

# Monitoring of the corrosion behaviour of the reinforcement at a cooling tower working in sea water operation using embeddable polymeric cathode sensors

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**Abstract.** Continuous monitoring of the effectiveness of repair measures carried out in connection with chloride-induced corrosion of the reinforcement is often only possible when using sensor-based monitoring systems. The targeted integration of sensors in existing structures represents a technical difficulty. For this purpose, special corrosion sensors based on the supplementary cathode principle have been developed and tested on a laboratory scale at the Institute for Building Materials Research (ibac) at RWTH Aachen University. For this purpose, a special polymer has been developed at ibac allowing the embedment of the sensors and a suitable electrical connection between sensors and the surrounding concrete. Laboratory tests have been carried out to show the general functioning of the system and to optimize the performance. The first practical application of the measuring system will be described and explained in the presentation: The corrosion condition of the reinforcement on the outside of a cooling tower in seawater operation is monitored at selected points following an extensive repair measure. The results of the first measurements on site will be shown and discussed. The theoretical background, the first project and the experiences from the installation and commissioning of the monitoring system under the challenging local conditions will be presented.

## 1 Introduction

### 1.1 General information

The monitoring of corrosion-relevant parameters during the repair of reinforced concrete structures affected by chloride-induced reinforcement corrosion offers significant technical and economic potential for building owners and planners. However, currently available sensors and measurement technology often do not allow for the utilization of this potential due to their high acquisition, application, or operating costs. Novel polymer-based sensors aim to unlock this potential and expand the application of corrosion monitoring in repair processes. Additionally, other challenges associated with integrating sensors into existing structures, such as the introduction of additional moisture and the resulting impact on measurement results, are also addressed. The following describes the systematics of this new approach.

### 1.2 State of the art

Even though the fundamental mechanisms of macro element corrosion of steel in concrete have been well understood for a long time, important aspects related to the repair of such corrosion damage remain the subject of scientific research. This applies both to the critical

chloride threshold concentration [1] that initiates corrosion in general, as well as to the chloride content that can remain in the structure for the successful application of the principle 8.3 according to DIN EN 1504-9 [2].

In this context, monitoring the success of repair measures using corrosion monitoring is proposed. A wide range of sensor systems is available for this purpose, but in practice, only two sensor types have proven effective for retrofitting in existing structures: sensors for monitoring the electrolytic resistance of concrete, such as the well-known multi-ring electrode [3], and so-called supplementary cathodes for measuring the corrosion activity of the reinforcement.

Multi-ring electrodes provide information on the temporal development of the depth-profiled electrolyte resistance, for example, after the application of a surface coating. However, this parameter only allows indirect conclusions about the corrosion state of the reinforcement.

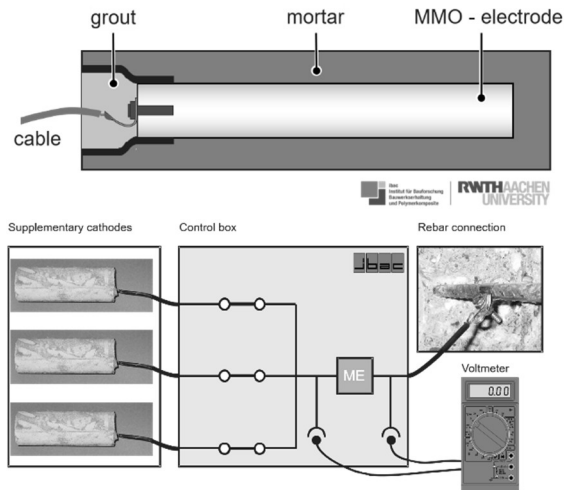
Supplementary cathodes, on the other hand, provide direct information on the corrosion state of the reinforcement by measuring the corrosion current that develops within a defined time interval after creating a short circuit with the reinforcement. Additionally, alternating current resistance measurements between individual cathodes or between each cathode and the reinforcement allow for an assessment of the structural

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moisture development. Furthermore, the potential of the reinforcement can be compared to that of the supplementary cathode, which serves as a pseudo-reference electrode.

In previous applications of this method, noble metal electrodes or mixed metal oxide (MMO)-coated titanium electrodes were typically embedded in mortar to minimize the risk of short circuits to the reinforcement and subsequently installed in drilled holes using grout, see Figure 1.



**Fig. 1.** Top: Structure of a supplementary cathode. Bottom: Illustration of the supplementary cathode measurement system.

Lay describes in [4] a successful application of the principle over a period of 800 days, during which a significant decrease in corrosion currents was observed following crack grouting.

However, the method has significant disadvantages, primarily due to the nature of the electrolytic coupling. The curing process of the grouting mortar takes considerable time, which is particularly disadvantageous when applied to walls or ceilings. Additionally, the necessary post-treatment must be factored into the construction schedule, leading to a significant extension of on-site time beyond the mere installation. This, in turn, negatively impacts the cost efficiency of the monitoring system.

From a measurement perspective, the water introduced into the structure through the drilling process and the coupling mortar presents a major drawback. As a result, the initial measurement cannot be directly compared to the original condition of the structure before or at the beginning of the repair, making it more difficult to assess the overall effectiveness of the intervention.

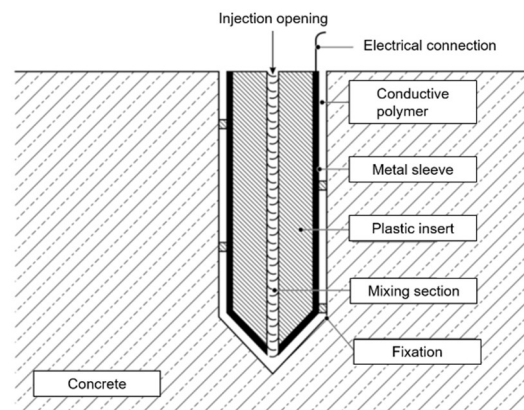
These issues are intended to be addressed by the application of the polymer-based corrosion sensors described in the following sections.

### 1.3 Polymeric supplementary cathodes

The presented sensors were developed at ibac as part of a research project within the framework of the "Central Innovation Program for SMEs" (ZIM), in collaboration with the Aachen-based company haupts IT Solutions

GmbH. The project focused on a novel sensor that, analogous to the supplementary cathode principle, exhibits a significantly more positive electrochemical potential than the depassivated reinforcement, functions as a pseudo-reference electrode, and can be used for impedance measurements.

Unlike the previously presented approaches, this sensor does not rely on a mineral-based coupling. Instead, coupling is achieved through a polymer that is sufficiently electrically conductive and exhibits favourable polarization properties. The electrical connection and a sufficiently positive electrochemical potential are ensured by a metal core, which also serves as the electrical contact point. A schematic representation of the sensor is shown in Figure 2.



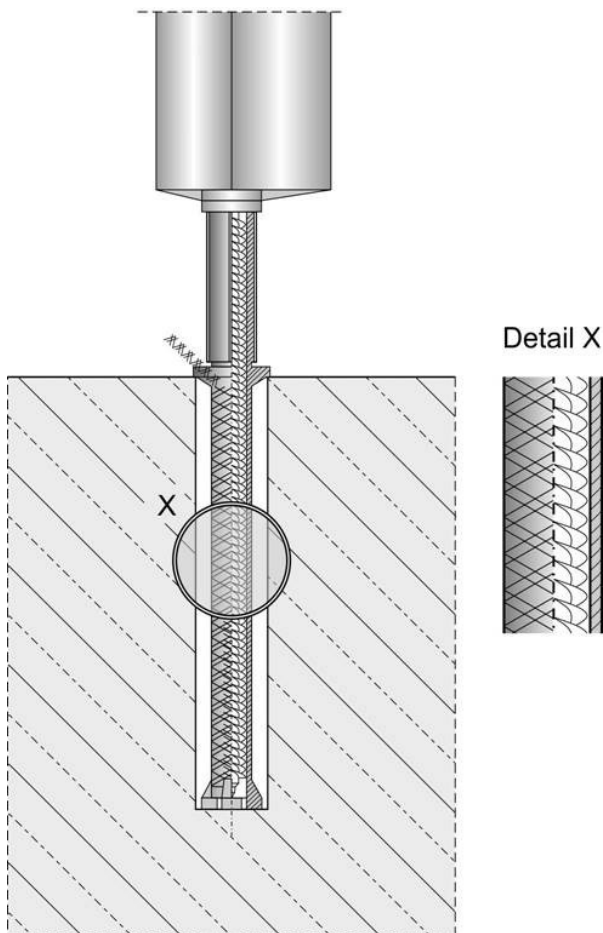
**Fig. 2.** Principle sensor schematic.

Furthermore, the core should be designed to both centre the sensor within the borehole and serve as a mixing channel for the injection of the 2K sensor polymer.

The key advantages of the polymer, which is derived from battery research, over a mineral-based coupling are:

- No additional water introduced, enabling meaningful measurements immediately after installation
- Simple installation in the borehole using a centering piece with connectors and 2K technology
- Fast work progress due to rapid curing
- Easy application in wall or ceiling areas
- No post-treatment required
- No influence of structural moisture on sensor properties

The latter is achieved because the coupling material consists of a system with negligible water absorption, where ion conduction occurs through so-called defect introduction. The corresponding laboratory investigations are described in detail in [5]. A schematic representation of the sensor geometry, as used in the practical application described here, is shown in Figure 3.



**Fig. 3.** Final sensor geometry.

A photographic image of the sensor is shown in Figure 4. The cathode carrier with an internal mixing channel is visible, enclosed by a mesh of MMO. The thickened base centres the sensor within the borehole, ensuring complete encapsulation by the polymer, which exits at the foot. The upper collar secures the sensor in place through friction, preventing movement within the borehole.

The top connector allows attachment to a standard 2K syringe and is detached from the sensor at a predetermined breaking point after the annular gap is fully filled. The curing time of the sensor polymer can be chemically adjusted and also depends on external conditions, particularly temperature.

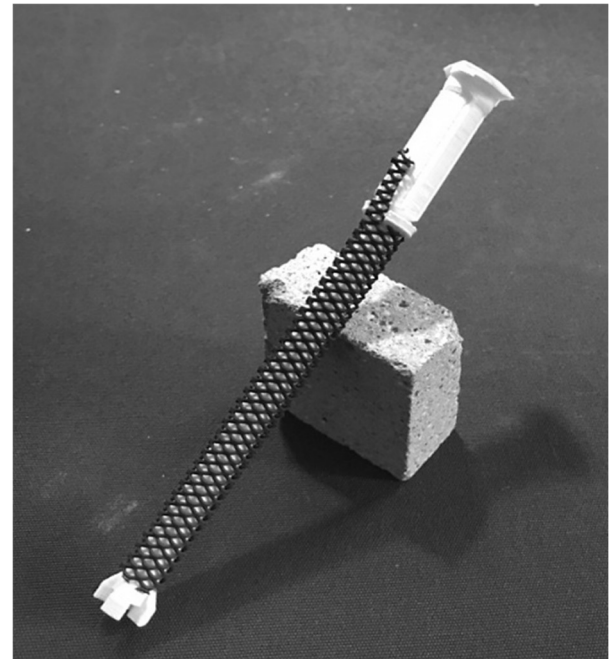
The wiring and measurement process for the sensors follow the well-established supplementary cathode principle, see [4, 5].

## 2 Repair object

### 2.1 General information

The cooling tower at the Rostock power plant was built in 1992. It consists of a shell approximately 140 meters high, with a lower diameter of about 96 meters and an upper diameter of about 60 meters. The cooling tower is divided into sections composed of meridional strips—areas between two wind ribs—and rings, which are one-meter-high concrete pouring segments. The tower has 48 meridional strips, each approximately 5 meters wide

at the lower edge of the shell, and a total of 134 rings. The entire shell surface covers an area of approximately 28,960 m<sup>2</sup>.



**Fig. 4.** Photographic sensor illustration.

The cooling system operates with seawater, which undergoes additional treatment and becomes increasingly concentrated during the cooling process, resulting in a high chloride content in the cooling water. In 2015, following the first visually detectable cracks in the lower shell area, a detailed structural investigation of the entire outer shell was conducted. This ultimately led to an extensive repair of certain sections. The objective of these measures was to ensure that the cooling tower could operate for at least 20 more years without further interventions, utilizing corrosion monitoring.

### 2.2 Structural investigations

Prior to the repair, extensive structural diagnostic investigations were carried out. These include, among others:

- Thermographic recordings for detecting voids
- Visual and coating-related inspections
- Concrete technological investigations
- Potential field measurements
- Chloride sampling and analysis

Details of the investigations carried out and the results are provided in [6].

### 2.3 Repair concept

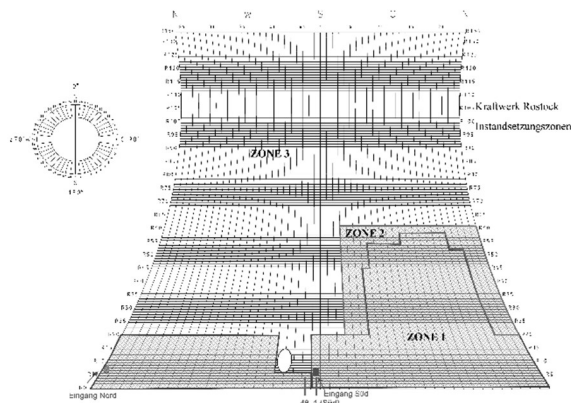
Following the structural investigations, test areas were established to assess the applicability and cost-effectiveness of different repair methods under the given conditions. The insights gained were incorporated into the development of the final repair concept to ensure the

most cost-effective and time-optimized approach could be implemented.

The specified execution period was 18 months, meaning that many tasks had to be carried out simultaneously across the nearly 30,000 m<sup>2</sup> surface. As a result, the entire shell was divided into several work/strain zones.

## 2.4 Repair zones

Based on the investigation results and the alignment of chloride sampling, potential field measurements, and identified voids, the shell has been divided into four zones, each of which is to undergo different measures. The individual zones are shown in the shell development diagram in Figure 5.



**Fig. 5.** Representation of the repair-related zones 1 to 4, with Zone 4 encompassing the entire shell.

### Zone 1

In zones 1 and 2, conventional repair was carried out according to Principle 7.2 of the DIN EN 1504-9 [2], as more than 50% of the surface exhibited voids. This principle involved the complete removal of the contaminated concrete down to the depth of the corrosion-triggering chloride content.

The entire Zone 1 was sealed with shotcrete and treated with a mortar that is resistant to post-treatment.

The entire procedure was carried out on only two meridional strips at the same time to ensure the structural stability.

### Zone 2

Zone 2 contained less than 20% of voids, making the conventional repair method according to Principle 7.2 too time-consuming.

The entire Zone 2 was examined using the hammer-tapping method to identify existing voids, which were then marked with colour. This method has proven effective in many cooling tower repairs for detecting damaged concrete. Additionally, the area was visually inspected using thermography to detect any voids that may have been overlooked.

### Zone 3

Zone 3 showed no large-scale structural concrete or reinforcement damage. However, there were localized areas with high chloride levels approaching 1.0 M.-%/cement.

The protective coating had completely weathered

over the entire surface, leaving the concrete surface unprotected from environmental stresses. In this zone, the old coating was removed.

The rare voids that occurred during this process were conventionally repaired.

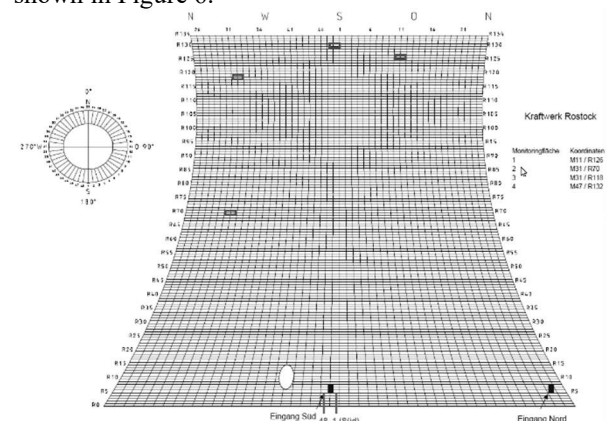
### Zone 4

After all the measures were completed, the shell surface was cleaned and coated with two layers of a surface protection coating. This coating, based on dispersion acrylic, has high diffusion permeability for water vapour, allowing the internally coated shell to dry out. It also has a CO<sub>2</sub> diffusion resistance of greater than 50 m, which stops the carbonation process. Additionally, the coating has a crack-bridging class of at least B3.1, protecting the surface from water ingress in the event of crack formation, particularly in connection with alkali-silica reaction (ASR) swelling.

## 3 Monitoring system

### 3.1 General information

A system based on the previously described supplementary cathode principle was chosen. A total of five measurement fields were arranged to monitor the success of the repair, representing the zones defined in section 2.4. The location of the measurement fields is shown in Figure 6.



**Fig. 6.** Location of the measuring points.

For each measurement field, 8 sensors were distributed over an area of approximately one square meter. The distribution was random, with the only prior step being the non-destructive determination of the reinforcement location to avoid hitting reinforcement during the drilling process. A total of 5 sensors from the new polymer sensor type were installed, as shown in Figures 3 and 4. Additionally, 3 "classic" supplementary cathodes, as shown in Figure 1, were embedded in the boreholes. This setup was intended to allow a comparative evaluation of the two sensor types, as well as to ensure the durability of the monitoring system. While the established form of the supplementary cathode has long-term experience, the polymer sensors had only been tested in the laboratory scale so far.

### 3.2 Installation

The installation of the sensors was carried out from work platforms. Figure 7 shows an example of the injection of a polymer sensor. All cable connections were pre-configured on the sensor side and routed into distribution boxes, where they were shortened and connected to a multi-core cable. This cable was then guided along a wind rib to the upper platform of the tower. Since later access for maintenance on the outer shell is not possible, all active components were to be mounted at an easily accessible location on the upper platform, which can be reached at any time via a staircase.



Fig. 7. Injection of a polymer sensor.

A representative impression of a completed measurement field is shown in Figure 8.

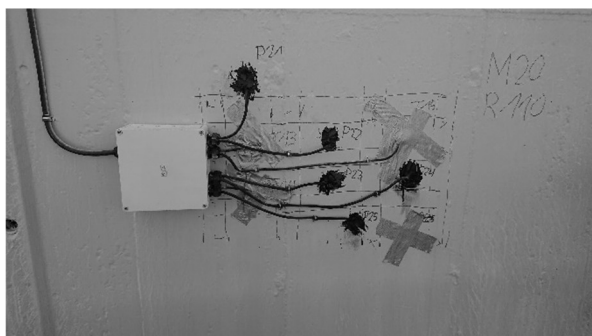


Fig. 8. Measurement field M20/R110 after sensor application.

The injection holes of the polymer sensors were widened in the head area using a drill before injection and sealed after application with a UV-resistant sealant based on PU. This is intended to prevent moisture from entering through the damaged area of the coating and to ensure the corrosion protection of the cable connection from the sensor to the copper cable. The adhesive tape, as shown in Figure 8, was meant to prevent the embedded supplementary cathodes from drying out too quickly, as there was not enough time at each measurement point for proper post-treatment.

### 3.3 Commissioning

The previously described work was carried out just before the completion of the repair work, a few days before the dismantling of the work platforms. At that time, it was not possible to complete the wiring on the upper platform and conduct an initial measurement, as it

was blocked by the upper carriages and the scaffolding rail system. For this reason, the completion and commissioning could only take place during the next maintenance break, approximately 8 months later. For this, measurement boxes were installed on the upper platform, and the cables were connected to pre-configured connectors. Additionally, the reinforcement connections necessary for the measurement, as shown in Figure 1, were created. The initial measurement, carried out before sealing the reinforcement connection, is shown in Figure 9 as an example.



Fig. 9. Measurement box during the initial measurement.

During the initial measurement, it was found that despite the challenging conditions due to wind, height, and the sometimes larger distances of the shell on the scaffolding, only a single measurement point was non-functional. It remains unclear whether this was due to a wiring error or a broken cable or connection. The remaining 39 sensors provided measurements within the expected range. Since the monitoring system is primarily intended to track the relative development of the measurements, no final assessment of the repair success or the performance of the monitoring system itself can be made at this stage. However, the basic functionality under challenging construction site conditions has been demonstrated, thus laying the foundation for the successful long-term operation of the system.

## 4 Conclusion and Outlook

A novel monitoring system developed at ibac, based on polymer supplementary cathodes, was used for the first time in the context of a practical project. The system was successfully installed and commissioned under challenging conditions on the outer shell of a cooling tower in seawater operation.

The installation demonstrated the following advantages of the polymer sensors:

- Quick and easy application through 2K injection technology without the need for post-treatment, allowing for higher work progress.
- Heavy equipment such as core drilling machines, embedding mortar, mixing water, etc., does not need to be carried.

Although no direct conclusions can yet be drawn regarding the evaluation of the success of the repair measure at this early stage, the presented system will provide important data over the coming years on the development of the corrosion state of the reinforcement in relation to the chosen repair concepts and will enable an overall evaluation of the monitoring concept. Of particular interest are:

- The comparability of measurement data from the "classic" and polymer supplementary cathodes.
- The durability of the sensor polymer under construction site conditions.

In the future, it is planned to use polymer supplementary cathodes in the context of further repair measures. Focus areas include parking garages and road tunnels. Currently, ibac is conducting research in a follow-up project to adapt the well-known multi-ring electrode also based on injectable plastics.

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