Experimental study of the influence of crack width due to corrosion behaviour using different measurement methods and different exposures

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Abstract. Corrosion of reinforcing steel has a great influence in reducing the lifetime of concrete structures; Carbonation of the concrete pore solution causes surface corrosion on the steel and diffusion of chloride ions through the capillary system of the concrete cover causes pitting corrosion on the steel surface. Corrosion of metals is highly dependent on the environmental conditions. Exposure to chloride ions can be critical to the service life of reinforced concrete structures. The durability of reinforced concrete structures exposed to deicing salt or marine environments can be affected by impact of chloride ions. Detection methods for the rate of corrosion of non-destructive and destructive procedures were analysed. The potential mapping applied on the concrete surface was discussed as a standard method for corrosion detection and will be explained in detail including the application boundaries of the method. It is assumed that the corrosion behaviour of reinforcing steel depends on crack widths. To analyse that, 8 coated and 8 uncoated test samples with different concrete strength classes were used. The concrete objects were exposed to a 3% sodium chloride solution. The corrosion behaviour of reinforcing steel is analysed by using potential mapping with different reference electrodes (Ag/AgCl and Cu/CuSO4). The results show a significant correlation between crack size and protection system on the surface. The maximum crack width with a low indication of corrosion was found to be 0.1 mm.

1 Cracks in concrete

The special feature of the composite material reinforced concrete is that the concrete protects the embedded reinforcing steel from corrosion. If this protection of the reinforcement steel is lost, it results in an influence on the durability. This can be caused by excessively large crack widths. The permissible crack width is specified in technical regulations and standards. Consequently, cracks with limited crack width are no longer considered a defect or damage. It should be noted, however, that cracks with small widths promote the penetration of harmful substances such as CO2 and chloride. For the assessment of the corrosion of reinforcement steel, electrochemical examination procedures are available. A relatively inexpensive non-destructive method is the half-cell potential measurement [1].

1.1 Exposure classes

To ensure the necessary durability, concrete elements must be sufficiently resistant to chemical and physical influences from environment or use. These effects on the building material are divided into exposure classes. The following exposure classes record effects on the reinforcement in the concrete: XC (Carbonation), XD (Deicing), XS (Seawater) [1].

1.2 Causes of Cracks

Crack formation in concrete occurs when the locally present stress exceeds the local tensile strength of the material. It is irrelevant at first whether the crack causing stress is generated from an external static or dynamic load or whether this results from an obstruction of the deformation effort of the concrete – residual stress or constrained stress. Of essential importance is the fact that concrete is not completely homogeneous and isotropic with regard to its properties, in particular its tensile strength [2].

• In fresh concrete cracks occur as a result of rapid volume reductions at the near-surface concrete layer - caused by unfavourable temperatures, solar radiation, wind and low humidity [3].
• In building practice, cracks may occur because of loss of the hydration heat or by shrinkage, in particular by early shrinkage [3].

In order to ensure sufficient protection of the reinforcement and the necessary durability, the crack widths are limited in standards and guidance. The limit values of the crack widths is dependent on the exposure class and the design class and are determined according to ÖNORM 1992 1-1.
1.3 Reinforcement corrosion caused by cracks

The type of crack plays an important role when it comes to assessment. For example, bending cracks usually have a lower risk potential for a component than separating cracks. CO₂, chloride and water can penetrate the component through separating cracks. In addition, separation cracks often cause a change in the static system. This can lead to extensive load redistribution and further crack formation. Surface cracks caused by inadequate post-treatment do not have the same serious consequences as large cracks caused by a lack of reinforcement steel. Cracks that occur along the reinforcement are particularly critical because they can lead to composite failure [5].

![Fig. 1. Typical damage pattern of pitting corrosion 5].

A special characteristic of reinforced concrete is the corrosion protection of the installed reinforcing steel by the concrete. Due to the high pH value of the concrete pore solution ranging from pH 12.5 to pH 14, a passive film is formed on the surface of the reinforcing steel, a few atom layers thick, to protect the steel underneath from further degradation. If the concrete loses its alkalinity or if a critical chloride content is exceeded on the steel surface, the corrosion protection of the reinforcing steel may be lost. If pollutants such as chlorides or CO₂ penetrate the concrete via a crack, rapid damage processes can occur to both the reinforcement and the concrete itself. This leads to depassivation and corrosion of the reinforcement steel [8]. The danger of chloride-induced pitting corrosion (local corrosion) lies in the combination of high corrosion rates of the steel with simultaneous invisibility of the damage process from the outside. This local corrosion leads to high corrosion rates, because a small corrosion scar results in a large cathode surface which accelerates the corrosion process. The steel removal rates associated with these high corrosion rates can reduce the steel cross-section of the reinforcement within a short time. At the same time, the damage processes in the interior of the component go on, so that the reinforcement steel can already be significantly damaged, without any appearance of damage on the concrete surface [6].

2 Corrosion due to chloride ingress

The corrosion protection of the reinforcement steel can be lost if the surrounding concrete loses its alkalinity or if a critical chloride content on the steel surface is exceeded. Small amounts of chloride in the concrete can be contained in the raw materials: cement, water or concrete aggregates. They are defined as natural chloride content of the concrete. Chloride ions diffuse into the concrete or are transported by capillary absorbed water and interact with the passive film of the steel when they reach its surface. If a critical concentration of free chloride ions on the steel is exceeded, the passive film of the steel fails and corrosion can begin. This phase of chloride penetration before the depassivation of the steel is called the initiation phase. With the beginning of corrosion, the propagation phase starts. The chronological sequence of the accumulated damage to the reinforced concrete structures exposed to chlorides is shown in Figure 2 [7].

![Fig. 2. Chronological sequence of accumulated damage to structures with chloride-induced corrosion 7].

2.1 Propagation Phase

A special type of corrosion is pitting corrosion. During this corrosion of steel in concrete, the positively charged iron ions (Fe²⁺) go into solution, where the concrete pore fluid is the electrolyte. At the same time a reduction of the oxygen takes place. Under the formation of negatively charged hydroxyl ions (OH⁻), the superfuse electrons at the steel/electrolyte interface react with water and oxygen, that is usually present and is dissolved in water in sufficient quantity. The formation of hydroxyl ions OH⁻ is called a cathodic sub-process. In

| Exposure class | maximum crack width |
|----------------|---------------------|
| X0, XC1        | 0,4 mm (appearance) |
| XD1, XD2, XD3  | 0,3 mm              |
reinforcing steel, but also in concrete (electrolyte), the charge balance is retained. Iron dissolution (formation of Fe$^{2+}$) is called an anodic sub-process. The processes described are simplified in Figure 3 below [8].

$$\text{Fe} \rightarrow \text{Fe}^{2+} + 2\text{e}^- \quad (1)$$

Oxygen is reduced in the cathodic sub-process. This absorbs the electrons emitted in the anodic reaction and reacts with the pore water to form OH$^-$:

$$\text{H}_2\text{O} + \text{O}_2 + 2\text{e}^- \rightarrow 2\text{(OH)}^- \quad (2)$$

Fig. 3. Corrosion processes and elements involved [8].

Basically the corrosion process can be divided into two simultaneously running sub-processes. In the anodic sub-process, metal dissolution takes place. In this process the reinforcement steel loses two electrons to the environment and converts into Fe$^{2+}$.

$$\text{Fe} \rightarrow \text{Fe}^{2+} + 2\text{e}^-$$

below the quasi-stable action combination. According to ÖNORM B 1992 1-1, if a crack width restriction is required, a minimum amount of reinforcement must be inserted in areas where tension is expected. The minimum reinforcement results from the balance of the tensile force before the incipient crack in the concrete and the tensile force after the incipient crack in the reinforcement. The actual load has no influence on the amount of steel, since the forces to be absorbed are purely a result of the tensile stresses in the concrete before the crack formation [4].

3 Experiment Setup

The aim of this laboratory experiment is to use the half-cell corrosion potential mapping to evaluate whether different crack widths have an effect on the corrosion behaviour of reinforcing steel. For this, 2 specimen series with two different exposure classes XD1 and XD3 as well as two different strength classes C30/37 and C35/45 were used. Half of the specimens were coated with epoxy resin. The cracks were artificially created by 3 point bending load. In order to determine the corrosion behaviour, the test specimens were coated with a sodium chloride solution and then observed during a period of one and a half months using half-cell corrosion potential measurement. Based on the resulting data, the behaviour of the reinforcement steel was evaluated.

3.1 Preparation of the test specimens

For the experiment, 8 coated and 8 uncoated test specimens with the dimensions 60x40x10 cm were produced and reinforced as shown in Figure 4.1 below.

Fig. 4. Chloride-induced corrosion in the crack area [8].

2.2 Crack widths

According to ÖNORM B 1992 1-1, the crack width must be limited in order to ensure that the proper use of the structure, its appearance and durability are not affected. The standards show permissible characteristic crack widths (wk) in dependence on the exposure classes. For reinforced concrete elements exposed to exposure class XD, the crack width shall be limited to wk = 0.3 mm.

The following concrete strength and exposure class was used for the production of the test specimens. Portland cement CEM I 42.5 N (270 kg) with an additive mixture consisting of slag sand, limestone and fly ash (40 kg) was used as binder.

| class    | exposure | w/c-ratio |
|----------|----------|-----------|
| C30/37   | XD1      | 0.55      |
| C35/45   | XD3      | 0.45      |

Table 3. Concrete formulation.
Ribbed structural steel B500B was used as reinforcement for 14 test specimens and B550B for two others. The diameter was 8 mm and the bar-to-bar distance was 10 cm. The concrete cover depth was 4 cm. The coating used was a two-layer epoxy resin coating with a layer thickness of 0.5 mm.

### 3.2 Crack initiation

The cracks in the test specimen were created by a 3 point bending load. As shown in Figure 6, the concrete slabs were placed in a hydraulic testing machine and loaded in a controlled manner until the crack was created. The desired crack width was 0.1 - 0.3 mm. In order to prevent the crack from closing again, wooden wedges were attached to both ends of the crack.

![Fig. 6. Crack initiation.](image)

### 3.3 Salt exposure

All specimens were loaded by a central load according to the bending tensile test to initiate cracks with different crack widths. The test specimens were contaminated from 16.05.2017 to 22.06.2017. During this period, the concrete slabs were loaded with 3% sodium chloride solution. In the first 5 applications, the test specimen was loaded with sodium chloride for the rapid increase of the chloride. After that, the other treatments were only carried out with water.

### 3.3 Measurement setup

In the laboratory test, 16 plate-like test specimens with the dimensions 60 x 40 x 10 cm were used. The test specimens were stored under a roof for the entire duration of the measurement in an outdoor climate. To carry out the potential measurement, the reinforcement of the two test specimen groups was connected separately with a cable. As shown in Figure 8, the reference electrodes were attached to the top near the crack. The potential measurement was carried out with two different types of electrodes. On the one hand silver - silver chloride and on the other hand, copper - copper sulphate was used. This allows comparing several measurement results with each other.

| date     | application                      |
|----------|----------------------------------|
| 16.05.2017 | 100 ml NaCl solution, 3 % Cl     |
| 18.05.2017 | 100 ml NaCl solution, 3 % Cl     |
| 19.05.2017 | 100 ml NaCl solution, 3 % Cl     |
| 22.05.2017 | 100 ml NaCl solution, 3 % Cl     |
| 23.05.2017 | 100 ml NaCl solution, 3 % Cl     |
| 24.05.2017 | 100 ml water                     |
| 29.05.2017 | 100 ml water                     |
| 30.05.2017 | 100 ml water                     |
| 31.05.2017 | 100 ml water                     |
| 06.06.2017 | 100 ml water                     |
| 13.06.2017 | 100 ml water                     |
| 22.06.2017 | 100 ml water                     |

![Fig. 7. Experimental setup.](image)

![Fig. 8. Position of electrodes.](image)
4 Results and evaluation

The electrochemical potential field measurement is a method for assessing the corrosion behaviour of the reinforcement of reinforced concrete components. By measuring the electrochemical potential difference, areas with a high corrosion probability can be detected. To determine the current potential at the steel/concrete interface of the reinforcement steel below the concrete surface, the potentials arriving at the surface are measured. The measurement is carried out by a high-impedance voltmeter connected to the reinforcement steel. If the electrode potential is determined at a standard electrode with the normal hydrogen electrode as reference, this is referred to as normal potential. The measurement is carried out by a high-impedance voltmeter connected to the reinforcement steel. If the electrode potential is determined at a standard electrode with the normal hydrogen electrode as reference, this is referred to as normal potential. The measured potential values can be interpreted as more negative potentials indicating a higher probability for corrosion processes. A difference is made here between two ranges. In the range above (more positive than) -200mV a low corrosion probability is given. In the range below (more negative than) -200mV a high corrosion probability applies [1].

Fig. 9. Position of the measuring points

The measured crack widths are given in Table 5 below.

Table 5. Crack widths of uncoated and coated Specimens

| Specimen No. | Measuring points | Mean value |
|--------------|-----------------|------------|
|              | 1 | 2 | 3 | 4 | x     |
| 1            | 0,1| 0,2| 0,4| 0,3| 0,25  |
| 2            | 0,2| 0,5| 0,1| -  | 0,27  |
| 3            | 1  | 0,5| 0,5| 0,6| 0,65  |
| 4            | 0,2| 1  | 0,8| 0,4| 0,5   |
| 5            | 0,4| 0,6| 0,4| 0,8| 0,58  |
| 6            | 0,4| 0,6| 0,4| 0,8| 0,58  |
| 7            | 0,2| 0,2| 0,3| 0,1| 0,23  |

4.1 Detection of cracks

In order to detect the crack widths as accurately as possible, these were measured at four points on the specimens, as shown in Figure 9. The results are summarized in the following diagrams.

Figure 10. Potential mapping of coated samples Cu/CuSO₄.

Figure 11. Potential mapping of uncoated samples Cu/CuSO₄.

Figure 12. Potential mapping of coated samples Ag/AgCl/Cl.
4.3 Evaluation of the potential measurement with Cu/CuSO₄ electrode system

As can be seen in Figures 10 and 11, there are increased fluctuations in the corrosion potential during early application. These variations are due to the salt solution application, as the first five applications were carried out using sodium chloride. At the beginning of the measurements the coated specimens show greater variations than the uncoated specimens. However, the amplitudes of the corrosion graphs drop again right after the application. After further application, some peaks are still visible.

4.3.1 Coated Specimen

After the second application, 2 samples with a measured potential of -550 to -600 mV stand out: Test specimen 5 with a mean crack width of 1.13 mm and test specimen 8 with a mean crack width of 0.15 mm. After the fifth application, all 8 specimens were in a range below the -200mV limit. The fluctuation range of the measured potentials of the test specimens was -230mV after 28 days.

4.3.2 Uncoated Specimen

During the early applications using sodium chloride, the test specimens reacted quickly with few fluctuations. This effect is most clearly visible in sample 3, which also shows the largest average crack width of 0.65 mm. After 15 days, all samples exceeded the critical -200mV range. After 28 days the fluctuation range of the determined potentials was -300mV.

4.3.3 Comparison of the test series

In the comparison of the two test series, there should be a difference between the coated and uncoated series, as the moisture in the crack area is rather higher and cannot leak through the surface. However, no such effect could be observed. After being exposed to sodium chloride, 15 of the 16 samples of the two groups of test specimens reached the critical -200mV limit in which corrosion is very probable. After 28 days, the different crack widths did not show any significant similarity. No correlation was found between the crack widths and the corrosion potential of the individual specimens.

4.4 Evaluation of potential measurement with the Ag/AgCl/Cl electrode system

The measurement with the silver-silver chloride electrode system began 10 days before the first application of sodium chloride in order to check the functional capability of the electrode system by corresponding reference measurements. After the first application of sodium chloride a clear reaction was observed. As can be seen in Figures 12 and 13, the further applications are only weakly visible on the diagrams. This effect can be observed in both groups of the test specimens. This could be due to a contact problem of the reference electrodes. In comparison with the copper - copper sulfate electrode clear differences were determined within the potential measurement.

5 Summary

The aim of this study was to determine whether different crack widths may have an influence on the corrosion behaviour of reinforcing steel. Two different electrode systems were used: Silver - silver chloride - electrodes and copper - copper sulphate - electrodes. For the specimens, two different strength classes and two exposure classes were used. The measured potentials, Figs. 12 and 13, show that the silver -silver chloride - electrodes in this case were not suitable for this type of measurement because a contact problem of the electrodes led to irregular measurement results. Therefore, it was not possible to make a representative evaluation of the measurement results. For this reason, the results of the measured potentials of the copper - copper sulfate - electrodes were used. These measurement results show that no noticeable improvement can be achieved using an epoxy resin coating. Neither with the strength class nor with the exposure class could clear trends be observed. A correlation between the different crack widths and the corrosion rate could not be established. As a result, it is clear that different crack widths have no influence on the corrosion behaviour of the reinforcing steel.

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