THE 7th INTERNATIONAL CONFERENCE
"CIVIL ENGINEERING - SCIENCE AND PRACTICE"

Vedran Carević[1], Ivan Ignjatović[2]

INFLUENCE OF CRACKS ON CONCRETE CARBONATION RESISTANCE

Abstract

In reinforced concrete (RC) structures carbonation induced corrosion is one of the biggest durability issue. There are many factors that affect carbonation process (CO_2 concentration, relative humidity, temperature, curing conditions and concrete porosity). Probably, the most important factor that affects carbonation process is the appearance of cracks on RC structures. With relatively low concrete tensile strength, cracks are almost inevitable. According to the current state of the art, the cracks have not yet been considered as a parameter in carbonation depth prediction model which is used for defining the service life of concrete structures. The main objective of this research is to analyse the influence of cracks on concrete carbonation resistance using own experimental results and the application of available prediction models regarding carbonation depth. For that purpose, prismatic RC samples without cracks and with different crack width (0.05 mm, 0.10 mm, 0.15 mm, 0.20 mm and 0.30 mm) were made and subjected to accelerated carbonation. The accelerated carbonation tests were performed during 28 days at a CO_2 concentration of 2%, relative humidity (RH) of 65±5% and a temperature of 20±2°C. The conducted analysis showed that even with low crack widths (0.05 mm) the maximum carbonation depth was significantly higher compared with the uncracked samples. In all cases, the cracks behaved as an additional exposed surface through which the CO_2 molecules were diffused perpendicularly to the crack wall. The crack impact area was approximately the same regardless of the crack width. Further than 10 mm, the carbonation depths remained constant. Also, with decreasing the length at which the average value of the carbonation depth was calculated (averaging length), the mean carbonation depth increased. Finaly, the ratio between the calculated carbonation depths (according to fib-Model Code 2010) of cracked and uncracked samples was up to three times.

Key words

Carbonation. Durability. Cracks. Service life. Accelerated test.

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[1] Teaching assistant, University of Belgrade Faculty of Civil Engineering, vedran@imk.grf.bg.ac.rs

[2] Associate professor, PhD, University of Belgrade Faculty of Civil Engineering, ivani@imk.grf.bg.ac.rs

1. INTRODUCTION

Deterioration mechanisms can lead to degradation of the concrete itself, but reinforcement corrosion is by far the biggest durability issue for reinforced concrete (RC) structures. Reinforcement is physically and chemically protected by the surrounding highly alkaline concrete environment. Degradation of thin oxide layer around the reinforcement allows corrosion to start (depassivation). One of the most important depassivation processes is carbonation. It represents the process of neutralization cement matrix, which reduces the chemical protection of reinforcement. A good reinforcement protection can be achieved with adequate concrete cover depth depending on the exposure conditions.

There are many factors that affect carbonation process (CO_2 concentration, relative humidity, temperature, curing conditions and concrete porosity). Probably, the most important factor is the appearance of cracks on RC structures. With relatively low concrete tensile strength, cracks are almost inevitable. Experience on existing structures showed greater carbonation depth at crack position compared with uncracked part of structure. Some practical examples of this phenomenon showed corrosion appearance on crack position [1]. Regardless, cracks have not yet been taken into account as a parameter in carbonation model which is used for defining the service life of concrete structures (e.g. *fib*-Model code 2010) [2]. On the contrary, it is considered that adequate quality of concrete cover and ordinary crack width limitation ensures sufficiently long service life (≥ 50 years) without extra protection [2].

There was an opinion based on studies from nearly 30 years ago [3], [4] that although the presence of cracks is a risk, their width cannot be directly related to the corrosion development. Several studies investigated the phenomenon of CO_2 diffusion in cracked concrete samples [5]–[10] in the last decade. The results obtained in those studies are shown in Table 1. The term "critical crack width" (Table 1), refers to the crack width which further increases, i.e. accelerates the affects the CO_2 diffusion. The crack widths below the critical values have no influence on carbonation depth, while wider cracks will increase carbonation depth compared with the uncracked samples. Obviously, no clear conclusion regarding the impact of the cracks can be drawn. Although there were some arguments that cracks have no effect on carbonation depth [5], [6], some experimental results showed that even with small crack widths (up to 0.10 mm) there was a change in the CO_2 diffusion, i.e. in the carbonation depth [7]–[10].

Table 1. The influence of crack widths on the CO_2 diffusion.

Reference	Method for crack producing	CO_2 conc.	Critical crack width [mm]
Neville (2006) [5]	–	–	no influence
Sillanpää (2010) [6]	notching and splitting	natural	no influence
Alahmad et al. (2009) [7]	expansive core	50%	0.01
Torres and Andrade (2013) [8]	three point bending	natural	0.08*
Zhang et al. (2011) [9]	embedded steel slices	20%	0.10*
Wang et al. (2018) [10]	four point bending	4%	0.10*

*lower crack widths were not examined

Although there were several studies on this subject, there is still a lack of results for general conclusions on their influence on the CO_2 diffusion and, especially, on carbonation prediction models. For that reason, the analysis of crack width influence on carbonation depth and prediction models is needed.

The objective of this study was to analyse the influence of cracked concrete cover as a good reinforcement protection. The analysis was carried out using own experimental results and the application of available prediction models regarding carbonation depth. For that purpose, samples without cracks and with different crack width were made and subjected to accelerated carbonation.

2. EXPERIMENTAL PROGRAM

2.1. PREPARATION OF SPECIMENS

Ordinary Portland cement concrete was prepared and tested. Concrete composition was presented in [11]. The mixture was designed to achieve the 90-days compressive strength of 40 MPa (150 mm cube sample) with the slump value after preparation in the range from 80 mm to 110 mm. The 90-days testing age was chosen because this is part of a larger research involving the high volume fly ash concrete, which has not yet been completed. This period enable the developing of pozzolanic reaction in high volume fly ash concrete and giving the proper time to each concrete to reach the majority of its compressive strength potentials. Concrete strength was design to ensure concrete class C25/30. The concrete was casted in steel moulds, and compacted using a vibrating table. After reparation, the specimens were cured 7 days. Workability of tested concrete was in the designed range (110 mm). The 28 days mean compressive strength obtained on 150 mm cube was 34.7 MPa, while at 90 days was 41.5 MPa, which would classify this concrete as class C25/30 according to [12]. The maximum CoV within any three cubes tested on the same day was 3.4%.

Carbonation resistance was tested on the 100x100x500 mm reinforced concrete prisms. At the age of 90 days, three point bending was applied on the prism samples to induce cracks. Setup of the experiment is shown in Figure 1. Prismatic RC samples without cracks and with different crack width (0.05 mm, 0.10 mm, 0.15 mm, 0.20 mm and 0.30 mm) were made and subjected to accelerated carbonation. Three samples were prepared for each crack width.

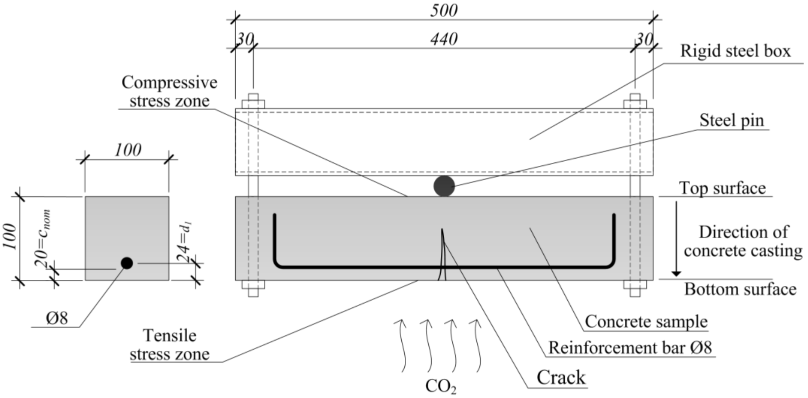

Figure 1. Experiment setup.

The rigid steel box was placed on the top of the sample to act as a support for the whole system. The force is applied using a torque wrench and a steel pin which is set in the middle of span, between the concrete element and a steel box. After the crack width reached a desired value, application of force using a torque wrench stopped. The crack width was measured using the DNT Entwicklungs und Vetrieb digital camera with magnification x45.

2.2. ACCELERATED CARBONATION TEST

The samples were placed in the carbonation chamber. The accelerated carbonation tests were performed during 28 days at a CO_2 concentration of 2%, relative humidity (RH) of 65±5% and a temperature of 20±2°C in a carbonation chamber Memmert ICH 260C (Figure 2). The carbonation depth was measured with phenolphthalein test according to the European standard EN 14630 [13]. Samples were broken along the longitudinal axis and then sprayed with phenolphthalein solution. The carbonation depth was measured at every 5 mm per top/bottom side, resulting in 58 (29 on each side) measurements for each different specimen.

Figure 2. Samples in carbonation chamber.

3. RESULTS AND DISCUSSIONS

3.1. ACCELERATED CARBONATION DEPTH

The measured carbonation depths along cracked sample surface in accelerated exposure conditions ($x_{c,ACC}$) in relation to the position of the crack are presented in Figure 3. The carbonation front was fairly flat except in the narrow area around the crack. It can be concluded from figure 3 that the impact of the cracks on the carbonation depth existed approximately around ±10 mm in relation to the crack position. The crack impact area was approximately the same regardless of the crack width. Further than 10 mm, the carbonation depths remained constant.

In all cases, the cracks behaved as an additional exposed surface through which the CO_2 molecules were diffused perpendicularly to the crack wall. Even for samples with small crack width (0.05 mm) this phenomenon was noticed, like in other studies found in literature [7]–[10].

With the increase of crack width, the increase in the maximum carbonation depth can be seen. Even with the lowest crack width of 0.05 mm the maximum carbonation depth was approximately two times higher compared with the uncracked sample. This implies that a sufficient amount of CO_2 molecules were continuously present even in the smallest crack widths due to CO_2-laden air circulation. With increase in crack width the maximum carbonation depth also increased.

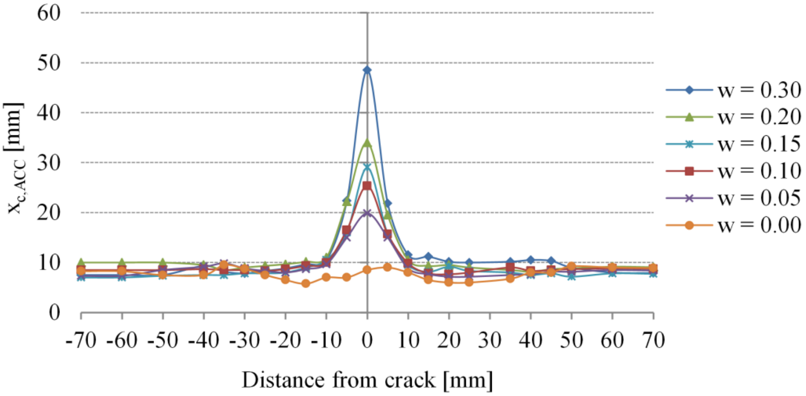

Figure 3. Carbonation depth in tensile zone along the sample in relation to the position of the crack.

If we look at the standards for determining carbonation depth in natural [14] or accelerated [2], [15] exposure conditions, it can be seen that the mean carbonation depth is an average value obtained at the certain length. Since cracks had a significant impact on the carbonation front only at ±10 mm in relation to its position, the length at which the average value was taken affects the mean value of the carbonation depth. In order to analyse this effect, the mean carbonation depths, ($x_{c,ACC,mean}$) in relation to the crack width for the different averaging length are shown in Figure 4. The averaging length represents the length at which the average value of the carbonation depth measurement was taken. The 20 mm averaging length (avg. 20 mm) was chosen having in mind crack impact area of 20 mm. The 50 mm averaging length (avg. 50 mm) was taken because it represents the length at which it is measured in accordance with the standard procedure for carbonation depth measurement, while the length of 140 mm (avg. 140 mm) represents the theoretical value of the crack spacing. The mean theoretical value of crack spacing was calculated based on the recommendation for small size reinforced beams, found in the literature [16], [17].

Having in mind the width of crack impact area, with decreasing the averaging length, the mean carbonation depth increased. The differences for uncracked samples were negligible (up to 5%), which was expected. However, for cracked samples, major differences were noticed. The differences between avg.50 mm and avg.20 mm compared with the avg.140 mm increased from 15% to 49% and from 46% to 91%, respectively, depending on crack width (from 0.05 to 0.30 mm).

It can be seen from Figure 4 that the difference between the mean carbonation depth of cracked and uncracked samples increases almost linearly with the increase of the crack width, regardless of the averaging length. Even for samples with a small crack width (0.05 mm), the differences between cracked and uncracked samples were significant: 21%, 43% and 74%

(depending on the averaging length). The differences increased with the decrease in the averaging length. For the avg.140 mm the differences between cracked and uncracked samples increased along with the crack width increase from 21% to 56%. For the avg.50 mm the differences increased compared with the avg.140 mm and increased from 43% to 140%. The highest differences were obtained using the avg.20 mm: the increase was from 74% to 192%.

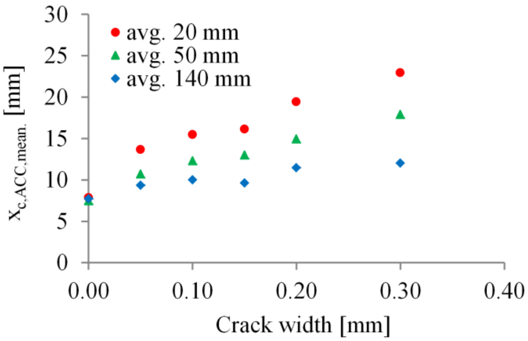

Figure 4. Mean carbonation depth in relation to the crack width.

In order to evaluate the impact of these two phenomena (averaging length and the presence of crack), it is important to analyse how much it will affect carbonation depth in natural exposure conditions. This was done using widely applied carbonation depth prediction model [2].

3.2. PREDICTION OF THE CARBONATION DEPTH IN NATURAL EXPOSURE CONDITIONS

Prediction of the carbonation depth in natural exposure conditions can be carried out according to the aforementioned *fib*-Model Code 2010 prediction model [2]. In addition to the ambient CO_2 concentration and the exposure time, this model takes into account the macro-climate conditions, curing conditions and concrete properties in explicit form:

$$x_c(t) = \sqrt{2 \cdot k_e \cdot k_c \cdot (k_t \cdot R_{ACC}^{-1} + \varepsilon_t) \cdot C_s \cdot t} \cdot W \qquad (1)$$

Where $x_c(t)$ is carbonation depth [mm] at the exposure time t [years], k_e represent environmental function [-] and W(t) weather function [-], k_c is execution transfer parameter [-], k_t regression parameter [-], ε_t error term [(mm^2/year)/(kg/m^3)], C_s is CO_2 concentration [kg/m^3], and R^{-1}_{ACC} is natural inverse effective carbonation resistance of concrete [(mm^2/year)/(kg/m^3)]. All parameters are defined in the *fib*-Model Code 2010 prediction model [2]. Due to the given exposure conditions during the accelerated test (2% CO_2, RH 65% and samples protected from rain) and 7 days concrete curing, values of the parameters of the micro-climatic (W(t) and k_e) and curing conditions (k_c) were set equal to 1. If the same parameters for macro-climate and curing conditions were adopted, the only difference in the prediction of carbonation depth (according to Eq. 2) will be the value R^{-1}_{ACC}, which is calculated based on average carbonation depth measurement. In order to evaluate the impact of cracks on the predicted carbonation depth in natural exposure conditions, the ratio between the calculated carbonation depths of cracked ($x_{c,NAT,cr}$) and uncracked ($x_{c,NAT,0}$) samples is shown in Figure 5.

The ratio between the calculated carbonation depths of cracked and uncracked samples was up to three, at the small averaging length (avg.20 mm). This practically means that in the case of samples with crack width of 0.30 mm, the natural carbonation depth will be three times higher than in uncracked samples. Even if larger averaging length (avg.140 mm) was used, the carbonation depth was up to 56% higher compared with uncracked samples.

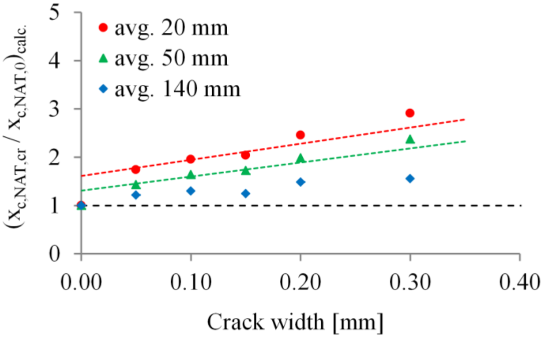

Figure 5. Ratio between calculated carbonation depths of cracked ($X_{c,NAT,cr}$) and uncracked ($X_{c,NAT,0}$) samples for various averaging length.

4. CONCLUSIONS

The main objective of this study was to analyse the influence of cracks on carbonation depth by using own experimental results and the application of prediction models. Based on the conducted carbonation depth measurements on samples with and without cracks, the following conclusions can be made:

- The increase in the crack width led to the increase in the maximum carbonation depth. Even with the lowest crack width of 0.05 mm the maximum carbonation depth was two times higher compared with the uncracked samples. The crack impact area was approximately the same (20 mm) regardless of the crack width.

- With decreasing the length at which the average value of the carbonation depth was calculated (averaging length), the mean carbonation depth increased. The difference between the mean carbonation depth of cracked and uncracked samples increased linearly with the increase of the crack width, regardless of the averaging length.

- The ratio between the calculated carbonation depths (according to *fib*-Model Code 2010) of cracked and uncracked samples was up to three times. This practically means that in the case of samples with crack width of 0.30 mm, the RC structure service life will be approximately three times shorter compared with the uncracked samples, if the depassivation of reinforcement is assumed as an ultimate limit state.

ACKNOWLEDGEMENTS

This work was supported by the Ministry for Education, Science and Technology, Republic of Serbia [grant number TR36017].

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