Corrosion Monitoring in Reinforced Concrete Structures with an Innovative rf-based Sensor

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Abstract

The research project carried out at the Institute for Building Materials, Concrete Construction and Fire Protection (iBMB) at Technische Universität Braunschweig, Germany, and at HERTZ-Systemtechnik, Germany focuses on the development of a wireless measurement system for corrosion monitoring. The measurement system detects the initiation of corrosion of reinforcement. The main goal is to develop a small and robust sensor that can be integrated into the cover-layer of reinforced concrete. Due to the chosen geometry of the sensor it is possible to detect the progress of the depassivation front in staggered intervals of depth (e.g. carbonation/critical chloride concentration). The sensor can be applied to new built and existing structures. This allows specific and cost-efficient maintenance work. There is a vast field of applications concerning new built and existing structures such as car parks and bridges. Therefore the development of the sensor is high in demand to the national economy.

For the subsequent installation of the sensor it is necessary to carry out a core drilling to place the sensor in its final location. Afterwards it is indispensable to bind the sensor physically with the help of a grouting mortar to the perimeter of the bore hole. In this case, the properties of the grouting mortar are extremely relevant since it is supposed to close the gap between the sensor and the perimeter of the bore hole. Voids in the grouting mortar can falsify the transport of harmful substances and consequently bias the measurement result. In order to avoid this error it is necessary to provide methods to prevent voids in-situ. Finally, the application of the sensor in an existing structure is presented.

Keywords: corrosion monitoring; wireless measurement system; structural health monitoring;

1 Introduction

Corrosion induced damage on reinforced concrete structures severely impairs the national economy. Therefore it is desirable to detect the damage as early as possible to start counteractions in time and in doing so, reducing overall costs and minimizing the risks. As a basic principle there is a thin protective layer on the reinforcement to prevent from corrosion. Due to carbonation or critical chloride concentration in the surrounding concrete this layer can get destroyed which leads to corrosion. Unfortunately, the exact starting point when corrosion is initialized, cannot be pre-estimated. The interaction relations between the environmental conditions and the properties of the concrete are too widely scattered.

In a current research project a small, robust, cheap and wireless sensor to detect corrosion has been developed. The sensor can be integrated into the cover-layer of reinforced concrete and is applicable to both new built and existing structures. The field of application encompasses corrosion exposed structures such as car parks, tunnel and bridges.
2 Sensor components

2.1 Setup

The sensor prototype is shown in Figure 1. The overall dimension amounts to 50 mm in height and 40 mm in diameter. Consequently, the application of the sensor is possible even in complicated installation conditions. The sensor shell features four notches at a spacing of 10 mm which contain the sensitive element (a tenuous iron wire). Due to the chosen geometry with its four wire layers it is possible to detect the progress of the depassivation front in staggered intervals of depth. The resistance of the wire is measured in constant intervals. In case of corrosive attacks, one or several of the wires depassivate and corrode on a short-term basis.

As a result the measured resistance escalates. Exceeding the resistance threshold the wire transection will be detected within the next measuring-cycle. Hereby the depth of corrosion damage becomes apparent.

![Figure 1: Sensor Prototype.](image1)

![Figure 2: Distribution of concentration of a vertically soaking chloride solution into a concrete and mortar sample after 20 hours.](image2)

2.2 Grouting Mortar for the Subsequent Sensor Installation

In an existing structure the sensor is installed in the grouting mortar. For the correct detection of corrosion, the mortar should feature the same transport properties as the surrounding concrete. Unfortunately, this is, e.g. due to time-dependent factors, permanently beyond reach. Therefore it is suggested to accomplish the mortar with a more dense structure. As soon as a concentration difference of contaminants is prevalent, transport orthogonally to the surface of the building structure and diffusion exchange processes between the grouting mortar and the concrete must be considered. Figure 2 shows that dense grouting mortar backed up by a narrow gap between the sensor and the perimeter of the bore-hole lead to a marginal difference in the distribution of concentration. Put in a cylindrical concrete sample is the sensor connected via a 3 mm thick layer of grouting mortar to the perimeter of the core-drilling. Within a few hours, a sodium chloride solution soaks into the layer near the surface. Diffusion processes lead to an adequate assimilation of the chloride-concentration between the concrete and the sensor.
The permeability of the grouting mortar is crucial for corrosion monitoring with the presented sensor. Within the scope of experiments it could be determined that the chloride migration coefficient $M_{\text{Cl}}$ [$\text{m}^2/\text{s}$] (referring to [1]) represents an appropriate reference point in order to assess various types of grouting mortar. On the basis of the experimental results it is recommended to use grouting mortars with

$$4 \cdot 10^{-12} < M_{\text{Cl}} < 6 \cdot 10^{-10} \left[\frac{\text{m}^2}{\text{s}}\right].$$

Several different installation positions are possible: horizontal, vertical or overhead. Hereby, the consistency of the grouting mortar has to fulfill different requirements. Soft grouting mortars connect better to the surrounding mortar but the grouting mortars used in overhead installations must be compacted to prevent voids (Figure 3).

Figure 3: left: non-compacted grouting mortar, right: compacted mortar; below: downscaled concrete vibrator.

Fig. 3 shows the cross section of two concrete/grouting mortars probes. The probe to the left is non compacted, the probe to the right is compacted using a self build vibrator made of a electrical toothbrush. While the left probe has voids and shows areas of insufficient bound, the right probe connects to the perimeter of the bore hole without showing voids.
3 Sensor Components

3.1 Sensor Shell

The optimal base material for the sensor shell has proved to be a fine mortar. Its main advantage is its porous structure enabling a good bond between the sensor and the surrounding concrete. The fresh concrete or the cement paste of the grouting mortar penetrates the pores of the sensor shell and locks into its structure.

The impermeable surface of non-cementuous materials often used for sensor shells has an accelerating influence on ion transport processes along the surface. This is erroneously taken for a fast progress of corrosive substances. A sensor shell made of fine mortar is not influenced by this. Furthermore, the thermal expansion coefficient of fine mortar correlates to the surrounding concrete resp. grouting mortar. Delamination processes or cracks due to variations in temperature are thus minimized.

3.2 Potting Compound

Intruding water can cause short circuits in the electric components (e.g. circuit board, battery) of the sensor. In order to prevent this, an appropriate potting compound is necessary to protect the electric components.

The potting compound has to meet the following requirements:

- quick hardening to reduce production time
- temperature resistance in a range from -30°C to +60°C
- medium viscosity
  If the viscosity is high, the compound cannot connect to the circuit board without voids. On the other hand, a compound with a low viscosity will soak through the sensor shell.
- resistant to alkaline liquids
- permanently imperviousness to water
- no toxic/carcinogen effects

The examined potting compounds were tested whether they fulfill the demands. The test showed that the most critical parameters are the viscosity and the hardening time.

The product which was finally selected displays a very low affinity to embrittlement after artificial deterioration (UV-light, temperature changes, NaCl and KOH-solution).

3.3 Electric Components

There are different industrial standards available to realize wireless communication between the corrosion sensor and an external data collecting device. Due to its various advantages, the Bluetooth Low Energy Standard (BLE) was selected. With a radio range of up to 30 m, it offers a far greater operating range than Near-Field-Communication (NFC) devices which are limited to a few centimeters. Furthermore, mobile devices as smartphones or tablets with an Android- or iOS-app can be used as data collecting devices. The BLE works in the 2,4 GHz frequency band. The disadvantage of an active power supply is given, but the power...
consumption is very low, thus enabling a long life expectancy of the sensor. An active power supply is also required to provide the sensor with data logger functionality. Given the low self-discharge of the selected battery type and an effective energy management of the measurement unit, the calculations show a life expectancy of 15-20 years.

The data collection unit consists of an external trigger unit to initiate the transmission sequence of the actual data and an iPad-tablet as data collector.

4 Tests

4.1 Laboratory Tests

A proof of concept was used to verify the suitability of BLE technology. Generally, the attenuation of radio waves in concrete rises sharply as the signal frequency increases, so only short radio ranges can be attained in the 2.4 GHz frequency band. However, the experiments showed that the BLE-technology of enabling an error-free data communication under difficult environmental conditions.

In figure 4 the results of a connectivity test with a sensor in a concrete probe are displayed. The y-axis shows the signal strength of the received signal, the x-axis the time since the concrete was set. The initial measurement was made in air. After that, the sensor was put in a fresh concrete probe with the overall dimensions 50 cm x 50 cm x 30 cm (length x width x depth) in a depth of 17 cm. As expected, the signal was highly attenuated but data communication was established. With increasing age resp. hydration of the concrete probe a higher proportion of the pore water was chemically bound and the signal attenuation decreased. After 37 days, the concrete probe was put in water with a 3 cm covering. The signal was higher attenuated but still readable. Other experiments showed comparable results.

![Figure 4: Attenuation during connectivity test.](image-url)
The results of the radio range test are:

- data communication is possible with a concrete coverage of 17 cm
- meshed reinforcement does not prevent communication
- signal quality increases with increasing age of the concrete probe/member
- signal quality is lower when ions exist in concrete environment (chlorides)

Other 15 cm x 15 cm concrete probes equipped with corrosion sensors were put in a salty spray chamber at a temperature of 32°C. Figure 5 shows the measured resistances of a sensor where all four sensitive elements were activated. The top wire layer was located 3 cm below surface, the other three in distance steps of 1 cm. The resistance increase from 1 Ω to values above 1 kΩ shows that the wire is transected by corrosion. The upper two layers were transected after 35-41 days, the other two layers after 71 days.

![Graph of resistances of different sensor layers](image)

**Figure 5:** Resistances of the different sensor layers in a salty air exposed concrete probe.

### 4.2 Tests on Site

The first corrosion sensor was installed in the experimental bridge “Concerto” a short time ago (Figure 6). The results of the tests will be published later.

![Installation of a corrosion sensor](image)

**Figure 6:** Installation of a corrosion sensor in the experimental bridge “Concerto” [2].
5 Outlook

The suitability of the sensors will be tested in further laboratory and on site experiments. Further corrosion sensors will be installed in horizontal, vertical and overhead positions in the experimental bridge “Concerto” using grouting mortar with different viscosities.

6 References
