

# Corrosion monitoring of cracked concrete structures - state of knowledge and case studies

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**ABSTRACT:** Reinforcement corrosion due to chloride ingress is probably the most important deterioration mechanism for our concrete infrastructure. Especially for parking structures, the formation of cracks can lead to an accelerated chloride ingress and as a consequence to corrosion initiation after a comparably short time of use.

The most common approach for the rehabilitation of chloride-contaminated concrete structures is to remove the concrete adjacent to the affected reinforcement layer, rebuild the concrete cover with chloride-free concrete and apply an adequate coating system in order to avoid chloride ingress during future use. However, this method is often very expensive and time-consuming and may cause significant inconveniences for users and consumption of resources. Both recent research activities and field applications suggest that for cracked concrete structures with moderate chloride contamination, the combination of a crack-bridging coating system and a corrosion monitoring system for the monitoring of time-dependent changes of corrosion activity may in some cases be an economic and resource-efficient alternative.

This contribution takes a closer look at the potentials of this alternative approach, taking the state of knowledge on corrosion mechanisms in cracked concrete into account. A possible solution for the corrosion monitoring of existing structures is presented. The design and installation of a corrosion monitoring system and the results of corrosion monitoring for an actual structure approx. two years after application are illustrated by means of a case study.

## 1 INTRODUCTION

Chloride-induced reinforcement corrosion is generally the most relevant deterioration mechanism for our reinforced concrete infrastructure. Depending on the type of structure and the individual exposure conditions, reinforcement corrosion can occur after comparably short time of use, leading to significant costs both for the potential repair itself and the use restrictions during the repair measures. This applies especially to horizontal surfaces exposed to a chloride load, as for instance bridge decks or parking decks. For these applications, different coating and/or sealing solutions with different properties regarding e.g. crack-bridging and robustness exist. In case the right coating system is selected and inspection and maintenance of the coating system are carried out with adequate care, these systems may safeguard the durability of the structural element over the target service life. However, in many cases either the crack-bridging properties are not sufficient for the individual requirements, leading to the formation of unbridged cracks, or poor workmanship and/or maintenance lead to an accelerated deterioration of the coating system and as a consequence the loss of chloride ingress protection of the exposed surface. Especially in the

case of crack formation, chlorides may penetrate into the concrete very quickly and lead to reinforcement corrosion. Depending on the exposure conditions, corrosion initiation can occur within less than a winter period and thus very strongly affect the service life of the structure. The conventional rehabilitation of chloride-contaminated, cracked concrete structures aims at completely replacing the chloride-contaminated concrete and in most cases leads to comparably high repair costs and downtimes. However, the characteristics of corrosion in cracked concrete, i.e. the localized chloride ingress within the crack region along with no increased chloride contents in the surrounding concrete, may also allow for alternative, more cost-effective repair measures. This paper will take a closer look at the specific mechanisms of reinforcement corrosion in cracked concrete and corresponding repair measures and explain both potentials and risks of alternative repair concepts. A special focus will be set on the corrosion monitoring of reinforcement corrosion in cracked concrete as an integral element of these repair concepts.

## 2 CHLORIDE-INDUCED REINFORCEMENT CORROSION IN CRACKED CONCRETE

### 2.1 Mechanisms of reinforcement corrosion in cracked concrete

Although cracks only offer a locally limited path, chlorides accumulate in the crack area and can exceed the critical corrosion-initiating chloride content of the reinforcement very quickly. Therefore, highly chloride exposed RC structures (e.g. parking decks) have a significant risk of reinforcement corrosion, since the discrete depassivation of the steel surface can promote the formation of macro-cell corrosion with high corrosion rates. The depassivated steel in the crack and adjacent concrete is subjected to the anodic reaction in which iron is oxidized and electrons are set free. When reduced in the cathodic process, hydroxide ions reach the anode via the concrete's electric conductivity (Figure 1) and the circuit is closed.

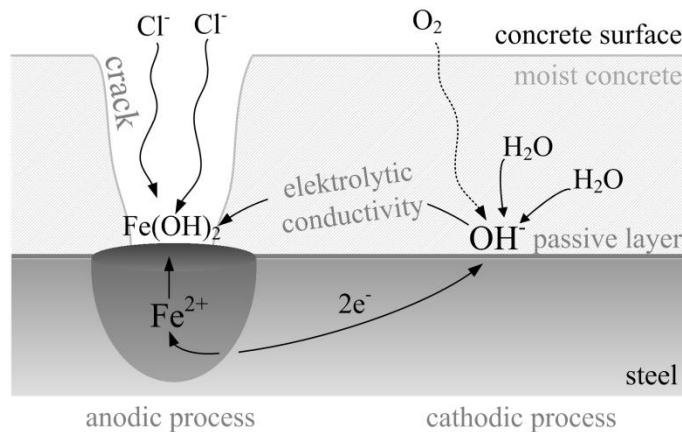


Figure 1. Scheme of macro corrosion in cracked reinforced concrete

As a result of the anodic and cathodic reactions, an electric current will flow in the reinforcement, accompanied by an ion transport in the concrete. The total corrosion current  $I_{\text{corr}}$  consists of macro-element current  $I_{\text{macro}}$  and micro-element current  $I_{\text{micro}}$ . The latter cannot be measured directly since both sub-processes, cathodic and anodic, contribute inseparably to the corrosion process.

$I_{\text{macro}}$  results from the potential difference  $\Delta E$  between open circuit potentials (OCP) of anode and cathode and the sum of all system resistances. These are caused by the obstruction of electrochemical processes on anode and cathode (anodic and cathodic polarization resistance  $R_{P,A}$

and  $R_{p,C}$ ) or in the electrolyte (electric resistivity of concrete  $R_e$ ). This electrochemical process can be expressed by Equation 1 [Beck et al. (2013)].

$$I_{\text{macro}} = \frac{\Delta E}{R_{p,A} + R_{p,C} + R_e} \quad (1)$$

## 2.2 Time-dependent change of corrosion activity after coating of cracks

In the lab, the parameters of macro-element corrosion can be directly measured and thus used to evaluate the development of the corrosion process. However, it needs to be ensured that the anodic and cathodic sub-processes are locally separated.

Such a laboratory setup was used to investigate reinforcement corrosion behavior in cracked, chloride-contaminated concrete after application of a concrete coating (CC) [Keßler et al. 2017, Hiemer et al. 2018]. Corrosion parameters were measured on reinforced concrete beams with bending cracks exposed to chlorides for 12 weeks (approx. one winter season) and subsequently coated with a crack-bridging coating system. A crack-crossing rebar was used as anode with two cathode cages installed outside the crack to avoid their depassivation. After the electrochemical measurements, chloride profiles were taken and the anodes were visually examined.

The investigation revealed, that for bending cracks subjected to chloride for one winter period, the CC (recommended in [DBV 2010]) was an effective measure to cease corrosion once it had been initiated on the crack-crossing reinforcement. On some anodes pitting scars with a maximum depth of 2 mm were found, but on average the corrosion loss was significantly lower, so that cross-section losses were not considered harmful for the load bearing capacity. However, the suspected increase in electrolytic resistance was not responsible for the standstill of corrosion. Under laboratory conditions, the anodic polarization resistance always proved to be the dominant system resistance reducing corrosion activity. The reason may be due to the lack of chlorides, their subsequent redistribution in the concrete and/or due to the surface layer formation during active corrosion [Keßler et al. 2017].

## 2.3 Repair strategies for reinforcement corrosion in cracked concrete

### 2.3.1 Replacement of contaminated concrete

The conventional approach for the rehabilitation of chloride-contaminated concrete structures is to remove the chloride-contaminated concrete up to a depth at which the threshold value for the critical chloride content is no longer exceeded and then replace it with chloride-free, highly alkaline repair mortar or concrete (repair method 7.2 according to EN 1504-9). To ensure proper bond between the new concrete and the existing structure, the concrete replacement should be carried out with sufficient depth so that the reinforcement closest to the surface is exposed. The concrete removal is best carried out by means of high-pressure water blasting as this technique will allow to remove the concrete without causing further damage to the reinforcement.

For horizontal concrete elements with crack formation over the complete cross section, the conventional repair consequently includes the removal of the concrete over the complete cross section with a total width of appr. 20 – 30 cm and subsequent replacement with repair mortar/concrete [Sodeikat et al. (2019)]. As this is a rather broad intervention into the structural system, in most cases supporting elements will be needed and the use of the structure both above and below the cracked element will be affected over a comparably long period of time. Impressions of a conventional concrete repair measure for a cracked concrete parking deck are shown in Figure 2.

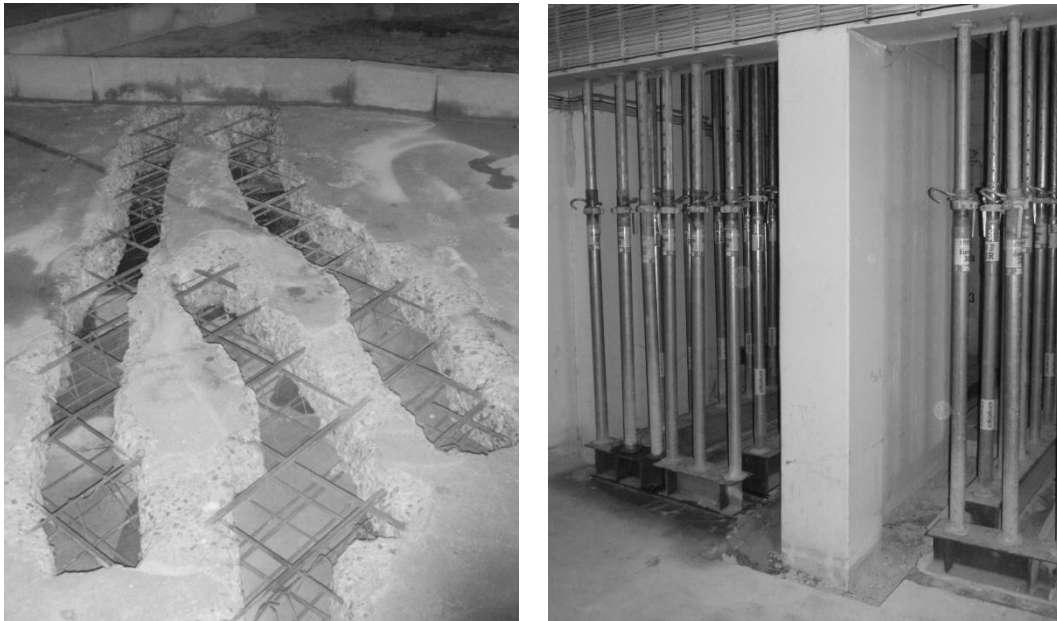


Figure 2. Conventional repair of cracked concrete structures.

### 2.3.2 Cathodic protection

Over the past decade, cathodic protection (CP – method 10.1 according to EN 1504-9) has developed into a widely accepted alternative to the replacement of contaminated concrete. The general concept of cathodic protection is to suppress the anodic corrosion process of iron dissolution by impressing a direct current between the reinforcement and an auxiliary anode (e.g. TiMMO anodes), thus forcing a cathodic polarization of the reinforcement. Cathodic protection will lead to a reduction of the corrosion process to negligible rates without removal of the chloride-contaminated concrete and is therefore in many applications a very economic and fast repair approach. In the case of cracked concrete, the appropriate anode system strongly depends on the type of crack formation. If only the upper reinforcement layer is affected, anodes placed on the concrete surface can be sufficient. If corrosion of both the upper and the lower reinforcement layer is initiated, the placement of anodes on the upper surface and the bottom side of the concrete element or as an alternative tube anodes placed in bore holes may be required.

### 2.3.3 Increasing resistivity

The basic concept of repair principle 8 – increasing resistivity is neither to restore passivity by replacing chloride-contaminated concrete nor to suppress the anodic iron dissolution by impressing a direct current, but to reduce the corrosion activity by increasing the concrete resistivity. This can normally be achieved by e.g. applying an impregnation or a coating to the concrete surface and thus stopping further water ingress into the pore system. While increasing resistivity is one of the standard repair concepts for carbonation-induced corrosion, its applicability to structures subject to chloride-induced reinforcement corrosion is still discussed controversially. This is due to the fact that in the case of chloride-contaminated concrete the drying-out process is hindered by the hygroscopicity of chlorides. Furthermore, experience shows that the drying-out after application of a coating is normally limited to the concrete layers close to the surface and

has only very limited effect at larger depths, so that its effect will probably be very limited for larger concrete covers. Results of recent research activities imply that the impact of coating of cracked, chloride-contaminated concrete structures on the corrosion activity can be attributed to other effects and the increased electrolytic resistivity is only of minor relevance, cp. chapter 2.2.

Due to the limited experiences with this repair procedure, its application in Germany in the case of chloride-induced corrosion is only possible in combination with a corrosion monitoring system to monitor the success of the intervention with time.

### 3 CORROSION MONITORING OF CRACKED CONCRETE STRUCTURES

Depending on the corrosion state of the reinforcement at the installation point of time and the actual measurement task, there are different measurement principles and sensor setups for corrosion monitoring of concrete structures. The German DGZfP specification B12 [DGZfP (2018)] provides a comprehensive overview on the current state of knowledge with respect to monitoring of reinforcement corrosion.

In the case of cracked concrete structures, chloride ingress into the concrete occurs within a comparably short time period. As sensor installation will in most cases take place subsequent to crack formation, it is generally not necessary to monitor the chloride ingress at different depths with time, but the main focus is set on the time-dependent change of corrosion activity at reinforcement level. This has an effect on the choice of the correct measurement techniques. To monitor time-dependent changes of corrosion activity, corrosion current measurements or linear polarization resistance measurements are generally considered to be most adequate. Half-cell potentials may give some additional information, but appear not to be sufficient to fully characterize the corrosion state of the reinforcement under consideration. Other sensor systems like wire sensors that aim to describe the corrosion state by measuring the electrical resistance of corroding wires at different depths can by definition not describe time-dependent changes of corrosion activity and are therefore considered inadequate for these more sophisticated monitoring applications.

As corrosion monitoring of existing structures is normally installed after corrosion initiation, one of the most difficult issues for the monitoring system design is to install sensors in a way that will allow to characterize the corrosion state of the reinforcement with sufficient reliability without changing the corrosion system significantly. This is especially true for corrosion in cracked concrete. As subsequent installation of sensors in the crack will almost always lead to a dramatic change of the corrosion system (i.e. closing of the crack, use of chloride-free contact mortars etc.), a different approach was developed for the corrosion monitoring of cracked concrete structures. No new anodes are introduced into the corrosion system, but all the measurements are being carried out using the actual reinforcement in the crack as the working electrode. To be able to do so, the reinforcement in the crack in a first step has to be separated from the remaining reinforcement cage. This can be achieved by locating the respective reinforcement bar in the crack by means of NDT and isolating it from the reinforcement cage by cutting or core drilling with a small diameter. Both the isolated reinforcement bar (“anode”) and the remaining reinforcement cage (“cathode”) can be contacted with a cable connection before the cut or the drill hole is filled with an adequate material (epoxy resin/mortar). An external reference electrode is placed in a drill hole close to the anode which is also filled with an adequate cementitious mortar. The time-dependent change of corrosion activity can then be monitored by continuous corrosion current and half-cell potential measurements in combination with e.g. periodic depolarization measurements and linear polarization measurements [Mayer et al. (2018), Hiemer et al. (2018)].



## 4 CASE STUDY

### 4.1 *Project description*

The underground car park in this case study was completed in an urban environment in South Germany in 1998. It has one ground floor with a total area of appr. 4,000 m<sup>2</sup>. The floor slab has a varying thickness between 25 and 40 cm and is not needed for load transfer, however, as the upper side of the floor slab is constantly appr. 70 cm below ground water level, the floor slab forms part of the watertight concrete structure. To avoid chloride ingress into the structure, the floor slab was executed with a fairly simple coating system.

A structural assessment appr. 15 years after completion rendered massive crack formation in the floor slab with a total crack length of appr. 3,000 m. The mean concrete cover was determined to be appr. 50 mm. The chloride concentration in the cracks at reinforcement level for most cracks was between 0.50 and 0.90 M.-%/cem with maximum values around 2.0 M.-%/cem. The uncracked concrete displayed locally very high chloride concentrations of up to 3.0 M.-%/cem at the surface, but generally uncritical chloride contents < 0.5 M.-%/cem at reinforcement level. The maximum loss of cross section due to corrosion was appr. 10% and thus considered still acceptable from a structural point of view. However, due to the high chloride contents close to the concrete surface in the uncracked concrete a conventional repair would not only include concrete replacement over the whole cross section in the cracked regions, but also concrete replacement up to a depth of appr. 80 mm in almost 60% of the uncracked regions. It is obvious that this repair strategy will not only cause immense costs, but will also lead to serious use restrictions and noise disturbances. As the reinforcement in the floor slab is only of minor static relevance, an alternative repair approach was developed with the owner which would do without concrete replacement and instead apply a new coating system and crack-bridging bandages in combination with an extensive corrosion monitoring system for monitoring the time-dependent changes of corrosion activity. It was agreed with the client that in case the corrosion monitoring showed further degradation, a conventional repair campaign would still have to be carried out.

### 4.2 *Design of the corrosion monitoring system*

To allow for a representative and comprehensive assessment of the time-dependent changes in corrosion activity, a total of 40 monitoring positions was selected. 30 monitoring positions were placed in cracks with high to very high chloride concentrations, 6 in the uncracked concrete with high chloride concentrations close to the surface as well as low concrete cover and 4 for reference purposes in the uncracked concrete with no increased chloride contamination. Due to the sealing on the concrete, half-cell potential mapping of the floor slab surface was not possible. Therefore, the monitoring positions were selected based on the results of concrete cover mapping, visual signs of corrosion stains and puddles, chloride concentrations etc.

The installation of the monitoring setup was carried out as described above, i.e.

- Locating of rebars in the crack parallel to the crack and rectangular to the crack,
- Isolating the rebar in the crack (“anode”) from the remaining reinforcement cage by means of core drilling,
- Extraction of drill cores and determination of crack formation over the cross section, concrete cover, corrosion state of the rebar and chloride content on the extracted drill cores (Figure 4),
- Fixing of cable connections both to the anode and the reinforcement cage (“cathode”),

- Coating of bore hole walls with epoxy resin to avoid mortar entry into the crack and filling of the bore holes with an adequate, cement-based mortar,
- Placement of a reference electrode and a TiMMO bar in drill holes close to the anode.

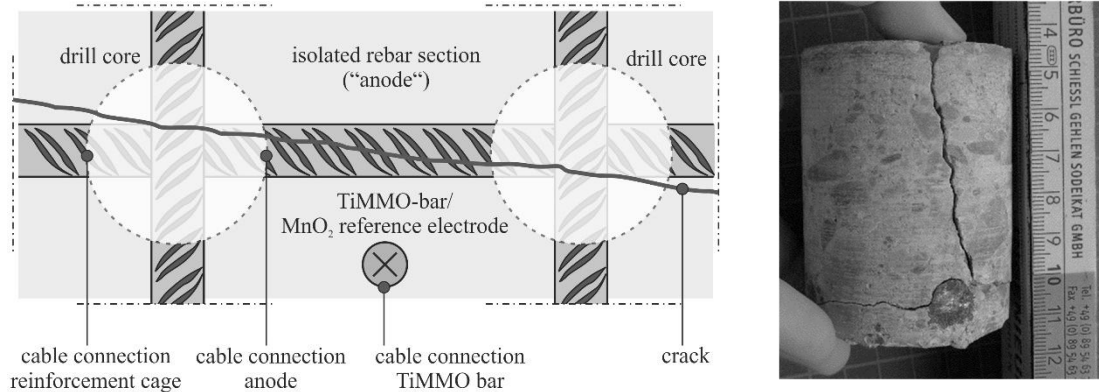


Figure 3. Schematic illustration of corrosion-monitoring setup

Figure 4. Concrete drill core after extraction. The crack formation over the cross section and concrete cover and the corrosion state of the reinforcement can be determined.

Once the installation was completed, a regular measurement routine was established, consisting of measurements of the macro-element current between anode and reinforcement cage and the half-cell potential of the macro-element while anode and reinforcement cage were short-circuited. Then, anode and reinforcement cage were separated and the depolarization of the anode was monitored. After a depolarization of two hours the free corrosion potentials of Anode and reinforcement cage were determined. Once the measurement routine was completed, anode and reinforcement cage were again short-circuited in order to reproduce realistic corrosion conditions.

### 4.3 Results

Figures 5 and 6 exemplarily display the results of measurements conducted on two sensor that showed active corrosion before coating, but the corrosion activity reduced significantly within a few months after coating. The reduction of macro-element current goes along with a distinct shift of the free corrosion potential of the anode towards more noble values. Currently, the potential difference between the anode and the reinforcement cage is in the range of only appr. 20 – 30 mV.

Appr. 2 years after the coating was applied, for 22 of the 27 corrosion sensors that originally showed active corrosion, the macro-element currents had reduced to a degree that can be assessed as structurally irrelevant. For most of these sensors the remaining current was in the same range as for the passive “reference” sensors. Only 5 sensors still showed increased element currents, however, also for three of these sensors the corrosion currents had decreased quite significantly. Until now, an increase of corrosion activity e.g. due to a redistribution of chlorides was not recognized for any of the sensors. Based on the current results of corrosion monitoring, no further repair measures will be necessary. Therefore, in this particular case the combination of coating and corrosion monitoring lead to significant savings in the range of appr. 80% both with respect to repair costs and downtimes.

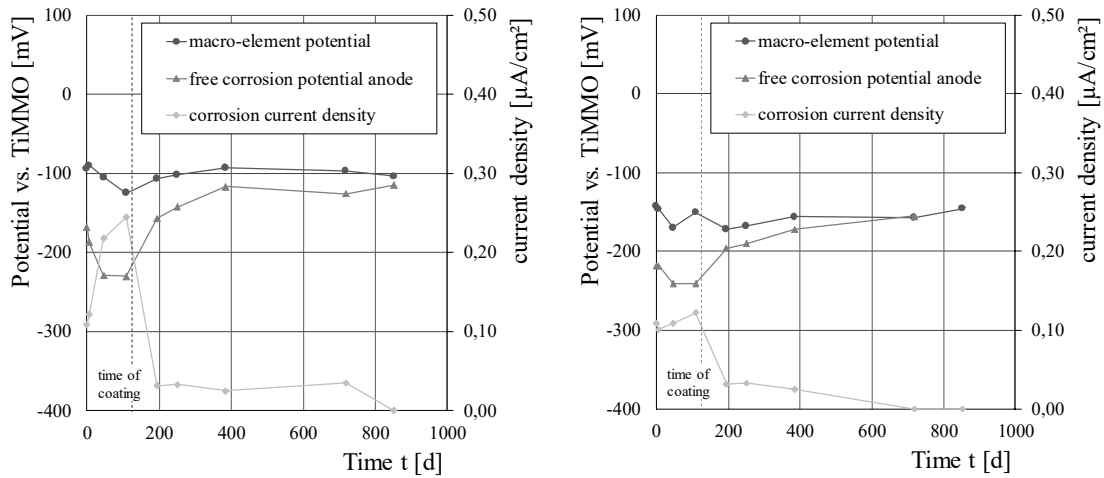


Figure 5. Results of corrosion monitoring on two representative sensors (left: sensor 24, right: sensor 36, both actively corroding before coating)

## 5 CONCLUSIONS

In the case of cracked concrete structures with moderate chloride contamination, a crack-bridging coating in combination with an adequate corrosion monitoring system may lead to significant reductions both with respect to time for repair and repair costs. However, it has to be emphasized that the applicability of this approach has to be checked thoroughly and individually for every structure, taking the specific boundary conditions into account. An intense discussion of potential risks of this approach with the client is strongly recommended.

## 6 REFERENCES

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