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Life cycle management of concrete structures with respect to reinforcement corrosion and concrete deterioration Part II: monitoring

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ABSTRACT: In Europe severe damages on reinforced concrete structures exposed to de-icing salt cause annual costs in a range of several billion Euro. There is a considerable saving potential just by detecting the deterioration with its dimension in time and subsequently carrying out appropriate intervention before damage is visible or even occurs. Corrosion monitoring enables a continuous condition assessment. By the implementation of moisture sensors the water content within the concrete can be measured. This enables the owner to assess the proper operation of coatings of e.g. bridges and park decks and the effectiveness of hydrophobic treatment. A modified corrosion sensor was developed to monitor the attack of sulphuric acids on concrete and reinforcement. These kinds of attacks often occur in sewage plants due to effluents, clearing sludge and night soil. For all applications examples are given. Besides it will be shown how such additional information from monitoring can be used to update a service life calculation as a valuable tool for life cycle management.

1 CONDITITON ASSESSMENT BY CORROSION MONITORING

1.1 *Deterioration process*

Chloride induced corrosion of reinforcement and prestressing tendons is 8causing damages on structures, which amount up to several million Euro annually in Germany. In most cases the degree of damage has reached a considerable extent by the time it is visually detectable. The corresponding intervention, which can include repair as well as strengthening measures, is therefore rather extensive and complex. In this respect a huge saving potential exists in case the point of intervention is adjusted to an early damage stage. In the following the continuous condition assessment of structures via corrosion sensors is introduced.

Reinforcement is protected against corrosion by the formation of a so-called passive layer caused by the alkalinity of the concrete. This protection can be destroyed due to the penetration of chlorides (Cl^-) from de-icing salt and seawater or/and due to carbondioxide (CO_2) leading to depassivation of the reinforcement.

Usually these depassivating substances penetrate into the concrete from the surface through the concrete cover towards the reinforcement. Once the carbonation front has reached the reinforcement or/and chlorides accumulate at the reinforcement up to a critical concentration corrosion is likely to occur provided that sufficient oxygen and humidity is present, which usually applies for outward structures.

The impairment of structures exposed to the road atmosphere such as bridges and tunnels is primarily caused by chloride induced reinforcement corrosion due to de-icing salt spread during winter time. Furthermore the reinforced concrete structure can be exposed to chlorides present in soils or seawater. After initiation of chloride induced corrosion cracking and spalling of the concrete cover may occur. In the further progress the load bearing capacity of the structure may be reduced as a result of bound failure or cross section reduction of the reinforcement.

1.2 *Functionality of corrosion sensor*

In the following the functionality of the most common corrosion sensor, the Anode Ladder, will be introduced (Fig.1). The installation of an Anode Ladder enables to locate the depassivation front continuously while the structure monitored is in service.

The Anode Ladder consists of several single sensors (anodes) in different depths. The distance between two sensors is normally 5 to 10 mm. These sensors give a signal as soon as the depassivation front has reached a sensor. Thereby it is possible to trace the time depending movement of the depassivation front towards the reinforcement. Further components of the corrosion sensor are the cathode made of activated titanium, a connection to the reinforcement and a junction box, Figure 1. Within this junction box a water-proof connector plug to the measuring instrument is placed.

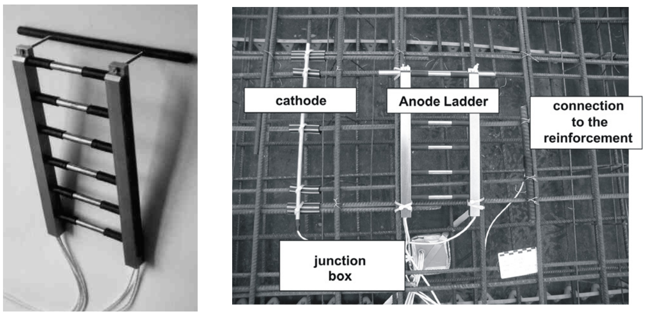

Figure 1. Corrosion sensor (here: Anode Ladder) before installation (left hand side) and attached to the reinforcement before casting (right hand side).

The measuring principle is based on the electrochemical processes, taking place during corrosion. Each sensor element consists of a piece of reinforcement steel, which is connected via a cable to the cast-in cathode. Since the cathode is made of activated titanium it will not corrode even if embedded in chloride contaminated or carbonated concrete.

In case the depassivation front (caused by chlorides or carbonation) reaches one of the sensor element (anode) a galvanic element will be formed between this anode and the cathode to which it is electrically connected, hence causing an electrical current and a potential drop of the anode. Current flow and potential drop can be measured at the respective sensor. As the depth of each anode and the time of activation is known it is possible to predict the progress of the depassivation front towards the reinforcement. With the information of the concrete cover the point of time of depassivation can be calculated. By implementing this procedure in a full probabilistic manner the reliability of the structure towards the initiation of reinforcement corrosion can be calculated and updated over service life. This is a strong tool for an economic optimisation of intervention costs, as by incorporating corrosion sensors in the condition assessment interventions can be carried out before severe damage occurs.

1.3 *Examples of application*

Since 1990 more than 1200 Anode Ladders have been installed world wide, for instance in the Biblioteca Alexandrina (Egypt), Great-Belt-Link (Denmark), Allianz-Arena (Munich, Germany) and the Ackermannbridge (Germany). The projects carried out so far show that the sensors feature a sufficient robustness under construction site conditions. Furthermore they provide reliable and distinct differentiable signals over a long period. The installation of corrosion sensors is especially suitable for construction elements which are not accessible for inspection or for such being exposed to an extreme aggressive environment. Examples for these boundary conditions are the outer side of tunnel elements exposed to chloride contaminated soil and foundations in sea water environment. About 200 anode ladders have been installed on the outside of the eastern tunnel wall being part of the **Great-Belt-Link (Denmark)**. Their objective is the detection of chloride ingress and consequently reinforcement corrosion as the tunnel elements are exposed to chloride contaminated soil.

Currently an immersed tunnel beneath the Shannon close to the town of **Limerick (Ireland)** is being built and equipped with sensors, since the tunnel will be immersed in river water containing chlorides. The tunnel has been designed for a target service life of 120 years.

Figure 2 illustrates the application of sensors on the reinforcement of a diaphragm wall, being part of a port foundation at **Al Sukhna, Suez Canal, Egypt**.

Figure 3 shows installed sensors at a tubbing segment belonging to a railway tunnel being part of a high speed track in **Netherlands**. This durability strategy has been implemented as the soil in contact to the tunnel elements contains a considerable amount of chlorides.

1.3.1 *Allianz-arena*

The Allianz-Arena is the soccer arena in which the opening match of the world cup 2006 was held. To ensure a sufficient durability for the adjacent parking garage a life cycle management concept was developed during the design stage. In this context the durability

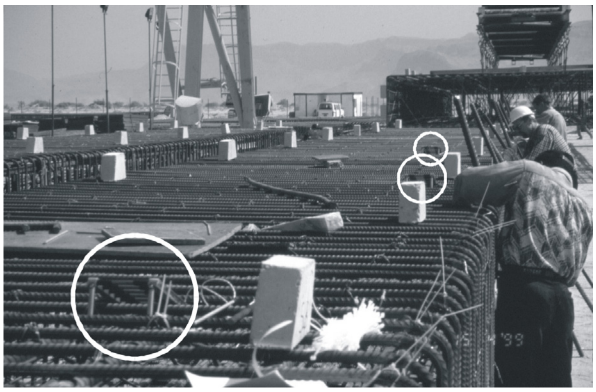

Figure 2. Sensors on the reinforcement belonging to a diaphragm wall, Al Sukhna, Suez Canal.

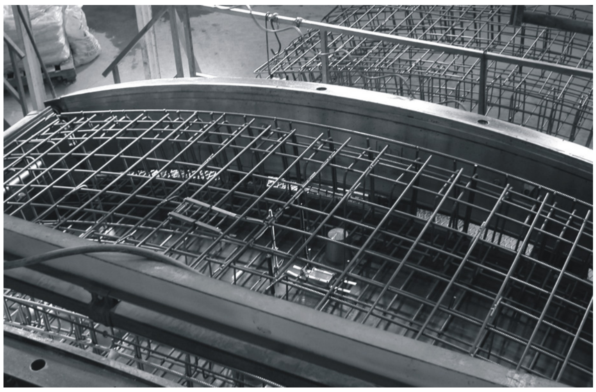

Figure 3. Grone Hart Tunnel, Netherlands.

concept played an important role since no coating was planned in the uncracked areas of the prestressed parking deck, although they are directly exposed to de-icing salt during winter time. In order to provide a sufficient reliability against chloride-induced corrosion of the horizontal uncoated areas of the parking decks an innovative solution has been created. Intensive optimisation of the concrete composition and the concrete cover took place by adapting full-probabilistic models to predict the reliability towards depassivation of the reinforcement over service life of the areas under consideration (preliminary design, cp. Mayer & Schießl (2008)). Within the framework of quality control measures the actual dimension of concrete cover and its resistance towards chloride ingress has been determined and incorporated in the calculation (update after completion, cp. Mayer & Schießl (2008)). As a further part of the durability concept park decks have been equipped with 30 Anode Ladders. The measurement of the sensors and the interpretation of the monitoring data take place in regular intervals. Apparently monitoring does not lead to an increased structural resistance and therewith to a more reliable structure. However, since the prediction of the depassivation is associated with several uncertainties the monitoring system gives additional information on the actual structural behaviour and hence helps to cut down uncertainties linked with the assumptions made.

By implementing these monitoring data within a service life design via a Bayesian update the accuracy of the model prediction will be enhanced. In the following this further utilization is outlined according to the procedure presented in Sodeikat et al. (2006).

The sensor gives a signal in case corrosion occurs at a single sensor element located at a certain depth. Hence, the possible location of the depassivation front must be between the last active and the first passive sensor element at any given time. The statistical evaluation of monitoring data for each sensor leads to a cumulative frequency of active and passive sensor depth and thereby describing the uncertain depth, in which the depassivation front has to be located (Fig 4). In the given example the analysis has been carried out after two years of exposure. By statistically analysing the location of active sensor elements (lower bound of depassivation front) and passive sensor elements (upper bound) and further assuming a uniform distribution within these bounds, the location of the depassivation front can be evaluated statistically (Fig. 5).

The location of the depassivation front derived from monitoring data can be incorporated by an additional equality constraint into the service life calculation. By adopting the Bayesian update the updated reliability index over service life (here: 50 years) can be calculated in a full probabilistic manner. The effect of implementing monitoring data derived from

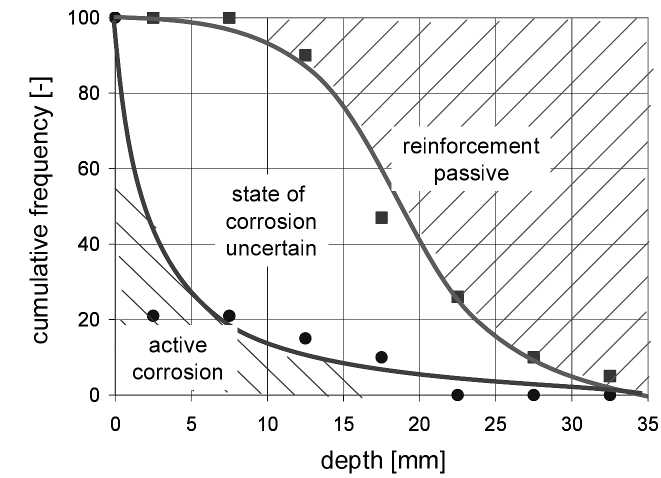

Figure 4. Evaluation of corrosion sensors after two years of exposure.

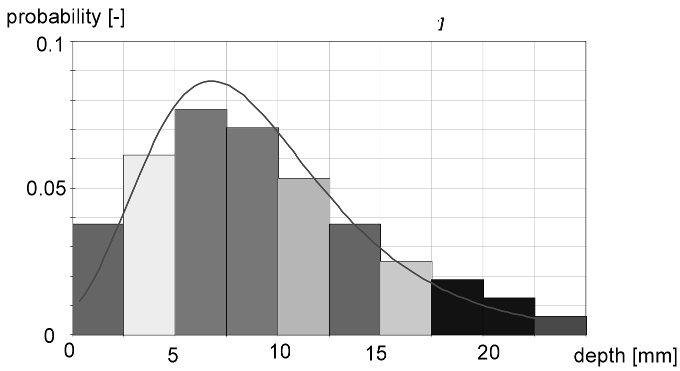

Figure 5. Probability distribution quantifying the location of the depassivation front after two years of exposure by using the information of active and passive sensor elements recorded from Anode Ladders.

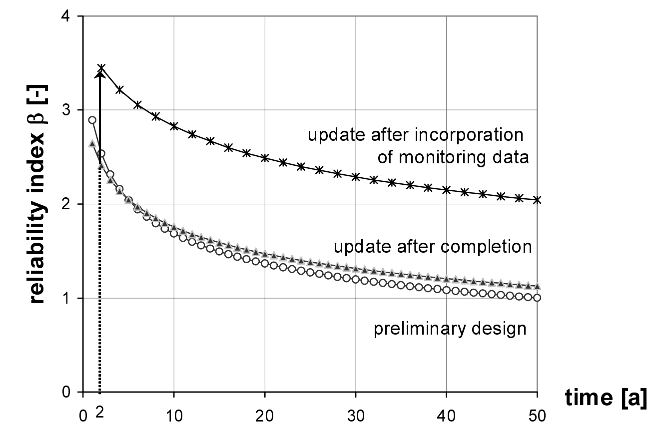

Figure 6. Calculated reliability indices (preliminary design and update after implementation of monitoring data) vs. time of exposure.

the Allianz-Arena after two years can be observed in Figure 6.

The demonstrated implementation of monitoring data into a service life calculation facilitates the possibility of an updated prognosis over service life linked to the depassivation of the reinforcement and therewith under the prevailing circumstances the onset of corrosion. This capability makes the service life calculation in combination with data achieved from the Anode Ladders an indispensable tool for the economic planning of intervention measures over service life.

2 CONDITION ASSESSMENT BY MONITORING THE WATER CONTENT OF THE CONCRETE - MOISTURE SENSOR

2.1 *Determination of the water content*

The determination of the water content in construction materials and in particular with regard to its depth and time dependent distribution is of high interest in the area of research and material development. This is due to the fact that material characteristics as well as the durability of the structure strongly depend on the water content of the construction material, Raupach et al. (2007).

An indirect measuring method is mapping the electrolytic resistivity of the concrete, which is directly correlated with the water content. For a quantitative determination of the water content within cementitious materials further issues have to be taken into account, such as the temperature of the electrolyte, ionic concentration and the pore structure of the material. For this reason material-specific calibration curves have to be generated, illustrating the correlation of the water content with the electrolytic resistance (Fig. 7).

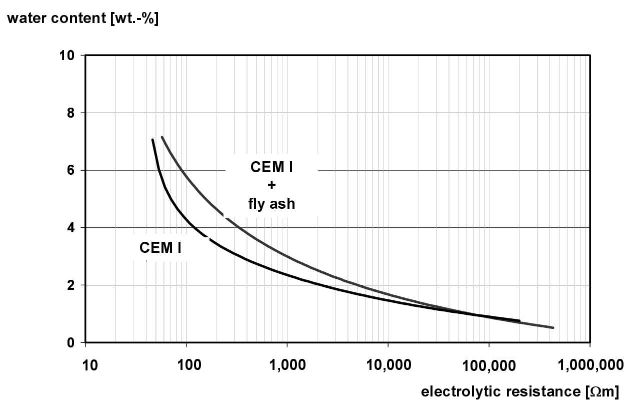

Figure 7. Dependency of the electrolytic resistance on the water content of the examined concrete specimen.

2.2 *Multiring-Electrode*

For multi-depth continuous measurements of the electrolytic resistance in cementitious materials the so-called Multiring-Electrode (MRE) has been developed at the Institute of Building Materials Research, Aachen University, ibac, Germany. The Multiring-Electrode can be integrated in existing and to-be-build structures.

The measuring principle of this sensor is based on the electrolytic resistance between two adjoining stainless steel ring electrodes located in different depths.

A standard MRE consists of nine rings with a thickness of 2.5 mm each, which are separated by isolating plastic rings in such a way that a centre distance of 5 mm between two adjacent rings is kept (Fig. 8). The application of an alternating voltage between two adjoining rings (ring 1 to ring 2, 2-3, 3-4,…) enables the generation of a specific resistance profile in eight steps in a depth from 7 mm up to 42 mm. For the conversion from the measured resistance in [Ω] to the specific resistivity in [Ωm], a cell constant is required, which has been determined experimentally to k = 0.1 m. This result is in good agreement with the results of numerical simulations.

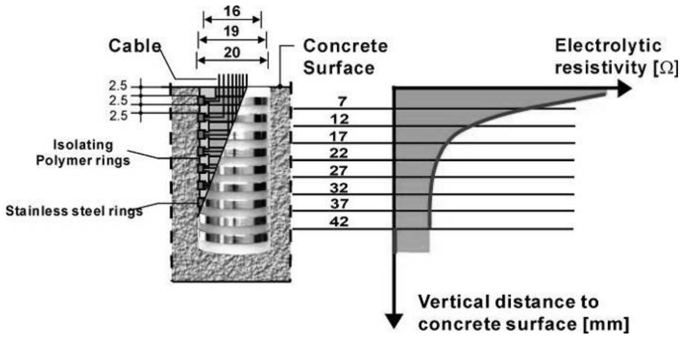

Figure 8. Schematic illustration of a Multiring-Electrode (MRE) and a typical resistance profile obtained from a esiccating concrete.

2.3 *Areas of application for road structures*

2.3.1 *Controlling the functionality of a bridge coating*

The Multiring-Electrode is a very effective tool when it comes to the assessment of concrete bridge coatings. According to a German guideline (ZTV-ING) the surface of an ordinary deck slab of a bridge has to be coated. Usually a further multilayered bituminous system will be applied on top. Hence there is no possibility to check the functionality of the coating beneath non-destructively.

The common investigation method carried out prior to a planned intervention is the opening of the bridge deck up to the concrete surface. Then potential mapping, determination of the chloride content and visual inspection of the reinforcement within local openings of the concrete cover can be carried out and assessed with respect to reinforcement corrosion. The disadvantage of these investigations is their destructive nature and the spatial limitation of the obtained measurement results. Furthermore the outlined intervention measures are comparably complex to plan since single lanes have to be blocked for traffic which is often solely possible during night time.

With the information gained through the installed Multiring-Electrodes the functionality of the coating can be checked at any time. In case that a local failure of the coating occurs a drop of the electrolytic resistance will be measured due to the increased moisture content of the concrete.

As part of a pilot project with the city council of Munich numerous sensors have been installed at so-called hot spots of a bridge in order to continuously check the functionality of the applied coatings. The installation of the MRE sensors was carried out subsequently in such a way that the upper ring of the sensor is located close to the surface of the deck slab of the bridge. The cables have been lead through the deck slab to the inside of the girder box, where they have been assembled in two terminal boxes.

Figure 9 shows the embedded Multiring-Electrode close to a drain outlet, which has been considered as a potential hot spot. The photograph has been taken before the interspace between sensor and concrete deck slab has been filled with mortar.

Besides the mentioned drain outlets also the transition structure has been considered as a hot spot for moisture ingress and consequently monitoring. Two further reference sensors have been installed at locations in which a failure of the coating is not to be expected in order to correct the changes of the electrolytic resistance from other effects than an increased humidity in the concrete due to water penetration (e.g. temperature influence, hardening of the mortar).

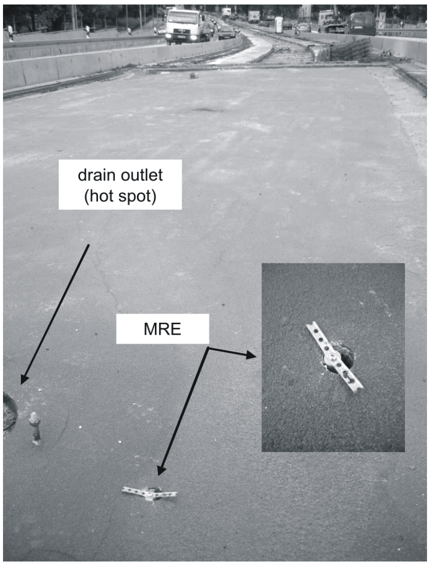

Figure 9. Prepared MRE on the deck slab close to a drain outlet (left hand side) which has been considered as a hot spot.

Figure 10 illustrates the change of the electrolytic resistance within the first 15 months of the installed sensors close to the rain outlet. The observed increase of the resistance over the complete depth of the MRE can be interpreted as the drying of the connection mortar applied between deck slab and sensor. This characteristic is a convincing indicator for a well functioning coating.

2.3.2 *Controlling the effectiveness of a hydrophobic treatment*

In the course of another pilot project a hydrophobic treatment has been applied on portals of a highway tunnel with the objective of reducing the penetration of chlorides into the structural concrete caused by traffic spray during winter time.

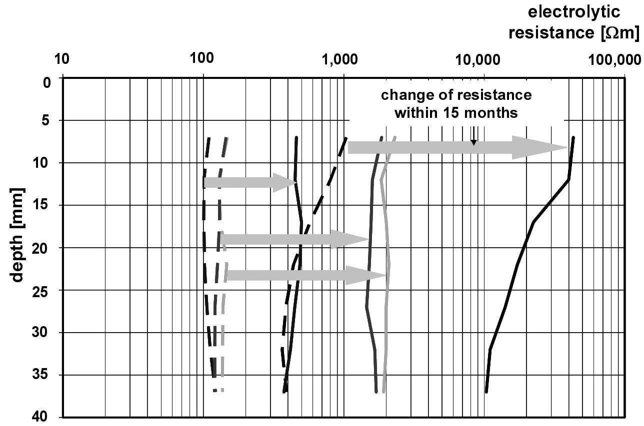

Figure 10. Typical change of electrolytic resistance within 15 month due to desiccation of the concrete (four MRE-sensors).

To demonstrate the effectiveness of this intervention, sampling plates with integrated MREs have been cast at the same time as one tunnel portal. For a start these plates (with and without hydrophobic treatment) were protected from driving rain and later exposed to traffic spray (Fig. 11).

The time dependent change of electrolytic resistance over a time period of 22 months is illustrated in Figure 12 for the sampling plate without hydrophobic treatment and in Figure 13 for the sampling plate with hydrophobic treatment respectively.

Close to the surface the electrolytic resistance of the sampling plate with hydrophobic treatment is up to ten times higher compared to the non-treated sampling plate. Also in a greater distance to the surface a significantly higher electrolytic resistance can be detected, which is presumably caused by the more distinctive drying behaviour of the plate with hydrophobic treatment. In this manner the effectiveness of a hydrophobic treatment can be checked non-destructively and continuously by the interpretation of data received from installed MRE sensors.

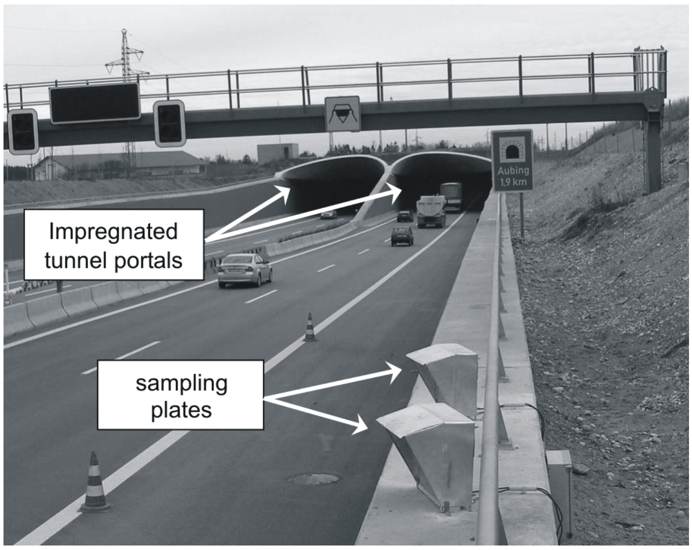

Figure 11. Tunnel portal with hydrophobic treatment and sampling plates.

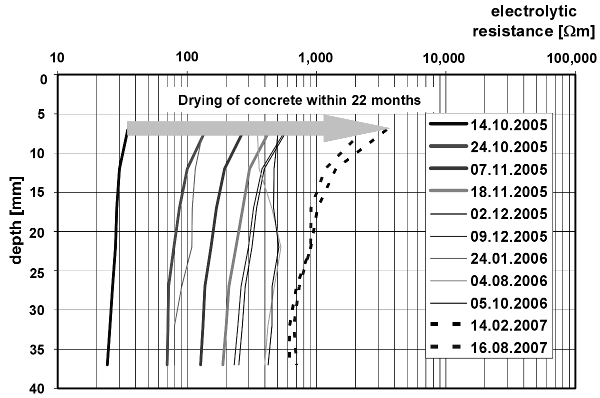

Figure 12. Change of electrolytic resistance of the sampling plate without hydrophobic treatment over a period of 22 months.

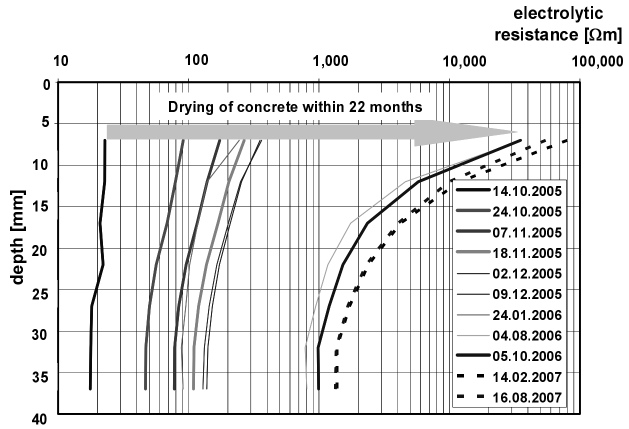

Figure 13. Change of electrolytic resistance of the sampling plate with hydrophobic treatment over a period of 22 months.

3 CONCRETE CONDITION ASSESSMENT BY MONITORING THE DEPASSIVATION DEPTH - ACID SENSORS

3.1 *Deterioration process of concrete due to acid attack*

In the following the principles of acid attack on concrete are shown on the basis of sulphuric acid attack. The mechanism of other acid attacks is comparable.

In components of sewage plants like sewers, digesters and pump stations attacks of sulphuric acid on concrete and reinforcement can occur. Generated by biological and chemical processes sulphuric acid H_2SO_4 evolves from hydrosulphide H_2S. The attack of sulphuric acid on concrete takes place in two steps which exacerbate each other. In the first step H_2SO_4 dissociates to acid ions H^+ and sulphur ions SO_4^{2-}. The acid part deteriorates the $Ca(OH)_2$ structure by a solving attack. In the second step SO_4^{2-} penetrates into the concrete along the solved $Ca(OH)_2$ channels and degrades the concrete structure by expansion reaction, Hillemeier et al. (2006).

3.2 *Principle of acid attack monitoring on concrete*

The penetration of sulphuric acid decreases the high ph-value of the concrete which ensures the passivity of the reinforcement - depassivation of the reinforcement and reinforcement corrosion in the penetrated concrete is the consequence. This corrosion can be measured with sensors and indicates the attack (penetration) depth of sulphuric acid. Therefore the principles of corrosion monitoring can be used to monitor acid attack on concrete.

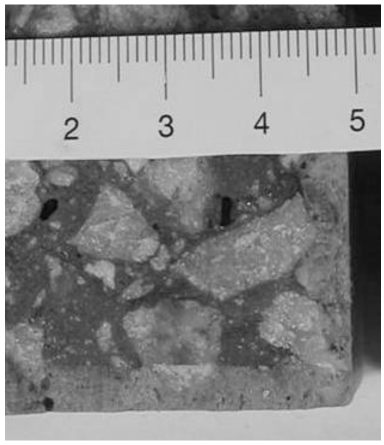

Figure 14. Typical depassivation of concrete due to acid attack, here: acetic acid, Beddoe et al, (2009).

For monitoring acid attack on concrete the operation mode of the anode ladder is the basis but the construction had to be adapted. The monitoring of concrete attack calls for smaller monitoring increments as it usually proceeds comparably slowly. Therefore, the Anode Ladder with its very robust, but relatively thick anodes and large distances between to neighbouring anodes is not suitable. Besides, it is very important to measure the original concrete or the repair materials. Therefore concrete cores of an existing structure have to be drilled out or cylinders have to be cast with original repair materials. Afterwards the cores/cylinders are equipped with single anodes with defined surfaces in different depths and a cathode made of activated titanium. All the cables (only very durable teflon cables are used) connecting the anodes and the cathode with a multipolar connector are running inside the cores/cylinders. Finally the cores/cylinders are inserted into bore holes in the structure to be monitored and the joints between cylinder and existing structure are filled with special grouts. The sensor data is collected by connecting a measuring device to the sensor at given intervals.

3.3 *Examples of application*

3.3.1 *Rehabilitation of a sewage plant with concrete damages*

Concrete members of a sewage plant in Düren, Germany, showed severe damages due to attacks of sulphuric acid, Taffe et. al. (2007). In most cases the depth of the deterioration was between 2 cm and 3 cm. The owner decided to carry out a research programme to test the durability of different protection materials like polyurethan, polyethylene, epoxy resin and glass plates.

To control the functionality of the different protection systems a monitoring system was installed. The following questions should be answered:

- is the particular protection system working?
- are there differences in the durability of the protection systems?
- if a protection systems fails, how quick is the deterioration of the concrete (penetration of the depassivation front)?
- in the case of a defect protection system, is there an application failure with respect to the expected durability of the system?

Monitoring system

The installed sensors are working according to the function principles of the anode ladder, but with a much finer spacing of the anodes. In pilot tests at the Technical University of Munich, centre of building materials cbm, the suitability of the measurement principle could be verified. The measurement of corrosion current and potential drop is a precise method to detect the penetration depth of attacking acids.

The acid sensors designed for this purpose consist of six single anodes with distances to the concrete surface between 1 and 9 mm, and one activated titanium cathode. The anodes and the cathode are embedded in the original repair mortar. The cables are running inside the acid sensor to a multipolar connector which is located in the middle of the top side of the acid sensor. The acid sensor builds a closed system which is finally installed in bore holes by filling the joint round the sensor with grout.

Results

The results after 8 months show that the acid sensors are working. Potentials and currents indicate no depassivation of the anodes and therefore no penetration of sulphuric acids. That means that the protection system is still functional. The electrolytic resistances of the concrete between the single anodes are low and homogenous. This shows that the concrete is drying out very slowly due to the tight protection system, Taffe et. al (2009).

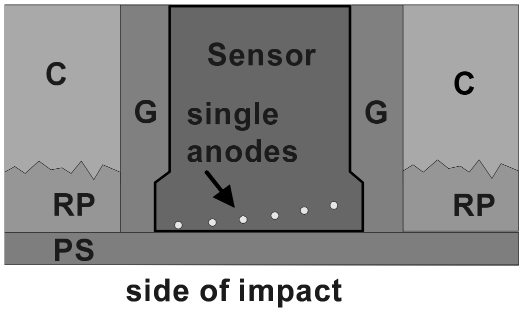

Figure 15. Cross section (scheme) of the acid sensor; concrete (C), RP (repair mortar), G (grout), PS (protection system).

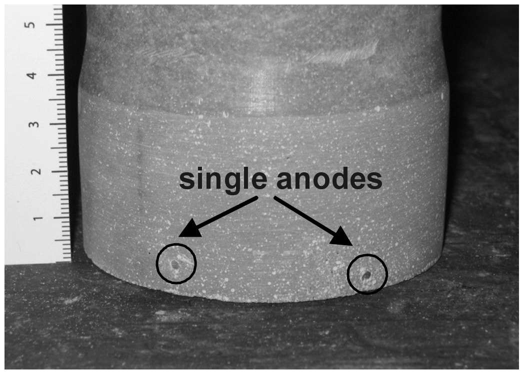

Figure 16. Side view of the acid sensor with two visible single anodes.

Figure 17. Top side of the acid sensor with connector.

3.3.2 *Condition assessment of a digester*

In Munich 4 new digesters have been built in 2006. To protect the concrete surface of the gas compartment a special coating system was applied. Even before starting up the coating system delaminated almost completely. After that the owner decided to test whether a protection system is necessary at all. To detect potential damages which can occur due to biogenous sulphuric acid a monitoring system was

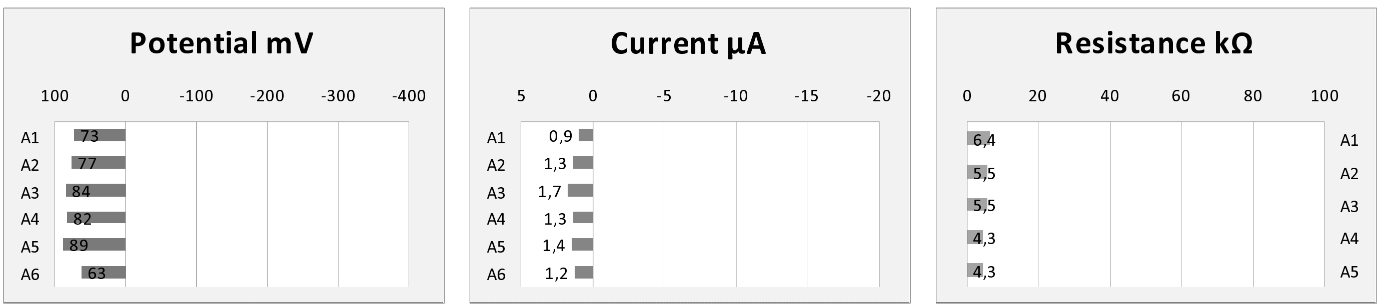

Figure 18. Acid sensor results after 8 months environmental exposure. The potentials are still noble, the corrosion current is low, the resistance is low and homogenous.

installed. Because the decision to monitor the building was made after finishing the concrete works the sensor could not be cast like for the sewage plant in Düren. Therefore concrete cores had to be drilled out of the structure and equipped with anodes, cathode, cables and connector.

Figure 19. Newly-built digesters in the north of Munich.

The owner had the special requirement that the operating of the acid sensor and of the measurement device must be carried out under explosion prevention conditions Therefore the cables of the acid sensors were laid through the digester walls to the opposite surface of the concrete member. The measurement is carried out with a complete galvanic separation of the measurement device and the acid sensor. To prevent high voltage at the sensor surface an additional low voltage fuse was installed between measurement device and sensor.

4 CONCLUSION

This paper demonstrates that the implementation of monitoring data is an economic, efficient and reliable method to achieve a more precise condition assessment. The introduced methods are particularly suitable for assessing the corrosion risk of reinforcement exposed to corrosion initiating substances (corrosion sensor), of coatings and hydrophobic treatments (Multiring-Electrode used as moisture sensors) and of concrete which is exposed to acid attacks (acid sensor). By evaluating monitoring data a failure of coating, hydrophobic treatment and protection systems can be detected in time before extensive damage is caused. This way the point of time for an intervention and an appropriate intervention measure can be identified and scheduled.

With data from corrosion sensors, such as the Anode Ladder, the condition assessment of reinforced concrete structures exposed to corrosion initiating substances can be carried out. The obtained measurement signal provides information on the depth of the depassivation front. This information can be integrated for the update of a full probabilistic service life calculation. This way, possible intervention measures can be optimised economically with regard to the point of time to be carried out.

Figure 20. Acid sensors ready for installation: The figure shows the drilled concrete core, the multipolar plug and a sealing gasket to ensure density of the sensor installation.

In addition the monitoring data can be used for an economic quality control of concrete structures. Consequently the information of sensors contributes to the enhancement of durability performance over the life time of the structure.

REFERENCES

Beddoe, R.E., Schmidt, K. Säureangriff auf Beton - Einfluss der Betonzusammensetzung; Teil 1, CEMENT INTERNATIONAL 3/2009, S 88-94.

Hillemeier, et- a.: Spezialbetone: In: Bergmeister, K.; Wörner, J.-D. (editor): Betonkalender 2006, Turmbauwerke - Industriebauten. Berlin: Verlag Ernst & Sohn, Bd. 1, Kapitel XI Spezialbetone, S. 521-583.

Mayer, T.F.; Schießl, P.; 2008: Life Cycle Management of Concrete Structures. Part I: Birth Certificate. - In: Proceedings of the 2nd International Conference on Concrete Rehabilitation, Retrofitting and Repair, Cape Town, South Africa.

Raupach, M.; Dauberschmidt, C.; Wolff, L.; 2005: Monitoring the Moisture Distribution in Concrete Structures. London: Taylor & Francis Group, 2006. - In: Proceedings of the International Conference on Concrete Repair, Rehabilitation and Retrofitting (ICCRRR), Cape Town, South Africa, 21-23 November, 2005, (Alexander, M.G.; Beushausen, H.-D.; Dehn, F.; Moyo, P. (Eds.)): 6-8.

Raupach, M.; Dauberschmidt, C.; Wolff, L.; Harnisch, J.; 2007: Monitoring der Feuchteverteilung in Beton – Sensorik und Anwendungsmöglichkeiten. - In: Beton 57 (2007), issue 1: 20-26.

Sodeikat, C.; Dauberschmidt, C.; Schießl, P.; Gehlen, C.; Kapteina, G.; 2006: Korrosionsmonitoring von Stahlbetonbauwerken für Public Private Partnership Projekte. - In: Beton- und Stahlbetonbau, issue 12: 932-942.

Taffe, A.; Pohl, M.; Roeser, W.; Schwamborn, B., 2007: Betonkorrosion durch Schwefelsäure an Abwasserbauwerken - innovative Schadensdiagnose Beton und Stahlbetonbau issue 10: S. 691-698

Taffe, A.; Pohl, M.; Roeser, W.; Schwamborn, B.; Schoßmann, A., 2009: Varianten bei der Instandsetzung eines Abwasserbauwerks mit Schäden durch Schwefelsäure und moderne Qualitätssicherung: will be published in: Beton und Stahlbetonbau issue 11.