

Corrosion monitoring of reinforced concrete structures: The DGZfP specification B12 Collaboration

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Abstract

Corrosion monitoring of reinforced or prestressed concrete structures has become increasingly important in recent years. Areas of application include components that are no longer accessible after completion or where potential field measurements cannot be carried out due to existing coatings. Corrosion monitoring can also be used to monitor the progress of corrosion in corroding systems, e.g. to prove the success of repair measures according to repair principle 8 in accordance with EN 1504-9 or repair method 8.3 in accordance with the DIBt repair guideline. It also could be used to prove the functionality of cathodic corrosion protection systems in accordance with ISO 12696. Despite the increasing importance of corrosion monitoring, no guidelines or recommendations existed until 2018. This gap was closed by the English version of specification B12, “Corrosion Monitoring of Reinforced and Prestressed Concrete Structures,” of the German Society for Non-Destructive Testing, which was published in 2021. This article introduces specification B12 by explaining the basic measurement principles and illustrating the potential of corrosion monitoring in new and existing buildings.

KEYWORDS

corrosion, corrosion monitoring, durability, nondestructive testing

1 | INTRODUCTION

1.1 | Initial situation

Chloride-induced reinforcement corrosion often leads to damages—especially in concrete structures linked to our infrastructure—after comparatively short periods of use. The repair of these damages is usually associated with high costs and restrictions on use, see Figure 1. In many cases, extensive repairs could be avoided if the risks of corrosion were detected at an early stage and appropriate countermeasures were taken. Today, nondestructive testing methods offer a

wide range of possibilities for assessing the condition and durability of reinforced concrete structures. However, there are many applications, particularly in corrosion risk assessment, where these methods still have limitations. For many of these applications, corrosion monitoring is a useful complement to conventional structural investigations. In the following, the term “corrosion monitoring” refers to procedures where measurements are taken continuously or cyclically over a long period of time using stationary sensors to assess the state of corrosion, while “structural inspection” refers to single, often areal inspections using mobile sensors.

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FIGURE 1 Extensive repair of a column in a parking garage due to chloride-induced reinforcement corrosion. [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com/doi/10.1002/maco.202313934)]

1.2 | Fields of application for corrosion monitoring

Corrosion monitoring can be particularly useful where individual structural components are inaccessible or difficult to access after completion (e.g., foundations, diaphragm walls, bridge piers, or the exterior faces of a tunnel in chloride environments). In these cases, sensors are usually installed during construction. But even on accessible surfaces, corrosion monitoring can be a useful addition to the usual building inspections, depending on the boundary conditions. This applies, for example, to coated surfaces where it is not possible to measure the electrochemical potential of the reinforcement by externally applied reference electrodes.

However, in addition to the advantages in case of limited accessibility, there are other technical reasons for using corrosion monitoring. If the methods are well chosen, they can provide insights that go beyond the results of conventional structural testing. For example, with a depth staggered sensor arrangement, a critical chloride ingress can be indicated nondestructively, reliably, and without the known uncertainties of lab-bound chemical chloride content determination of drilling-dust samples.^[1] This is even before the reinforcement surface is reached by chlorides. Corrosion monitoring is also a valuable tool for monitoring the progress of corrosion in corroding systems,

for example, for proving the success of repairs based on principle 8 “Increasing the electrical resistivity of the concrete” and especially the repair method 8.3 “Applying a coating to increase the electrical resistivity” in chloride-containing concrete in accordance with EN 1504-9^[2] or the DIBt repair guideline.^[3] In the context of the ongoing discussion on the correct handling of cracks in car park decks that have only been exposed to chlorides for a short time, it can be assumed that corrosion monitoring will become much more important in the future, especially in this area. For cathodic protection systems designed and operated in accordance with DIN EN ISO 12696,^[4] corrosion monitoring has already established itself as a standardized means of demonstrating functional efficiency.

2 | STATE OF THE ART

2.1 | Initial situation

For most of the nondestructive testing methods used in structural investigations (e.g., potential field measurement, concrete cover measurement), comprehensive guidelines and specifications are now available. These define the possible areas and limits of application for the designer and contractor, and regulate the performance of the tests, thus helping to establish a uniform standard of quality.

In contrast to these procedures, there are no guidelines or recommendations for corrosion monitoring. This is all the more surprising as the 2001 repair guideline of the German Committee for Reinforced Concrete^[5] requires the installation of a corrosion monitoring system to prove the success of the repair using the repair principle “W-Cl.” According to the actual guideline,^[3] the effect on the corrosion progress of the reinforcement has to be checked, for example, by installing suitable sensors, which indirectly requires a corrosion monitoring system. Also in other research,^[6] it is recommended to install a corrosion monitoring system when chloride-affected cracks in parking decks are grouted for a short time without removing the chloride-affected concrete. However, there is little information in the literature on the possible implementation of corrosion monitoring techniques.

2.2 | The German Society for Non-Destructive Testing (DGZfP) specification “corrosion monitoring”

This gap was closed by specification B12, “Corrosion Monitoring of Reinforced and Prestressed Concrete Structures,”^[7] of the DGZfP. The specification was elaborated between 2015 and 2017 by the subcommittee “Corrosion

Verification” of the DGZfP’s Technical Committee for Civil Engineering with the active support of corrosion experts from Austria and Switzerland. Specification B12 was first published in German in the Spring of 2018, and an English version of it was published in 2021.

The corrosion monitoring specification describes several different measurement principles established in practice, depending on the monitoring task. The corrosion monitoring specification takes this into account by first presenting the different measurement principles with their mode of operation, measurement setup, evaluation, and main influencing variables, as well as their practical application. This provides the designer with a condensed overview of the topic. Based on this, information on the design of corrosion monitoring systems, the applicable measurement principles, the positioning of sensors, and so forth are given in a second step. Practical examples are used to illustrate the design and evaluation of corrosion monitoring for some important applications. Unlike, for example, the potential field specification B03,^[8] this specification deliberately refrains from providing detailed instructions, as it is common sense among the authors that the complexity of the subject does not allow for this. Design and assessment lie within the responsibility of a competent designer with an appropriate technical background in corrosion and corrosion protection.

An introduction to some common measurement principles and application examples for corrosion monitoring is given in Sections 3–5.

3 | MEASUREMENT PRINCIPLES

3.1 | Fundamentals of reinforcement corrosion

The DGZfP specification B12 deals with various measurement principles used in practice under the generic term “corrosion monitoring,” each of which is based on the monitoring of a subprocess of rebar corrosion or corrosion initiation. For a better understanding of these principles, the basics of rebar corrosion are briefly explained below.

Steel in concrete is protected from corrosion by the passivating oxide layer due to the highly alkaline environment. This oxide layer reduces further corrosion to a negligible level. Destruction of the oxide layer under practical construction conditions can be caused by two main mechanisms:

- a drop in the pH of the concrete as a result of a reaction of the carbon dioxide in the atmosphere with the alkali hydroxides and calcium hydroxide in the pore structure of the concrete (“carbonation-induced corrosion”),

- the penetration of chlorides from the component surface into the concrete structure and the subsequent exceeding of a limit concentration, the so-called critical corrosion-inducing chloride content, at the level of the reinforcement (“chloride-induced corrosion”).

For the application of corrosion monitoring, chloride-induced corrosion is by far the most relevant mechanism, so the following descriptions are limited to it.

The period before the critical corrosion-inducing chloride content is exceeded at the level of the reinforcement is usually referred to as the initiation phase. The (local) exceeding of the critical corrosion-inducing chloride content at the level of the reinforcement usually leads to local destruction of the oxide layer and marks the transition from the initiation phase to the so-called damage phase. As a result, there is usually a significant reduction in the reinforcement potential in the affected area. Iron ions (Fe^{2+}) enter the solution at the depassivated surfaces (anodes). The electrons released as a result of the anodic partial process are transferred to passive surface areas (cathodes) where they are involved in the formation of hydroxide ions, referred to as the cathodic partial process. Thus, a corrosion current flows between anodes and cathodes, which is proportional to the iron dissolution at the anode and which corresponds to an oppositely directed ion transport between the cathode and anode in the concrete matrix, see Figure 2.

3.2 | Overview of measurement principles

Depending on the individual problem, different measurement principles are available for different subprocesses, both during the initiation phase and during the damage phase.

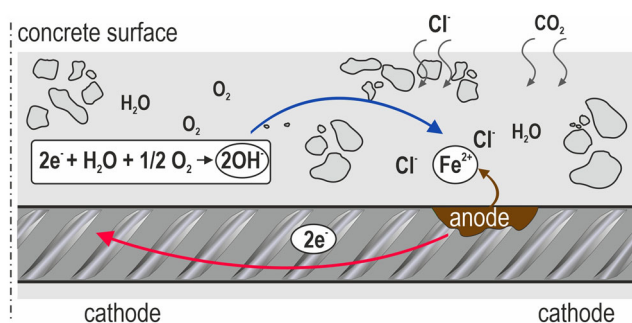


FIGURE 2 Schematic sketch of chloride-induced reinforcement corrosion. [Color figure can be viewed at wileyonlinelibrary.com]

- The change in chloride content in the concrete during the introduction phase cannot yet be determined with sufficient reliability in practice using ion-selective electrodes. However, chloride ingress into the concrete only occurs with simultaneous moisture ingress, so for coated (or sealed) surfaces, for example, a comparatively simple contribution to corrosion monitoring can be to demonstrate the functional efficiency of the coating system by monitoring time-dependent changes in the moisture content of the concrete near the surface, for example, by measuring the electrical resistance of the concrete at different depths. In this case, moisture penetration into the pore structure leads to a decrease in the electrical resistance of the concrete near the surface, continuing into greater depth with exposition time.^[9]
- The potential drop in anodic areas as a result of the loss of passivity during the transition from the initiation to the damage phase can be followed by potential measurements, in which the potential difference is measured between the reinforcement or built-in substitute anodes and permanently installed, potential-stable reference electrodes (usually MnO_2 reference electrodes).
- The corrosion current flowing between anodic and cathodic areas as a result of the loss of passivity can be monitored by corrosion current measurements. This is usually achieved by installing small area “proxy anodes” in the component or by electrically isolating anodic reinforcement areas from the rest of the reinforcement over a small area and short-circuiting them with cathodes of sufficient size for the corrosion current measurement. The cathodes can be either the

existing reinforcement or separately installed cathodes (usually Ti/MMO rods as used for cathodic protection). Time-dependent measurements of the corrosion current can also be used to make qualitative statements about the time-dependent change in corrosion activity during the damage phase.

- Linear polarization resistance measurements on the reinforcement or on separately inserted replacement anodes also allow a statement to be made about the transition from the initiation phase to the damage phase or a qualitative statement to be made about time-dependent changes in corrosion activity after corrosion has been initiated.
- If the potential and corrosion current or linear polarization resistance measurements are carried out on proxy anodes which are installed in a depth staggered way between the concrete surface and the reinforcement, the time-dependent penetration of the critical corrosion-initiating chloride content can be tracked on the basis of these measurements and a reliable prediction of the depassivation time can be made, see Section 4.1 and Figure 3.

4 | MONITORING DURING THE INITIATION PHASE

4.1 | Basics

Corrosion monitoring during the initiation phase is mainly used to monitor the penetration of the depassivation front (i.e., the penetration depth of the critical corrosion-initiating chloride content) into the interior of

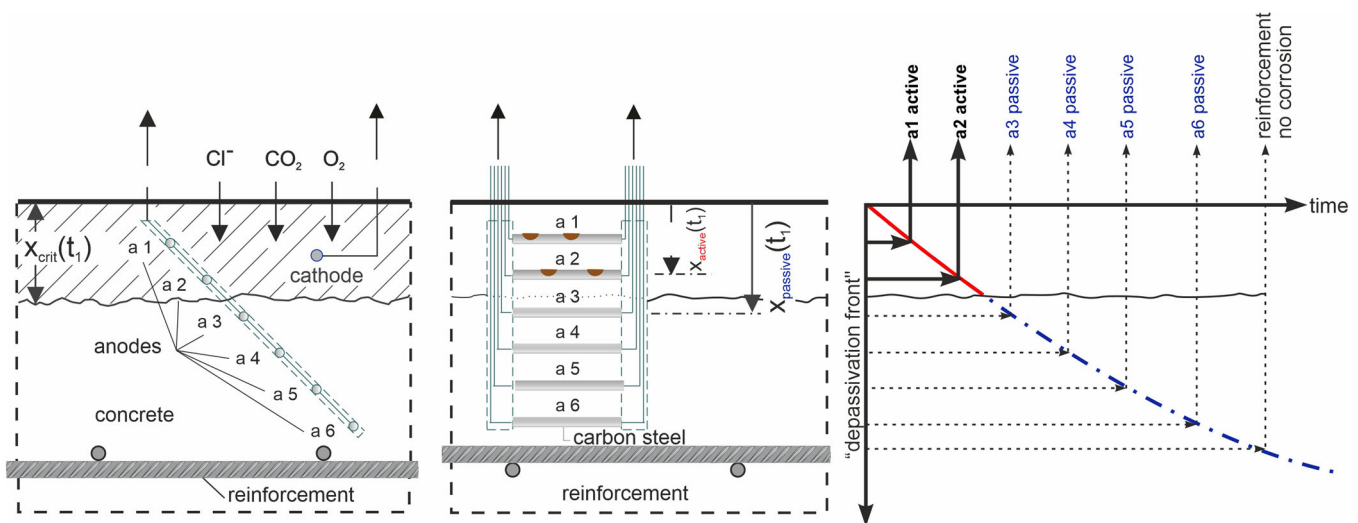


FIGURE 3 Sensor installation at different depths for predicting the point in time of depassivation. [Color figure can be viewed at wileyonlinelibrary.com]

the initially passive-reinforced component. Accordingly, this kind of monitoring is mainly used in new construction projects or in extensive repairs according to the repair principle R.

For monitoring during the initiation phase, sensor systems have been developed, which can monitor the penetration of the depassivation front by measuring electrochemical (potential, corrosion current, linear polarization resistance) or electrical (wire resistance) parameters at the individual anodes using a depth-staggered arrangement of anodes between the concrete surface and the reinforcement. If the depths of the individual anodes and the concrete cover are known, the time of depassivation of the reinforcement can be estimated from the sensor readings, see Figure 3. Depth-staggered concrete resistivity measurements, for example, for monitoring the effectiveness of surface protection systems, can be a valuable contribution here, see Section 4.2. This enables the facility operator to detect a potentially critical chloride input at an early stage and to plan and initiate necessary measures. In conjunction with durability assessment models, corrosion monitoring during the initiation phase can be used to calibrate the prediction results and thus improve the accuracy of the used models.^[10–12]

4.2 | Application Example 1: Motorway tunnel with deep hydrophobic treatment

During the construction of a new motorway tunnel near Munich in 2006, a deep hydrophobic treatment was applied to the portal area to increase its durability.^[9] The aim was to reduce the water absorption of the concrete when exposed to spray water and thus reduce chloride ingress to negligible levels. Due to the comparatively limited experience with the effectiveness and durability of such systems, separate test specimens were produced for the test, which were fitted with multiring electrodes (MREs^[13]) for depth staggered measurement of the electrical resistance of the concrete. One-half of each test slab was equipped with a deep hydrophobic treatment, the other half was nonhydrophobic as a reference. The sample panels were then installed in the portal area of the tunnel where they were exposed to spray mist and splashing water.

Figure 4 shows the time-dependent development of the electrical concrete resistance over the installation depth of the sensor for one MRE each in a hydrophobized and a nonhydrophobized sample slab.

The hydrophobic treatment has caused the concrete to dry out, especially near the surface, so that the resistance of the hydrophobic specimens near the

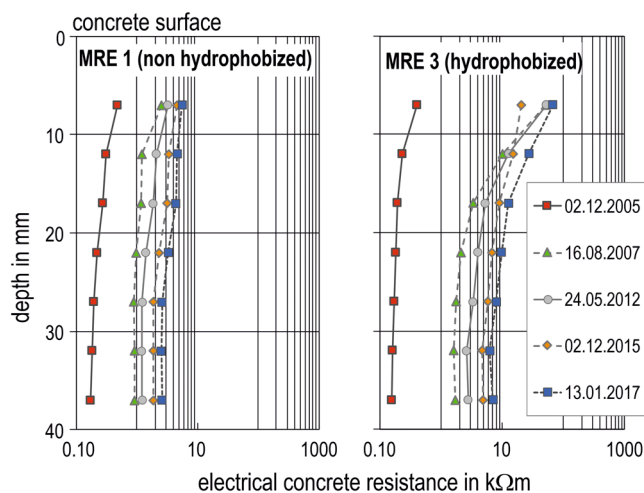


FIGURE 4 Time-dependent development of the electric concrete resistivity for specimens with (left) and without (right) hydrophobic treatment. Specimens stored under tunnel exposure conditions. MRE, multiring electrode. [Color figure can be viewed at wileyonlinelibrary.com]

surface is more than an order of magnitude higher than the resistance of the nonhydrophobic samples at the same depth level. Based on these results, it can be assumed that the effectiveness of the hydrophobic treatment is still given after about 10 years of aging. As soon as the measurements show a significant decrease, especially in the near-surface resistances, a renewal of the deep hydrophobic coating is necessary to ensure durability.

4.3 | Application Example 2: Car park without full surface protection system

The car park considered in this case study was completed in 2006.^[10] The intermediate floors of the car park were designed as a continuous system with centric prestressing so that load-induced cracking in the field area could be ruled out due to the prestressing and the structural design on the upper side. Where cracking was expected on the top face, a crack-bridging surface protection system was applied. In those areas where the top surface is permanently overstressed in all load combinations considered, the application of a surface protection system was waived and instead, the durability against chloride-induced corrosion was ensured using a fully probabilistic service life design in conjunction with a maintenance plan that requires an annual inspection of the parking deck surfaces for cracking and immediate coating of newly formed cracks.

To monitor chloride ingress into the uncoated structural concrete, a corrosion monitoring system consisting of a total of 25 corrosion sensors of the “anode ladder” type (Sensortec GmbH) was installed in the entrance and parking areas of the car park. The sensors were located on the entrance level and on the parking levels directly above and below the entrance level as the highest chloride exposure was expected there. Due to the relatively short dwell times of the cars in the car park, it was not possible to predict whether the higher chloride load would occur in the parking area or in the lane area, unlike in car parks with an average of only one change of occupancy per day. Therefore, corrosion sensors were installed in both, the parking and lane areas.

The sensors were mounted on the top reinforcement layer before casting the parking decks (Figure 5) and the sensor inclination was adjusted so that the top rung had a planned concrete cover of approximately 15 mm after casting. After completion, a functional check was carried out and the concrete cover of the top rung of each anode conductor was determined nondestructively.

As part of the regular sensor readings, the potential against a Ti/MMO rod embedded in the concrete next to each anode ladder and the corrosion current 10 s after establishing the short circuit with the Ti/MMO rod, as well as the alternating current resistance between two adjacent anode rungs, are recorded. The onset of corrosion on an anode rung is shown in the measurement results as a clear drop in potential and an increase in corrosion current. This is illustrated for an anode rung in Figure 6, where a clear drop in potential and a corresponding increase in corrosion current was detected on anode rung a1, closest to the surface, during the 2010 measurement. All other rungs are passive at this time. In 2015, a significant drop in



FIGURE 5 Installation of a corrosion sensor “anode ladder” on the upper reinforcement layer. [Color figure can be viewed at wileyonlinelibrary.com]

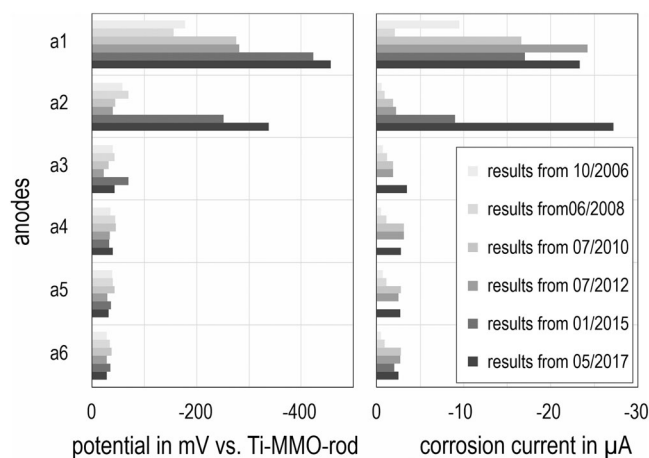


FIGURE 6 Time-dependent development of potential and corrosion current of an anode ladder sensor showing corrosion initiation of the first (2010) and second (2015) ladder steps. Based on the results obtained from the corrosion monitoring system, it has been shown that the actual chloride penetration rate in the uncracked concrete is still significantly lower than the penetration rate calculated at the design stage. For more information on the project and the use of sensor data to update durability design.^[11–13]

potential and an increase in corrosion current are also measured at the second ladder a2, which increases in the subsequent measurement in 2017, while ladders a3–a6 remain passive.

5 | MONITORING DURING THE DAMAGE PHASE

5.1 | Basics

Monitoring during the damage phase, that is, after depassivation, is mainly used to monitor the time-dependent changes in corrosion activity after a repair measure (e.g., application of the repair method 8.3).^[14,15] Corrosion current or polarization resistance measurements are particularly suitable as a measurement principle, often in conjunction with potential measurements and concrete electrical resistance measurements.

Depth grading, which is essential for predicting the time of depassivation during the initiation phase t , plays a minor role after depassivation has taken place. Instead, the critical corrosion parameters at the level of the reinforcement should be determined on the existing corrosion system without changing it too much. Therefore, if possible, no new anodes should be introduced, but the measurements should be carried out on the existing reinforcement or subsequently insulated reinforcement sections. As with measurements on passive systems, both

the passive reinforcement and separate retrofitted metal rods can be used as cathodes.

Measurements on corroding systems—both corrosion current and linear polarization resistance measurements—can be used to make qualitative or semiquantitative statements about the time-dependent change in corrosion activity. However, conclusions about the actual loss of cross-sectional area are afflicted with very large uncertainties, so that there is agreement among the authors that this should not be done in practice.

5.2 | Application Example 3: Repair of an underground car park floor slab with cracking

The single-story car park in this application example was completed in 1998 and provides approximately 160 parking spaces over an area of 4000 m². The car park is founded on individual foundations under the columns and strip foundations under the walls. As the floor slab is located approximately 70 cm beneath the ground-water level, the reinforcement of the floor slab was dimensioned to limit the crack width according to the technical rules for water-tight concrete constructions. Depending on the construction, the floor slab has component thicknesses between 25 and 40 cm. To protect it against chloride ingress, the top of the slab was coated with a rigid surface protection system immediately after completion.

A condition survey after approximately 15 years of use revealed extensive cracking in the floor slab with a total of approximately 3000 m of cracking. The cause of the cracks is recurrent forced loading due to seasonal temperature changes. The chloride content in the cracks was locally very high at the level of the reinforcement (concrete cover on average about 50 mm) with values up to 2.0 wt.%/c. In most of the cracks, the chloride content at the level of the reinforcement was between about 0.50 and 0.90 wt.%/c. Even in the noncracked areas, chloride loading was present on approximately 60% of the surface due to wear of the surface protection system, so that future corrosion of the reinforcement could not be ruled out solely as a result of redistribution processes, even without further chloride input. Visual inspections on the reinforcement in the crack area showed maximum cross-sectional losses at the reinforcement of about 10%.^[15]

Conventional repair of the floor slab (removal of the chloride-contaminated concrete down to several centimeters behind the first layer of reinforcement, followed by reprofiling and coating and bandaging of newly formed cracks) would have resulted in very high costs and long-term restrictions on use during the

repair measure. Therefore, due to the low static relevance of the floor slab reinforcement and the low corrosion progress, an alternative repair approach was chosen in close cooperation with the client, which did not involve the removal of concrete but the application of a coating on the top side and crack bandages along the cracks. A comprehensive corrosion monitoring system was installed in cracked and noncracked areas to monitor the change in corrosion activity over time after coating.

A total of 40 monitoring points were selected—mainly in cracked areas with highly elevated chloride levels and partly in noncracked areas with elevated chloride levels and, as a reference, in noncracked areas without elevated chloride levels. At each monitoring site, a single section of reinforcement in the crack path was electrically isolated from the reinforcement cage by drilling a core hole across the intersection with the crack-crossing reinforcement, and a cable connection was made at the intersection of the isolated section of reinforcement (“anode”) and the reinforcement cage. The core holes were then closed with a suitable mortar. In addition, a Ti/MMO rod and, if necessary, a reference electrode were installed in holes outside the crack course and the holes were also filled with cement-based mortar.

Measurements were initially taken every 2 months. Between measurement dates, the anode and the reinforcement cage were short-circuited to ensure that the conditions were as close to reality as possible. At the measurement dates, the element current between the insulated reinforcement element (anode) and the reinforcement cage and the corrosion potential of the short-circuited system were measured against the Ti/MMO bar or reference electrode. The short circuit was then removed and, after a depolarization period of approximately 2 h, the free corrosion potential of the anode and the reinforcement cage and, at random, the linear polarization resistance of the anode were determined. At the end of the measurement routine, the short circuit between the anode and the reinforcing cage was restored.

The time course of these measurements is shown in Figure 7 for a representative sensor. To take into account the different sizes of the insulated anode elements that lead to different total corrosion currents, the element current density was chosen as the quotient of the measured current and the total surface area of the anode. In the case of the sensor shown here, with initially increased corrosion activity, there was a significant increase in the free corrosion potential of the anode after the coating was applied, together with a distinct decrease in the element current.

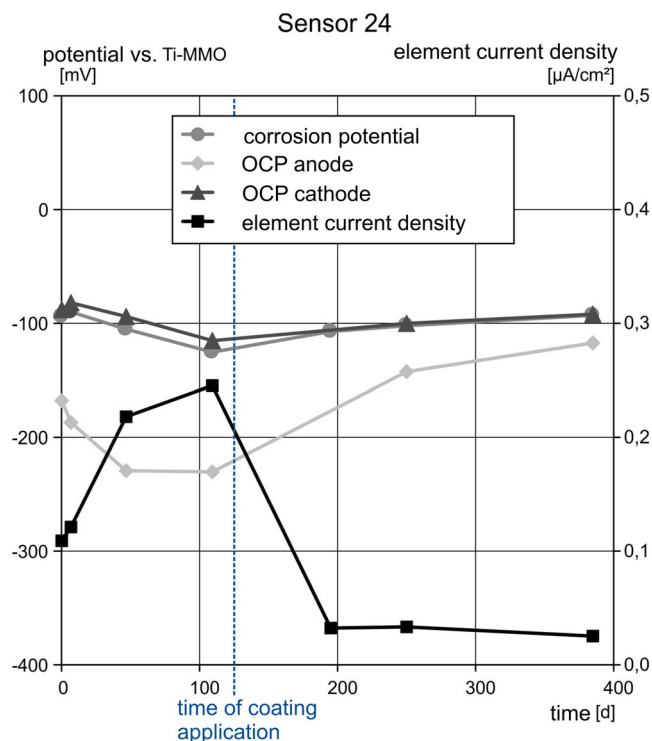


FIGURE 7 Time-dependent development of potential and corrosion current after coating application. OCP, open-circuit potential. [Color figure can be viewed at wileyonlinelibrary.com]

The behavior of the sensor in Figure 7 is representative of the majority of sensors, where a significant decrease in corrosion activity was observed shortly after coating. Notwithstanding this, elevated element currents were still recorded on individual sensors several months after coating. Corrosion initiation on sensors classified as passive before coating, for example, as a result of redistribution processes, was not detected on any sensor, at least during the first year of monitoring.

6 | CONCLUSION

The German version of the DGZfP specification B12 “Corrosion monitoring of reinforced concrete structures” has been published in the English version in 2021. The authors are convinced that this specification is an important step toward the implementation of corrosion monitoring as a standard option for repair strategies for reinforced concrete structures. Most of the existing literature on corrosion monitoring of reinforced structures focuses on in situ measurements that are not integrated into the concrete structure, for example, ASTM C876^[16] or part of the publications on electrochemical measurements of RILEM TC-154,^[17,18] except for^[19] “Electrochemical techniques for

measuring corrosion in concrete—measurements with embedded probes.” All these types of measurements are based on the application of the measuring equipment to the concrete surface. With these types of setups, it is difficult to establish a data timeline for, for example, half-cell potential, corrosion current, or concrete resistivity. Furthermore, certain monitoring tasks can only be realized by the use of built-in monitoring systems. For example, the success of a deep hydrophobic treatment could not be obtained by half-cell potential mapping at the surface of the concrete structure. Therefore current measurements are more common and useful as shown in Application Example 1. Nevertheless, embedded corrosion monitoring systems could evaluate the depassivation stage of the embedded reinforcement before it starts to corrode by using a so-called “anode ladder.” Also, the observation of a change in the electric resistivity of the concrete by using principle 8 according to Deutsches Institut für Bautechnik^[3] will be an advantage to ensure safety by using those kinds of repair principles. This is an advantage that could lead to lower costs for structural health maintenance, for example, by evaluating the early stage of chloride ingress, or corrosion properties due to the environment, which is also described by Vennesland et al.^[19]

DGZfP Specification B12 Collaboration

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are from a commercial project and are available upon request.

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