimens with different crack widths going from 0 until 0.2mm. The main advantages of this test procedure are the small amount of concrete used and the ease to create cracks with different crack openings.

2.3.4 Conclusion

Taking the limiting conditions into account, together with the practical execution, it was decided to use the adapted Brazilian splitting test, as described in 2.3.3, for the crack formation for the testing programme.

3. Chloride penetration

3.1 Test method

After removing the FRP of the specimens, the crack width on the concrete surface that will be exposed to the chlorides is measured with a portable crack microscope. From each concrete core from the Brazilian splitting test, three test cylinders are sawn. From the middle core, it was decided to expose the surface with the largest crack width. The exposed surface of the two other cores was the moulding or levelled face. A non-steady state migration test was carried out on the obtained concrete specimens, following NT BUILD 492 (1999). This method was developed by Tang (Tang 1996) and is using an electrical field, see figure 1. Firstly the specimens are vacuum saturated with a saturated $Ca(OH)_2$ solution. Afterwards an external electrical potential of 25 V is applied across the specimen for 2 hours that forces the chloride ions from the 10% NaCl solution to migrate into the specimens. Afterwards the specimens are axially split, perpendicular to the crack. On the freshly split sections, a 0.1 M $AgNO_3$ solution is sprayed and the chloride penetration depth is measured on each part at 17 points from the visible white silver chloride precipitation. In total 117 concrete cores were tested. In the experimental equipment present, 3 cores are tested simultaneously.

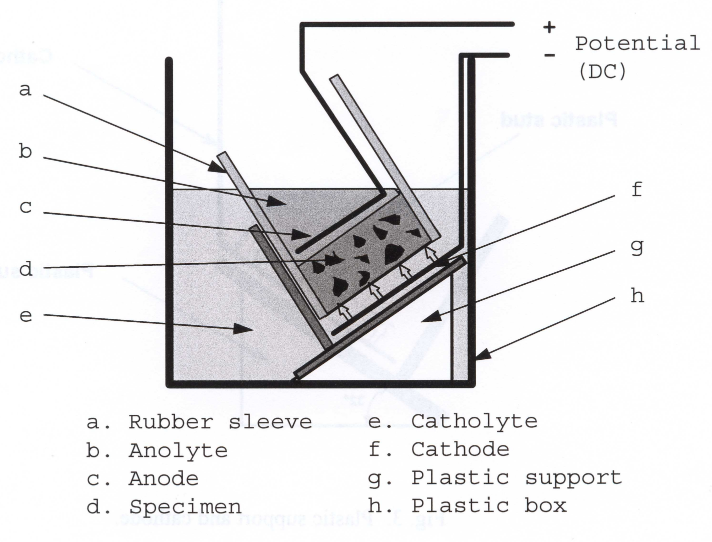

Fig. 1 Test method developed by Tang (1996)

From each concrete specimen, two penetration profiles are obtained. The mean value of both is calculated. The penetration profiles were organised in 11 groups, depending on the measured crack width, going from 0mm to 0.2mm in steps of 0.02mm. For each group, the mean penetration profile is calculated. The mean penetration profile for crack width 0.08mm is given in figure 2 (the test results are already converted to the reference age of 6 months, as explained in section 3.2.1). On the horizontal axis, the distance from the crack is given. Distance 0 means that the crack is at that place.

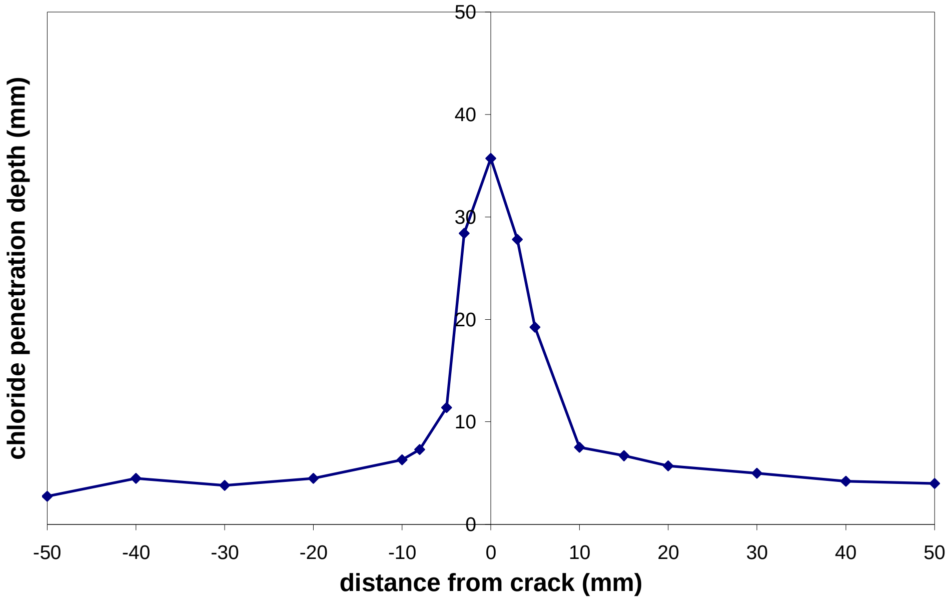

Fig. 2 Chloride penetration depth for crack width 0.08mm

3.2 Penetration profiles

3.2.1 Introduction

Before presenting the obtained chloride penetration profiles, some general remarks are to be made regarding the testing age and the penetration profiles of the 'uncracked' specimens:

- The concrete mixtures were made on two different days. Because of the duration of the preparation of the test specimens (wrapping with FRP, splitting test, sawing in discs, removing FRP), the chloride penetration test was not executed on the same age for all specimens but varied between 163 and 190 days. Because of the ongoing hydration of the specimens, the age of testing has a large influence on the penetration profile. The relation mostly used in literature to take into account for this time dependency is (Tang et al. (1992), Mangat et al. (1994), Costa et al. (1999)):

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

with D and D_1 respectively the migration coefficient and the migration coefficient at an age of 1 year (m^2/s), t the time (s) 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 (Audenaert (2006)), a value of 0.27 for m is used. This value is corresponding very well with values in literature (Bamforth (1999), Tang et al. (2001)).
From equation (1), the following equation for the calculation of the migration coefficient on 6 months could be derived:

$$\frac{D_{28}}{D_t} = \left(\frac{180}{t}\right)^{-0.27} \tag{2}$$

with t the time, expressed in days. The relation describing the chloride concentration in function of the distance from the concrete surface is given by Fick's second law:

$$x = 2\sqrt{D}\ \mathrm{erf}^{-1}\left(1 - \frac{C_d}{C_0}\right)\sqrt{t} = A\sqrt{Dt} \tag{3}$$

with x the penetration depth (m), A a constant (-) and C_d and C_0 the chloride concentration (N) which leads to a colour change and at the concrete surface respectively. From this equation, the following equation is obtained, giving the penetration depth at a concrete reference age of 6 months in function of the measured penetration depth at a concrete age t:

$$x_{6m} = x_t\sqrt{\frac{D_{6m}}{D_t}} = x_t\sqrt{\left(\frac{180}{t}\right)^{-0.27}} = x_t\left(\frac{180}{t}\right)^{-0.135} \tag{4}$$

With this formula, the chloride penetration depths at the reference age of 6 months are calculated from the measured chloride penetration depths.

- All specimens subjected to the chloride migration test, have been split in the adapted Brazilian splitting test. However, some specimens did not have a crack on the concrete surface exposed to chlorides that was noticeable on the microscope. For this reason, the penetration profiles of these test specimens are classified as 'crack width = 0'. As can be seen in figure 4, a small increase of the chloride penetration front could be noticed at 0, meaning that a micro crack was present.

From the obtained penetration profiles, two aspects were investigated in more detail: the influence of the crack width, measured on the concrete surface, on the maximum penetration depth and the extent of the crack influencing zone.

3.2.2 Influence of crack width on maximum penetration depth

The maximum penetration of the chlorides was defined as the mean value of the measurements at the crack (0) and the measurements at a distance of 3 mm from the crack (-3 and 3mm). This method was chosen because of the crack pattern observed. At the concrete surface, the crack is located at 0. However, the crack does not have a straight path but a tortuous one, due to the presence of e.g. aggregates. For this reason, it is possible that the maximum penetration depth is not located at 0. For this reason, the mean value of a zone of 6mm around the crack is used. In figure 3, the maximum penetration depth in function of the crack width, measured at the surface is given.

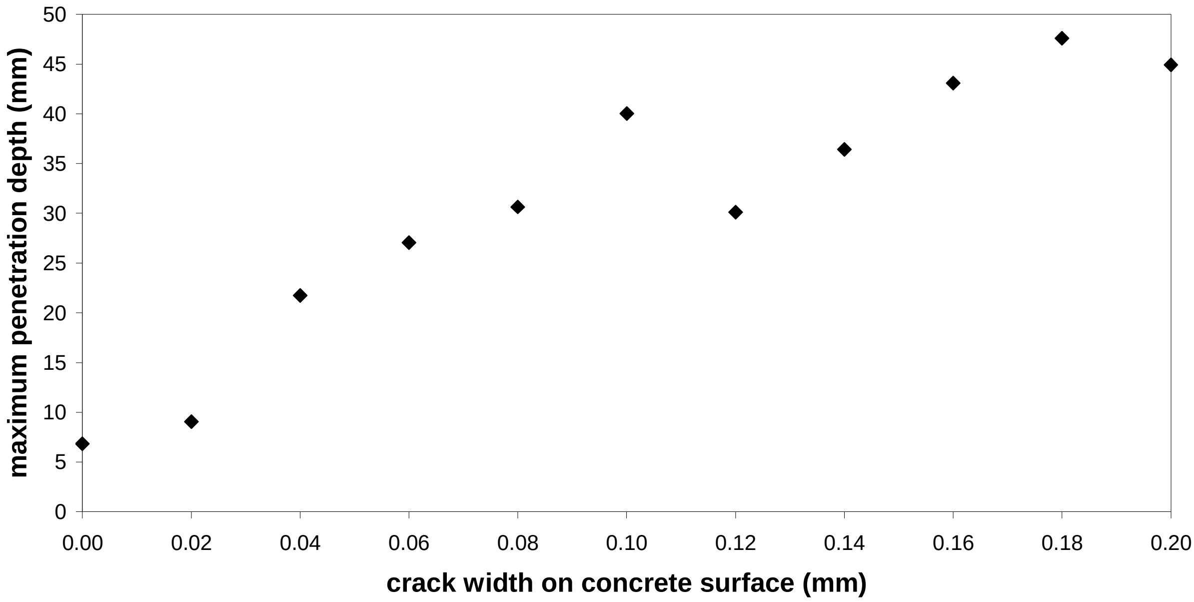

Fig.3 Maximum penetration depth in function of crack width on the concrete surface

From figure 3, it is clear that for increasing crack width, an increasing penetration depth is obtained. In the future, this relation will be theoretically analysed.

3.2.3 Extent of crack influencing zone

The extent of the crack influencing zone is investigated by the mean chloride penetration profiles. The chloride penetration profiles are given in figure 4 for the crack widths existing of the mean value of at least 5 profiles.

In this research program, the crack influencing zone is defined as the zone wherein the chloride penetration depth is larger than 1.1 times the mean penetration depth for uncracked concrete specimens. This penetration depth is 4.3mm and was determined on specimens which were not subjected to the Brazilian splitting test. From this criterion, the crack influencing zone in function of different crack widths is given in table 1. In this table, s is the distance from the crack until the proportion is lower than 1.1.

Table 1 Extent of crack influencing zone

w (mm)	0.02	0.04	0.06	0.08	0.10	0.12	0.14	0.16	0.18	0.20
s (mm)	10	10	15	15	20	20	20	20	20	30

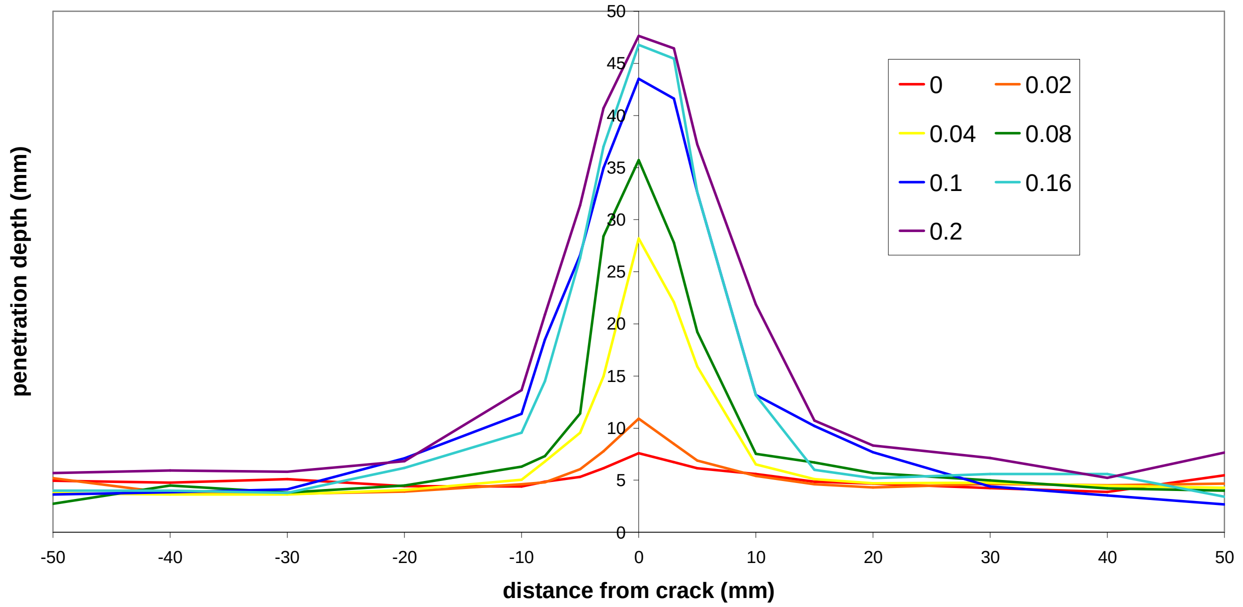

Fig. 4 Penetration profile for different crack widths

From table 1, it can be noticed that the crack influencing zone is enlarging for higher crack widths, as can be also noted in figure 4. Concluding, it can be stated that for crack widths up to 0.08mm, the influenced zone reaches up to 15mm from the crack. For larger crack widths, the influenced zone reaches up to 30mm.

4. Conclusions

Since the presence of cracks has an immense influence on the penetration of chlorides in concrete and on the remaining service life, this relation has to be investigated. Therefore, an experimental programme was carried out, developing a method to make cracks in concrete, based on the Brazilian splitting test. Crack widths between 0.02 and 0.2mm were obtained. The influence of the crack width on the penetration depth is leading to a relation stating that for increasing crack width, the maximum penetration depth is increasing. The extent of the crack influencing zone is depending on the crack width: for smaller cracks (maximum 0.08mm), the influence zone is less than 20 mm, for larger crack widths the influence zone is reaching up to 30 mm from the crack.

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