A long-term study on the effect of a hydrophobic treatment on the moisture balance and durability of a reinforced concrete structure in a road tunnel

M. Brem[1,*], *J.* Lohner[2] , and *M.* Büchler[1]

[1]SGK Swiss Society for Corrosion Protection Technoparkstrasse 1 8005 Zurich Switzerland
[2]Sika Services AG, Tueffenwies 16 8048 Zurich Switzerland

Abstract. Concrete structures in the vicinity of seawater or deicing salts on roads in regions with cold climatic conditions, are exposed to chlorides. Transport of chlorides in concrete due to capillary suction during drying and wetting cycles as well as diffusion in combination with carbonation tends to result in corrosion of the rebar and loss of structural integrity. This damage mechanism mainly applies to directly weathered components. After a longer service life, however, components that are not directly exposed, such as concrete surfaces outside the spraying water area of a tunnel, are also affected. A long-term study over 12 years was performed to investigate the effect of hydrophobic treatment on the moisture balance and durability of a suspended tunnel ceiling compared to an untreated surface with the same exposure. Embedded sensors installed in the concrete structure and an online monitoring system were used to measure the electrical resistivity of the concrete and the corrosion rate of the steel reinforcement over time. Furthermore, the data obtained were combined with climate measurements in the tunnel to gain new insights on the effect of tunnel climate on the damage mechanism. The measurements allowed to prove the long-term effect and correct application of hydrophobic treatment. With these results it is possible to make a more precise estimation of the condition and the deterioration process of the tunnel ceiling and to optimize the rehabilitation schedule.

1 INTRODUCTION

In 2006, inspection of the concrete of a suspended tunnel ceiling (built in 1973-1978) showed strong signs of deterioration. In the middle of the tunnel the ceiling with concrete cover (cc) locally down to view a millimetre, was completely carbonated. The concrete was chloride contaminated, with particularly high values at the portal zones (2.4 m%/c at 9 mm cc in the portal zones, 0.6 m%/c at 9 mm cc in the tunnel centre). The chlorides, derived from road de-icing salts used outside the tunnel, were carried to the tunnel ceiling through the mist of the vehicles (speed limit 80 km/h, dual carriageway).
This deterioration process (reinforcement corrosion from pitting or carbonation) threatened to produce traffic incidences through concrete spalling or that the tunnel ceiling reaches its critical load capacity and collapses.
As critical infrastructure, it was necessary to keep the tunnel save and operational and extend the service life until a bigger repair job with tunnel closures could be done in a later period.

As an immediate measure it was decided to reduce the corrosion rate of the depassivated rebars, by reducing the moisture content of the concrete. This was done by applying a silane based hydrophobic treatment (that protects by drying out the concrete) on the deteriorated tunnel ceiling and monitor its effectiveness. For the latter a newly developed electrochemical concrete monitoring system was installed, consisting of sensors and data loggers, that automatically provide information on the corrosion process and humidity of the concrete. The location and type of sensors was proposed by SGK (Swiss Society for Corrosion Protection). For better evaluation untreated reference concrete was monitored as well. A regular consumption of the silane treatment (when applied in a creamy consistency) and the similar quality and condition of the concrete substrate, allowed to extend conclusions with respect to the reinforcement steel corrosion process from the local sensor spot to the surrounding concrete area.

2 MATERIAL AND METHODS

Corrosion of reinforcement steel (rebars) in concrete requires three conditions:

1. Water or moisture
2. Oxygen
3. Depassivated rebars

At the time close investigations or repair measures are taken, rebars are often partly depassivated. Oxygen levels are very complex to control. Therefore, the best way to reduce the corrosion rate is to reduce the moisture content in the concrete. An effective way to do so is using a silane based hydrophobic treatment.

* Corresponding author: martin.brem@sgk.ch

Silane based hydrophobic treatment:
This concrete protective measure protects concrete by:

- preventing liquid (e.g. chloride contaminated) water penetration
- allowing fast evaporation of water after wet-cycles
- allowing water vapour permeability and release of concrete core moisture (from hydration)

Together these characteristics allow the concrete to dry out from the inside and prevent onset of rebar corrosion. This treatment works also in case of small cracks. Cracks with width < 0.3 mm are protected with silane treatment (6 mm penetration depth in C25/30, XC4 concrete) and need no particular attention [1]. A positive effect of hydrophobic treatment (400 g/m^2) can be seen also in cracks with 0.6 mm width [2].

For good protection by means of a hydrophobic treatment freshly applied material shall be protected from evaporation and rain. Even though dependent on the type of concrete used, for good protection of exposed structures, a penetration depth of 6 mm is recommended [3,4]. With this penetration depth (tested in core drills) the treatment stays water repellent even for pressured water (10-12 bar) and is less dependent on superficial material removal over time. This not only requires sufficient consumption (> 300 g/m^2), but also a cleaned concrete surface (~180 bar, 80°C water pressure) and a dry concrete matrix at the surface (min. 1 cm depth) prior to application. The surface applied material requests several days for establishing a chemical bond to the walls of the concrete pore network. Especially in tunnels, where the air draft is high, the fresh material should be given enough time to absorb and react in the concrete. The performance of hydrophobic treatment depends not only on the physical condition, but also on the type and age of concrete substrate.
This preconditions are one of the reasons that the effectiveness of a hydrophobic treatment sometimes can't always be ensured.

In this tunnel a hydrophobic treatment with ~ 80% silane content and creamy consistency was applied by two overnight spray applications on the concrete ceiling (until 245 m from South and 287 m from North portal) in 2006. The creamy consistency allows to apply a higher and more regular consumption per application step. Special silane molecules penetrate the concrete through capillary absorption and diffusion.

Monitoring system:
The objective of the monitoring system is to monitor the performance of the silane based hydrophobic treatment on the underside of the suspended tunnel ceiling with respect to the corrosion progress and the moisture balance within the cover concrete.
For the measuring of the corrosion progress, sensor elements made of reinforcing steel (Ø 8 mm) with a cover of 8 and 20 mm, which are integrated in a sensor carrier (stainless steel tube), were installed in the concrete ceiling. Individual sensors (anode) begin to corrode after a short time due to the chloride ingress, so that the macro-element current between the sensor elements and the surrounding reinforcement grid (cathode) can be measured. Two sets of sensor elements were installed in each measuring zone.

The moisture balance of the suspended concrete ceiling is recorded with the aid of concrete electrical resistivity measurements. For this purpose, in each measuring zone two cores (Ø 100 mm) were collected from the concrete ceiling. The removed cores were equipped with sensors and then reinserted into the slab. In each measuring zone two of these concrete cores instrumented with resistivity and temperature sensors were installed in the ceiling for each test field. The resistivity sensors (steel rods made of stainless steel, Ø 4 mm) were arranged in the form of a ladder with distances of 12 mm, 21 mm, 30 mm and 40 mm from the surface. To compensate the temperature dependence of the concrete electrical resistivity, temperature sensors were installed at the level of the resistivity sensors. A two-point resistivity measurement was performed between the sensors and the surrounding reinforcement grid.
To avoid measurement inaccuracies, the sensors are placed not more than 5 m from the data logger. With the battery powered data logger the measuring intervals and input data for each sensor can be set. A measurement interval of one hour was applied over the entire measurement period. Figure 1 shows a schematic and a photograph of the installed monitoring system in the tunnel.

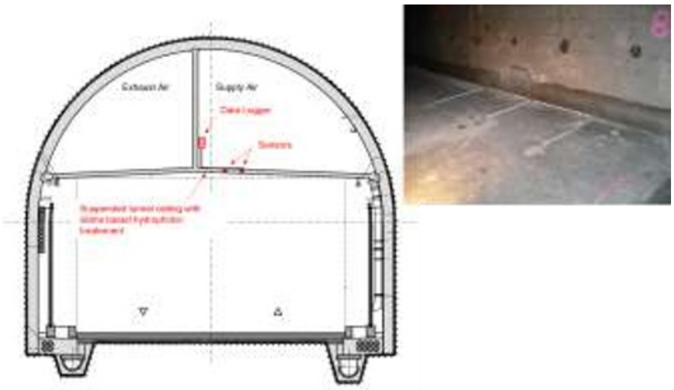

Figure 1. Schematic / photograph of the installed monitoring system in the tunnel.

The electrochemical measured data are converted into digital signals in the data logger and sent wireless through a LoRa Wan protocol to the next gateway and then stored in a cloud. From there the data is accessed, processed, and visualized. Because of the lack of a public LoRa Wan network in the tunnel, own gateways were installed that forward signals to the public 4G network in the tunnel.
Sensors can be installed either from the back (If accessible, like in this case above the tunnel ceiling), or from the front of the exposed concrete surface. Especially, if the monitoring setup is applied for a long duration, accessibility of the cables and control units for maintenance reasons (e.g. change of battery) is necessary. But also, protection against vandalism should be considered. The cases and cables should always be labelled and contain contact information of the responsible organization

Measurement methods:
<u>Corrosion current (CC)</u>
The current flowing within a macro-corrosion element between anodic and cathodic surface areas is a parameter for characterising corrosion activity.
Measuring the corrosion current is based on measuring the current flowing in the electrical contact between the anode (sensor) and the cathode (reinforcement grid). However, it may

happen that cathodic areas are also present on the element acting as the anode (sensor). The measured current of the macrocell is therefore only the current measured in the external macro element between sensor and reinforcement grid, which may only represent part of the actual corrosion current. For determining the corrosion current density (CCD), the anode surface is required. In the following results, the entire sensor surface was assumed to be the anode. This leads to an underestimation of the corrosion rate if part of the sensor surface remains passive. By integrating the CC over time, the cumulated mass loss can be calculated using Faraday's law. The cumulated mass loss can be transformed in a cumulated corrosion removal (CCR) of the sensor using the anode area (sensor area). The CCR is an average corrosion removal (cross-sectional loss) at the sensor. In this study, it is used as a parameter for the comparison of the individual monitoring fields.

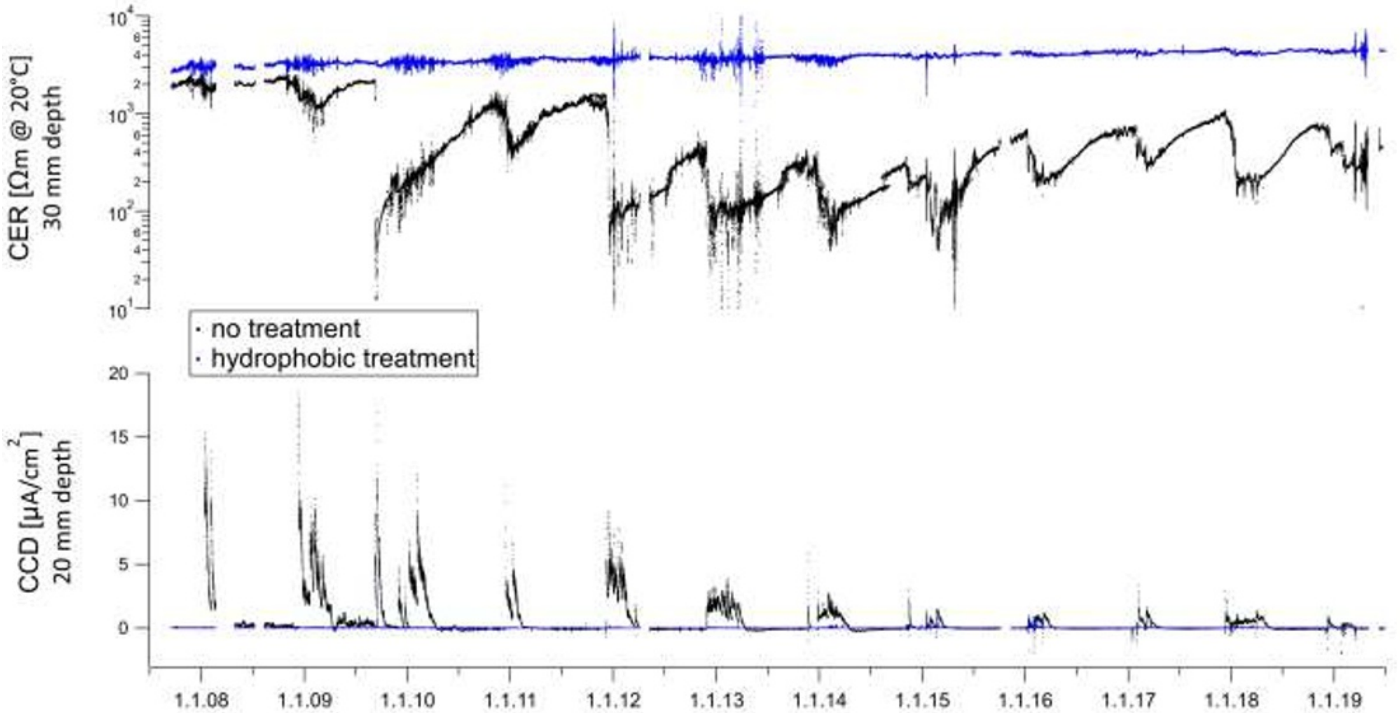

Figure 2. CER (top) and CCD (bottom) of an untreated (black) and a treated (blue) concrete 240 m from the tunnel south portal during a 12-year period.

Concrete Electrical Resistivity (CER)

The electrical concrete resistivity is an influencing factor in the corrosion system. Cement-bound building materials can exhibit a wide range of electrical resistivity (from a few Ωm to several kΩm), depending on their composition and the prevalent ambient conditions. Drying of the material always leads to an increase in electrical resistivity. This is due to the reduction of the pore water volume, which ultimately impairs the mobility of the ions responsible for the charge transport. Under dry conditions, the CER may become the controlling factor in the corrosion process [5, 6].

The CER was measured using an alternating current resistance measurement with a two-electrode arrangement. A frequency of 1 kHz was used. With the two-electrode method, current application and voltage measurement take place at the same electrodes.

The CER depends largely on the mobility of charged particles in the concrete pore solution. The viscosity of concrete pore solutions decreases with increasing temperature, which leads to an increase of ion mobility. The CER decreases with increasing temperature under otherwise identical conditions. The relationship is described by the Arrhenius equation. This allows to normalize CER values to a reference temperature in a good approximation. This is necessary, for example, when determining water contents using CER measurements [7].

Location

The monitoring system consist of a total of ten measurement zones of 8 m tunnel length. In each portal area (north and south) four measuring zones were situated and two were arranged in the middle of the tunnel. In the portal areas, two measuring zones with and without hydrophobic treatment were arranged next to each other. This made it possible to monitor the effect of the hydrophobic treatment under the same environmental conditions.

The climate in the tunnel is recorded by taking temperature and humidity measurements in the tunnel as well as in the supply air and exhaust air duct over the entire length of the tunnel.

In the present paper the results of two measuring zones in the south and north portal area are presented.

3 RESULTS

Monitoring data at the tunnel portal over a 12-year period

Figure 2 shows the results of hydrophobic treated and untreated concrete zone at 240 m from the tunnel south portal during a 12-year period (June 2017 to June 2019). The upper graph shows the CER at 30 mm depth and the lower the CCD of a macro-element at 20 mm depth. The CER values are temperature compensated using the Arrhenius equation with a reference temperature of 20°C.

The CER values of the untreated zone in black show strong yearly drops in the winter months (November to April) followed by concave recover for the remaining year. Sometimes the CER doesn't recover completely from the drop during winter. After 2010 the high CER values from the beginning of the 12-year period (2 kΩm in 2007) are never reached again (0.5 kΩm in 2019). The steep yearly onset of the CCD correlate with the drops of the CER. CCD measurements reach more than 15 [µA/cm^2] and stay above 5 [µA/cm^2] for many days during a year. After 2013 the CCD decreased during the activation periods.

The blue curves in Figure 2 show the data of a silane based hydrophobic treated concrete in the portal zone. The CER (at 30 mm depth) stays at a relatively constant level with a slight increase at around 3 - 4.5 kΩm during the 12-year period. No significant or only short drops (quick recovery) can be seen. The CCD of the treated zone (at 20 mm depth) stays constantly at zero (blue in Figure 2).

Monitoring data at a south portal zone during one reference year

Figure 3 and Figure 4, respectively illustrate the monitoring results during a reference year (September 2017 to September 2018). At that time the hydrophobic treatment is 11 years old. The data of the untreated concrete is shown in Figure 3 and of the silane treated concrete in Figure 4. The results at different depths (12, 21, 30 and 40 mm for CER and 8 and 20 mm for CCD) are shown.

Untreated concrete

In Figure 3 the 12 mm deep electrical resistivity of the untreated concrete decreases from ~ 1200 Ωm to ~ 5 Ωm in three drops over a 2-month period (between December and February). With increasing concrete cover the CER is less impacted during the winter months. At 21 mm depth the resistivity is roughly one third lower than at 12 mm depth, with the biggest decrease to 40 Ωm. The CER in 30- and 40-mm depth is less impacted by single resistivity drops, showing higher inertia and a more general trend. After the resistivity reaches its lowest levels between February to May, it increases without fluctuations.

The CCD at 8 mm depths shows strong peaks of up to 30 µA/cm^2. At 20 mm depth CCD values of less than 3 µA/cm^2, occur during that year.

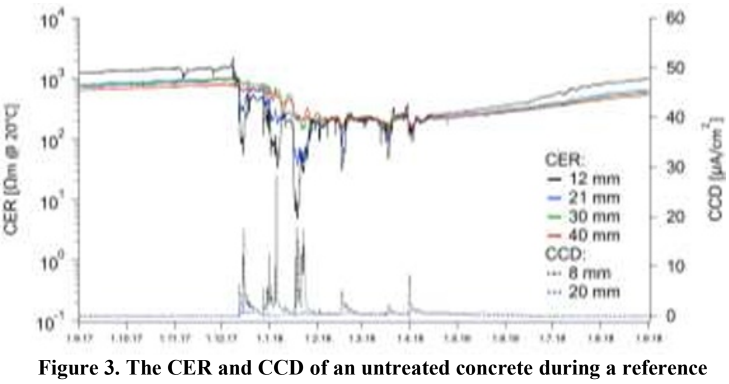

Figure 3. The CER and CCD of an untreated concrete during a reference year 240 m from the tunnel portal.

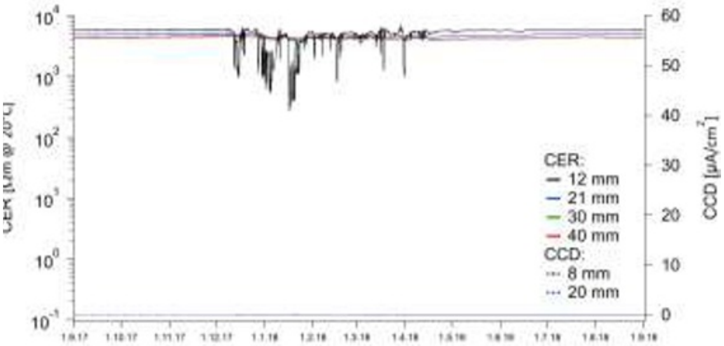

Figure 4. The CER and CCD of a silane treated concrete during a reference year 240 m from the tunnel portal.

Treated concrete

Figure 4 shows the data of the silane treated concrete during the reference year. The CER at 40, 30 but also 21 mm depth stay constant at around 5 kΩm. Only at 12 mm depth decreases of the CER are visible that go down to 300 Ωm. Again, three resistivity drops can be seen that correlate in time with the CER drops of the untreated concrete (Figure 3). During the entire year no corrosion current (above 0 µA/m^2) was measured for the 20 mm or 8 mm deep sensor electrode.

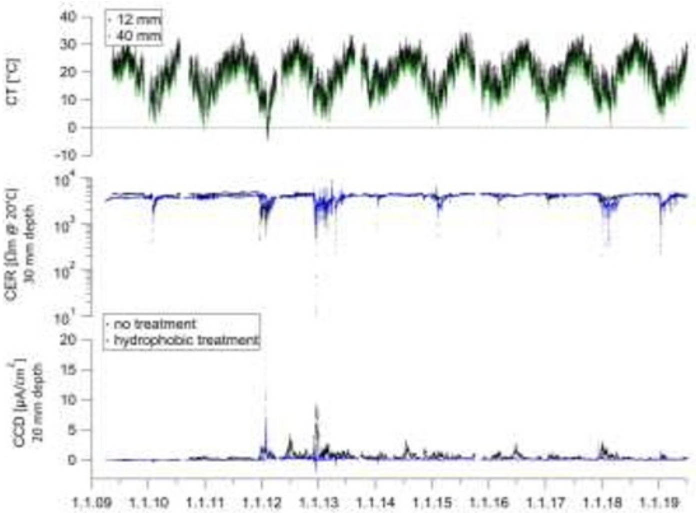

Figure 5. Temperature change at different depths, CER and CCD for untreated (black) and treated (blue) concrete during a 12-year period, 287 m from the tunnel north portal.

Monitoring results at a north portal zone during a 12-year period

Like the data shown in Figure 2 for a south portal zone, Figure 5 shows data of a reference area 287 m from the north portal. In the graph the concrete temperature values 12 mm and 40 mm inside the concrete, which are used for the temperature compensation of CER, are shown on top. The yearly fluctuations between summer and winter months are around 30°C in magnitude. The temperature 40 mm inside the concrete is always slightly lower than at 12 mm. The 30 mm deep CER reach a maximum of around 5 kΩm for the untreated (black) as well as treated (blue) concrete areas during the 12 years period. The resistivity values of both areas go down to 10 Ωm with regular drops to 400 Ωm. The CCD at 20 mm depth (see bottom of Figure 5), shows more corrosion for the untreated vs. the silane treated zone. The CCD peaks correlate in time with the CER drops.

Corrosion removal between north and south portal

Figure 6 shows the cumulated corrosion removal (CCR), at different depth (8 mm and 20 mm) for the treated and untreated zones at the tunnel south portal (field 1) and at the tunnel north portal (field 2), during 12 years in mm. The strongest cumulated corrosion removals, with 0.13 mm (at 8 mm depth) and 0.07 mm (at 20 mm depth), appear in the untreated, south portal zone (field 1). The silane treated concrete in the same area shows less than 0.01 mm CCR removal at 20- and 8-mm depth.

The untreated concrete zone at the north portal zone shows lower CCR than the untreated concrete at the south portal zone. The reduction of the CCR between the untreated and the treated zone is lower in the north compared to the south portal zone.

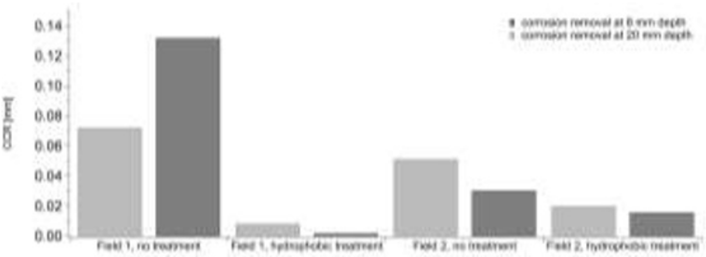

Figure 6. Corrosion removal at 20 and 8 mm for non-treated and treated zones at south portal (Field 1) and north portal (Field 2).

South vs. north portal

Moisture, that reduces the resistivity of the untreated concrete at the south portal zone, initiates corrosion. The corrosion initiates very quickly at 8-mm concrete depth and more slowly (over the course of 3 months) at 20-mm depth (Figure 3). The drying process, especially at 30-, 40- and 21-mm depth, is relatively slow compared to the treated zone of the south portal (Figure 4).

Moisture inside the untreated concrete has increased over the 12 years at the south portal (decrease of CER).

A comparison of the data of the untreated concrete zones at the south portal (Figure 2, 0.5 kΩm CER in 2019) to the one of the north portal (Figure 5, 5 kΩm CER in 2019) shows that the CER values at the north portal have been consistently higher over the 12 years. Furthermore, the positive effect of the hydrophobic treatment is less at the north portal.

4 DISCUSSION

Environmental conditions

The temperature at 40 mm concrete depth is always lower compared to 12 mm depth, which indicates that the back of the suspended ceiling, where the ventilation system is placed, is always a bit cooler than in the tunnel driveway. The repetitive yearly drops in CER (between the months November and April), their duration and slow recovery indicate that condensation within the concrete (instead of rain or snow) is the source of the yearly increasing moisture (illustrated through the CER) inside the concrete. Chlorides, transported onto the concrete surface through mist in the portal area, penetrate the concrete through the condensated humidity within the concrete. Temperature inside the tunnel has increased slightly over the 12 years. This is a result of the complex interaction of the climate outside the tunnel, the traffic volume and the operation of the ventilation. The ventilation system has been optimized over these years to reduce energy consumption and operational wear.

North vs South Portal

In the beginning, the CER of the untreated concrete at the north portal (4 kΩm) is roughly 2 kΩm higher compared to the south portal. At the end of the 12-year period this difference increases to roughly 4.5 kΩm. While the CER of the untreated zone at the north portal stays similar, the CER at the sourth portal is reduced to 0.5 kΩm.

Assuming that the concrete properties are comparable, the difference in CER can be attributed to different climatic conditions. In the north portal zone, the environmental conditions (condensation, moisture ingress) are less aggressive than in the south portal zone.

CER vs CCD

The corrosion current density (CCD) and the concrete electrical resistivity (CER) correlate very clearly (Figure 2 to Figure 5). This confirms that in this case the corrosion reaction of the macro-element is mainly controlled by CER and not by the electrochemical reactions of the anode or cathode.

Reinforcement corrosion

The high and increasing moisture penetration (21 mm depth in Figure 3 or 30 mm depth in Figure 2) as well as high corrosion removal at 8 mm (0.13 mm CCR) and 20 mm (0.07 mm CCR) depth indicate rebar corrosion at the untreated zone of the south portal, where concrete cover is low. At the treated concrete of the south portal no CRE value below 1 kΩm and no significant CCD could be measured over the course of 12 years. These values show high protection effectiveness of the silane based hydrophobic treatment.

Silane based hydrophobic treatment

In general, the shown data highlight the performance advantages of silane based hydrophobic treatments in terms of longevity, correct application, right measure, suitability to environmental conditions and concrete substrate, etc.

The reduced effect of the treatment at the north portal, compared to the south portal could hint to suboptimal conditions during the application. Too moist concrete, high humidity, condensation, wind (eg. from quick reopening of the tunnel after application) or penetration depth could be some reasons for that. Anyhow, since the CER measurements (for the treated and untreated concrete) don't reach critical values and the CCD of the treated zone are low, the risk of corrosion is still moderate, and no measures need to be taken regarding the hydrophobic treatment.

5 SUMMARY AND OUTLOOK

The measurements have shown that the monitoring system is suitable to demonstrate the effectiveness of the silane treatment. It could be shown that the silane treatment permanently prevents moisture penetration. Thus, the progress of damage due to corrosion can be greatly reduced.

It is possible to detect time-dependent processes such as the present corrosion reaction, which mainly takes place in the winter month. This would not be possible in case of inspections that are only carried out at arbitrary times over the year. Hence, the monitoring system allows to obtain more information about the corrosion mechanism and the associated transport processes.

In this case, it was assumed at the beginning that the moisture ingress into the concrete was caused by spray from the vehicles. However, measurements have shown that water only enters the concrete in the winter months, even though there is sufficient precipitation outside the tunnel all year round. Additional measurements of the tunnel climate have confirmed that condensation leads to the moisture entry.

While these monitoring results don't replace traditional inspection, they provide information with respect to critical corrosion situations, can reduce inspection intervals, improve decision making, provide an early warning system, indicate when reapplication of the hydrophobic treatment might be necessary etc. All this is a contribution to a safer and more effective infrastructure management and thereby increases service life of concrete structures.

Corrosion monitoring of critical structures, as described in this publication, can also be applied to bridges, cooling towers, car parks, silos, industrial structures etc. Depending on the type and deterioration process, a combination of different sensors is usually necessary. For instance, combining electrochemical sensors with structural sensors in bridges.

In connection with the future digitalization, which will also be used in the construction industry, monitoring offers the tool to obtain the basic data required for condition monitoring and durability calculations.

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