

Corrosion Monitoring of Reinforced Concrete Structures – Actual Research Results and New Guidelines

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Abstract. The corrosion of reinforcing steel in concrete, caused by de-icing salt or carbonation, represents a considerable repair expense in Germany every year. Electrochemical corrosion monitoring can be a helpful tool to determine the ingress of the depassivation front into a chloride exposed structure. The installation of appropriate sensors in existing structures can make the success of the repair verifiable after the repair work has been completed. To date, however, there is no set of rules for corrosion monitoring. In 2018, a leaflet B12 of the DGZfP [1] was published for the first time, which can serve as a guideline. Furthermore, in the last 3 years a broad-based research project has been carried out in Germany on open questions of corrosion monitoring. The knowledge gained in this way will be incorporated into a DAfStb-Leaflet that is currently being processed. Both the relevant findings of the investigated part at the University of Applied Sciences Munich HM and the content of the leaflet are presented.

1 Introduction

Corrosion leads to immense costs in the infrastructure sector alone. *Yilmaz and Angst* [2] estimate the annual direct corrosion-related costs in the Swiss road network at around 0.08 % of the gross domestic product. Chloride-induced corrosion in particular has a strong damage potential due to the locally pronounced damage character of the pitting corrosion that occurs. In the case of reinforced concrete structures, the chloride-contaminated concrete is usually removed invasively for repair and replaced with a concrete substitute. Long construction times and costly shoring measures are usually the rule, cf. **Fig. 1**. Possible repair procedures are regulated in Germany in the TR-Instandhaltung [3].



Fig. 1. extensive concrete replacement whilst the repair of a column in an underground car park according due to chloride-induced reinforcement corrosion

Repair methods in which the chloride-contaminated concrete can remain in the structure are based on preventing one of the sub-processes necessary for corrosion. This is possible, for example, by means of

cathodic corrosion protection, which prevents the dissolution process of the reinforcing steel by its cathodic polarization. Cathodic corrosion protection is regulated separately in a separate standard [4], which takes account of this complex special area. The situation is different for electrochemical corrosion monitoring (hereafter monitoring).

Even if this is not a repair method, the application of monitoring is necessary, for example, for procedure 8.3 according to [3], also W-Cl according to [5]. The repair method is based on the idea of increasing the electrolyte resistance of the concrete by drying it out (e.g. by applying a coating that is open to diffusion but waterproof from the outside) to such an extent that corrosion stops. The lack of water content should prevent any significant transport of ions between the anode and the cathode. Corrosion monitoring must be used to verify the success of the repair process. However, there is no standard regulating this procedure.

2 The DGZfP-Specification B12 “Corrosion Monitoring”

In 2018, the Specification B12 [1] of the DGZfP on corrosion monitoring in reinforced and prestressed concrete structures was published. The leaflet was launched via a panel of experts from science, research and practice from the countries of Switzerland, Austria and Germany in the field of corrosion and corrosion protection and is intended to serve as an aid in the planning and execution of monitoring systems. Monitoring has been

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used by experts in the corrosion field for a long time in some cases, and there are already a large number of publications on the subject, such as [6 - 9]. Nevertheless, the procedure is also accessible to a broader spectrum of planners via Specification B12, although pronounced special knowledge in the field of corrosion is still required in order to design and ultimately also interpret a target-oriented monitoring concept.

Corrosion monitoring according to Specification B12 [1] refers in particular to permanently installed sensor systems, which distinguishes it from existing leaflets such as Specification B3 [10] of the DGZfP, which refers to potential measurements with mobile sensors. The aim of corrosion monitoring is to enable the most accurate possible recording of the condition of the corrosion process on the structure at neuralgic points by means of permanently installed sensor systems using stationary or transient measurement methods.

3 Measurement principles

The measurement principles of monitoring mostly refer to the recording of the most common influencing parameters in order to be able to evaluate the corrosion processes, cf. Fig. 2.

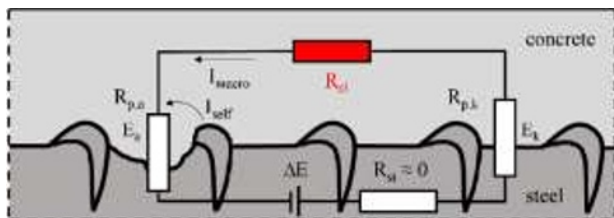


Fig. 2. Simplified equivalent circuit of the pitting corrosion process of steel in concrete acc. to [11]

Components from Fig. 2:

E_a	=	free corrosion potential of the anode
E_k	=	free corrosion potential of the cathode
$R_{p,a}$	=	polarisation resistance of the anode
$R_{p,k}$	=	polarisation resistance of the cathode
R_{el}	=	electrolytic resistivity of the concrete
I_{macro}	=	macroelement current
I_{self}	=	self-corrosion current

In some cases, it may be useful to include supplementary measurements such as polarization resistances.

It is also important to consider the self-corrosion. This is the corrosion current which is converted as a cathode reaction on the anode considered for measurement and thus cannot be recorded electrochemically. Results of investigations on this subject can be found, for example, in [6, 12, 13]. At University of Applied Sciences Munich HM, investigations are currently being carried out in this area, especially under dry boundary conditions, as part of the "KoMICS" research project.

Other parameters may also be necessary to be measured. For example, fluctuating component temperatures have a strong influence on almost all corrosion parameters and should be temperature-compensated for a clean evaluation according to Arrhenius, see also results of [6].

4 Possible applications of monitoring

4.1 Monitoring during the initiation period

Even without the repair procedures mentioned at the beginning, corrosion monitoring proves useful in many cases. For example, the installation of monitoring sensors in new construction can be used to derive the progress of depassivation fronts [8, 9], cf. Fig. 3. In particular in areas that are difficult to access later for further investigations, such as joints, tunnel shells or bridges, monitoring can prove to be very advantageous for subsequent maintenance work.

When monitoring during the initiation phase, sensors are installed in the new building, for example, which can be used to record changes relevant to durability depending on depth. An example of this is the anode conductor, which can be used to detect a critical chloride concentration depending on depth, see [9].

4.2 Monitoring during the deterioration period

In existing structures, corrosion monitoring can also be used as an alternative to prove the success of a repair measure, in order to observe a desired remaining service life more predictably after a detailed examination of the structure at critical points or to be able to delay the time for an upcoming repair if necessary, cf. Fig. 3.

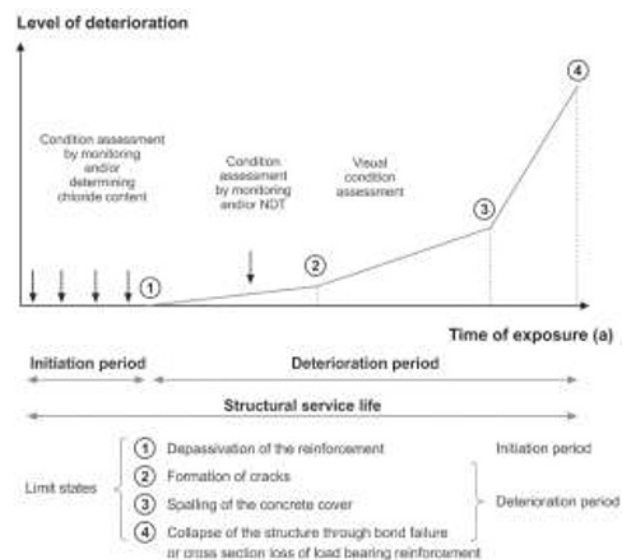


Fig. 3. Service life of concrete structures. A two-phase modelling of deterioration with possibilities of assessment [8] (adapted from [14])

For monitoring in the damage phase, it is important to isolate reinforcing steel from the existing structure as a

measuring anode so that the corrosion system is changed as little as possible, see [1]. Optionally, there is the possibility of using subsequently installed anodes, such as measuring coupons or the Expanding Ring Anode [15], which should provide an inference about the reinforcement in the structure. However, since proxy anodes are always subject to somewhat different boundary conditions, the measurement results from them should always be treated with greater caution.

It is important to note, however, that the monitoring system can only ever be used to trace actual conditions and cannot be used to make future forecasts. Likewise, although quantitative and semi-quantitative statements can be made about the corrosion state, it is not possible to make statements about the loss of cross-section at the reinforcement in the case of chloride-induced pitting corrosion [8].

5 Research on corrosion monitoring

5.1. General

The cooperative research "KoMICS" with the Munich University of Applied Science (HM), the Federal Institute for Material Research and Testing (BAM), the Technical University Munich (TUM) as well as four industrial partners and the German Committee for Reinforced Concrete (DAfStb) as the guideline-giving institution, aims to answer open questions in corrosion monitoring for reinforced concrete structures exposed to chloride. These include both the suitability of various sensor systems and the specification of relevant measurement parameters to be recorded. The project is funded by the German Federal Ministry for Economic Affairs and Energy (BMWi) within the framework of the WIPANO guideline

(Knowledge and Technology Transfer through Patents and Standards). In the course of this, the incorporation of the results developed in the project into a draft set of rules is to take place at the end of the project.

The subproject of the Munich University of Applied Sciences HM aims to partially develop and investigate sensor systems for the deterioration phase. The focus is on the mutual comparability of the measurement results. The aim of the subproject is to determine boundary conditions that must be taken into account during the design, installation and evaluation of the sensor systems.

5.2. Design of the test specimens

The test specimens were designed to investigate a wide range of currently used sensors for corrosion monitoring with regard to the mutual transferability of the measurement results. Additionally, existing sensors were further developed. For reference purposes, corrosion sensors with anodes, cathodes and reference electrodes were installed in each specimen, which allows the direct measurement of element current and potentials. The following sensor types were used, among others:

Measurement on the existing corrosion system (Specimen Type A, Fig. 4):

- Directly embedded measuring anode: Rebar $d = 10 \text{ mm}$, $l = 50 \text{ mm}$, connected with stainless steel welding wire.
- Subsequently isolated measuring anode: by electrically isolating a piece of anodically acting rebar through selective core drilling and then electrically connecting the isolated anode to the measuring system – described in [7].

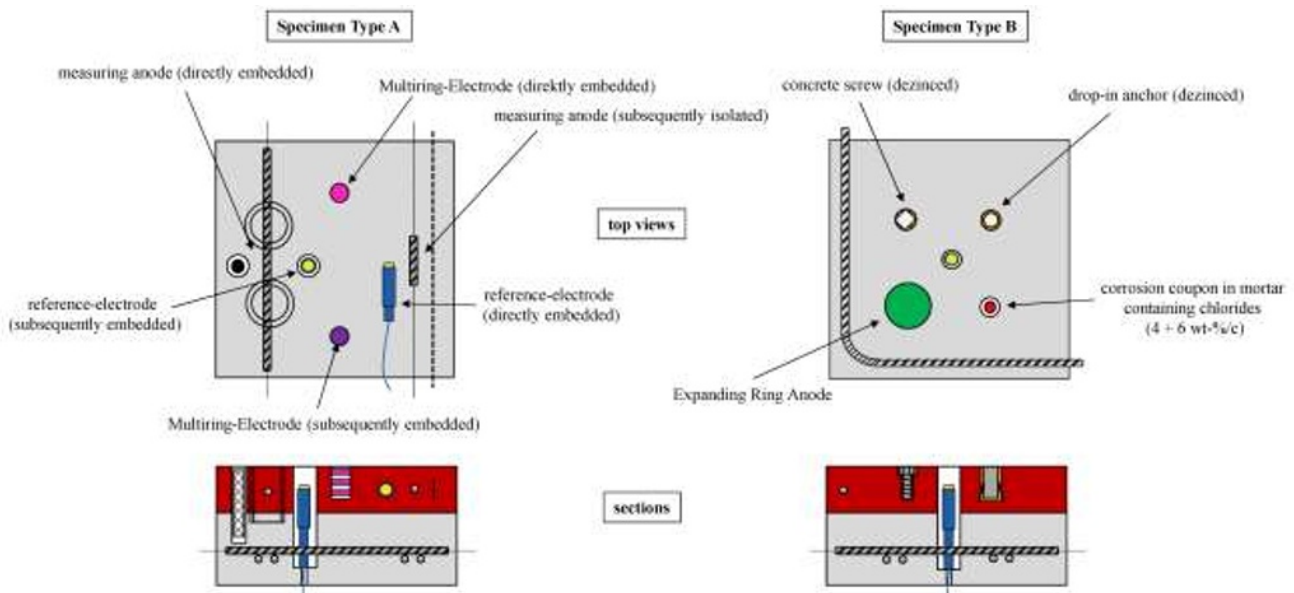


Fig. 4. Specimen Type A for measurement on rebar anodes and Type B for measurement on substitute anodes

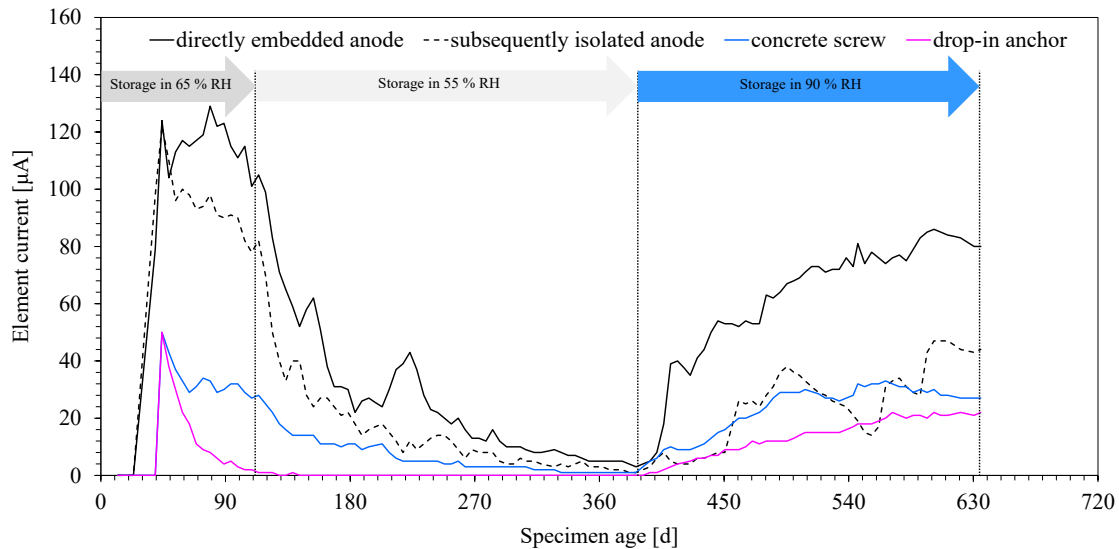


Fig. 5. Exemplary preliminary test results of different measuring anodes (OPC-concrete)

Measurement on substitute anodes (Specimen Type B, Fig. 4):

- Measuring coupons in mortar containing chloride.
- Concrete screw (dezincd)
- Drop-in anchor (dezincd)
- Expansion Ring Anode [15]

Additionally the resistivity of the concrete is measured in several depths using Multiring-Electrodes [16], which are embedded directly as well as subsequently.

5.3. First test results

First test results are shown in **Fig. 5** for the test specimen type A. It shows that the recorded element currents, as a measure of the corrosion activity during storage in a dry climate (65 – 55 % RH), decrease significantly with time until they are below 10 µA after about 1 year. The decrease in the element currents of the anodes isolated directly before concreting is very similar to the decrease in the element currents of the anodes isolated and electrically connected afterwards. After about 1 year of storage at 65 - 55 % RH, the test specimens were placed in a humid climate (90 % RH) for selective rewetting. It can be seen that the elemental current of the anodes increases again after a few weeks. The difference between the directly embedded anode and the subsequently isolated anode seems to be more random, as this behaviour could not be observed at the BFC samples (not given in **Fig. 5**).

In general it can be stated that in the tendency of the curve course all shown sensor systems deliver a similar behaviour. However, the drop-in anchors in particular show a clearly faster decay of the element currents during drying, which in the present setup is specifically attributed to the free annular gap between the impact anchor and the

concrete, through which drying can take place more quickly.

Overall, it has to be mentioned, that especially in dry storage, only part of the corrosion currents are detected by element currents. An unmeasured portion of the corrosion activity takes place on the measuring anode itself, which of course also acts as a cathode. This portion, referred to as self-corrosion, cannot be detected by measurement.

Particularly in the case of large sensors (concrete screws or drop-in anchors) and dry exposure conditions, there is a risk that the corrosion activity will be significantly underestimated due to a high proportion of self-corrosion.

For this reason, additional test specimens are currently being investigated to show the influence of anode size on the self-corrosion factor. The results will be presented on site at the conference.

6 Conclusion

Since spring 2018 the new DGZfP Specification B12 "Corrosion Monitoring of Reinforced Concrete Structures" is available filling a long-existing gap in the German set of rules concerning repair measures on reinforced concrete structures. With this specification at hand, the planning engineer has access to basic information about the components, the planning and application of the most commonly used corrosion monitoring principles and equipment. The authors believe that this specification is an important step forward towards the implementation of corrosion monitoring as a standard option for repair strategies for reinforced concrete structures.

Furthermore, the results of a research project called "KoMICS" currently carried out show that corrosion

sensors installed subsequently can also record corrosion activity well. Preference should be given to anodes that are already present on the existing structure. Ideally, these are areas of corroding reinforcing steels in which anodically active areas can be electrically isolated and the element currents recorded over time. Substitute anodes show comparable corrosion behaviour over time, but in terms of the magnitude of the measured element current, direct anodes show more realistic values and are therefore easier to evaluate. Special attention is currently being paid on the estimation of self-corrosion under dry environmental conditions. Self-corrosion must be taken into account when evaluating the measured element currents so as not to underestimate the corrosion activity on the unsafe side.

16. <http://www.sensortec.de/sensoren-sensors/multiring-elektrode-multiring-electrode.html>, visited at 28.02.2022

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