

# AUTOMATIC MONITORING OF CATHODIC PROTECTION FOR CONCRETE STRUCTURES

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## **Abstract**

In combination with repairs of steel corrosion in concrete structures, automatic monitoring of the corrosion activity over a certain period of time both before and after the repair should be applied for evaluating the results obtained and the efficiency of the repair. Sensors for giving information about the environmental parameters such as temperature and moisture content should also be part of the instrumentation.

In the present paper, the results from an automatic monitoring of the cathodic protection (CP) of three concrete decks in a garage building are presented and discussed. During current interruption, information on both applied voltage, current density and reinforcement potentials provided a valuable basis for evaluation of the long-term performance and the efficiency of the CP installation. As a result, a good basis for control and adjustment of the driving force or current, in such a way that a more optimal utilization and increased service life of the CP installation, was also obtained.

## **1. Background**

In order to provide long-term corrosion protection, a cathodic protection (CP) system must operate continuously at a proper operating level, and therefore, a continuous monitoring of the CP system is fundamental in order to obtain a successful prevention of the corrosion. This is the main reason for the monitoring of the CP system with advanced, remote-controlled equipment. Often, supplementary sensors for moisture, temperature and resistance measurements are also implemented in the monitoring unit. This is important in order to better understand and to better interpret the effect of diurnal and seasonal variations on the measured electrochemical parameters.

For steel in soil or seawater, the CP effects are thermodynamic in nature, e.g. the steel potential is brought to a value equal or lower than the equilibrium potential so that the corrosion current density approaches zero. In this case, immunity conditions are reached. The protection of steel in soil or seawater by use of potentials more negative than -850 mV vs. Cu/CuSO<sub>4, sat.</sub> -950 mV in the presence of sulfate reducing bacteria, operates under these conditions [1].

For concrete structures under atmospheric conditions, however, a CP system does not operate under immunity conditions unless the structure is overprotected. For steel embedded in concrete, the CP effects are mainly of kinetic nature, e.g. the driving force is not reduced to zero but so much that the corroding steel is brought to a passive condition. The reduction of potential and the value of the current necessary to obtain passivity are then much smaller than that necessary to reach immunity.

Due to the electrochemical reactions involved ( $O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$ ) during the cathodic process an increased alkalinity on the surface of the embedded steel is also produced. In the concrete the current is transported by ions proportionally to their concentration and mobility. Positive ions move in the same direction as the current, e.g. from the anode to the cathode and the negative ones in the opposite direction. In chloride contaminated concrete, the current circulation also produces a flux of chlorides from the cathodic to the anodic areas. In other electrolytes, the consequences of this electrophoretic migration are often minimized by diffusive and convective phenomena. In concrete, however, migration is not negligible if the CP operates at a sufficiently high current density. In such a case, the current circulation results in a reduced ingress of chlorides into the concrete. In addition, there is a building up of an impervious barrier around the reinforcement [2]. These effects are beneficial because they promote a decrease in the  $[Cl^-]/[OH^-]$  ratio and thus favor the process of passivation.

As soon as the potential is lowered, its beneficial effects are immediately, but it ceases again if the protective current is interrupted. However, the changes in composition at the steel surface produced by the cathodic reaction and by the migration of anionic species inside the concrete do not have immediate consequences, but provide a more persistent protection.

The monitoring of a CP installation is used to document both the thermodynamic, e.g. the lowering of the reinforcement potential and the kinetic effects, e.g. the re-passivation. A typical monitoring unit measures the applied protective current density, the applied voltage between the external anode and the reinforcing steel and the potential of the reinforcement versus stable reference electrodes. Often, environmental parameters like concrete temperature and moisture content (relative humidity) are also included in the measurement setup.

In order to ensure sufficient protection, the application of protection criteria is implemented in the monitoring program. Depending on the measurement results the

applied current density is then adjusted either automatically or according to the judgment of an operator.

The amount of polarization is usually determined by use of a so-called depolarization test as described in the NACE standard RP0290-90 [3]. Most often this is the only criterion applied for CP of concrete structures. However, careful interpretation of the above mentioned measurements can also be used in order to provide a basis for a more complete evaluation of the performance of the CP installation.

When stable reference electrodes are used, a change of the static potential can be used to provide information about how fast the chemical environment around the reinforcing steel is changed due to the applied potential. From the amount of decay and the applied current density, information about the degree of passivation induced by the CP can be obtained by applying the formula for evaluation of the polarization resistance  $R_p$ :

$$R_p = \frac{\Delta E}{i_{app.}} \quad \text{eq. 1}$$

with:  $\Delta E$  ..... 24-hours depolarization value  
 $i_{app.}$  ..... applied protective current density

It should be noted that the electrochemical laws do not allow the application of this equation for higher polarization values than 10 to 20 mV. However, this equation may be used in order to obtain an indication about the change of corrosion activity.

From the measurements of both the  $iR$ -drop between the external anode and the reinforcing steel and the applied current density, the overall concrete resistance can be calculated by use of Ohm's law. This parameter is considered to be very important, since the concrete resistance is normally the limiting factor for the obtained current density at a given voltage [4]. Finally, an integration of the current-time curve delivers the amount of total charge, absorbed which in itself can be used to correlate the measured effects with the administration of the amount of active agent.

## 2. Experimental

In three concrete decks of a 28 year old car park, each being 800 m<sup>2</sup>, a CP system was applied by use of a conductive paint as anode, and the paint was protected by a synthetic wearing layer. Nine MnO<sub>2</sub> reference electrodes [5] were installed in each deck, mostly at anodic sites, in parallel to the reinforcing bars at a distance of approximately 1 cm from themselves. The concrete around the reinforcing bars was not physically disturbed. Sensors for measurements of concrete temperature and relative humidity in drilled holes were also used for supplemental measurements. The rectifiers were operating at a constant voltage level, and two data-loggers with 24 channel capacity were used for monitoring the structure and controlling the rectifiers. Via modem in the loggers, stored

data were downloaded every second week and the data evaluated by use of a worksheet program.

### 3. Results and Discussion

Fig. 1 shows some typical measurements in one of the concrete decks (deck 09), including the development of both relative humidity (RH) and temperature (T) in the concrete as well as applied voltage (U), applied current density ( $i_{app.}$ ) (related to the concrete surface) and the rebar potentials (E).

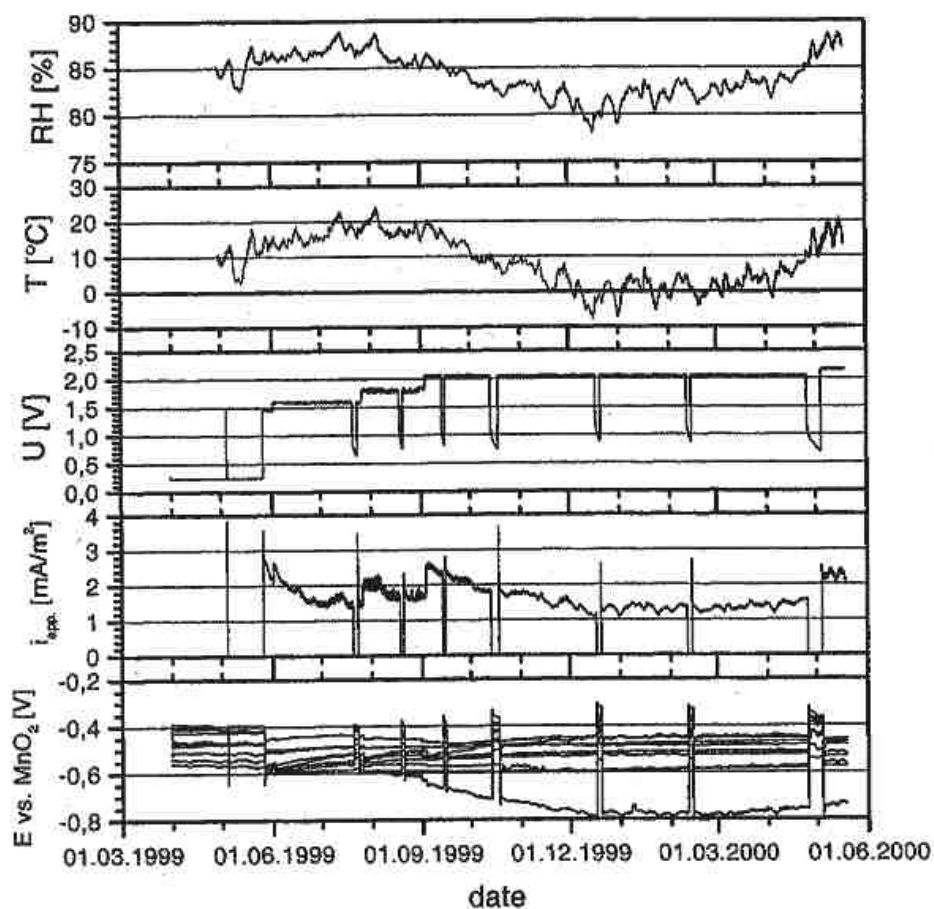


Fig. 1: Typical measurements in one particular concrete deck (measurement interval: 1 hour).

When the protective current was interrupted for decay measurements, both the total absorbed charge and the concrete resistance were determined. The development of these parameters for all three decks together with the concrete temperature is shown in Fig. 2. A value of  $31.6 \text{ kC/m}^2$  for the absorbed charge corresponds to an average protective

current density of  $1 \text{ mA/m}^2$  through one year. The values are related to the concrete surface, and the ratio of rebar surface to the concrete surface was assumed to be approximately 0.7.

In Fig. 3 the values of the applied voltage, the protective current density and the measured and  $iR$ -corrected 24-hour decay values are presented for the various times of current interruption. Due to the low depolarization values at the beginning of the CP-period, the applied voltage was adjusted to higher values. The decay values after a few months of CP reached an average value of close to 100 mV.

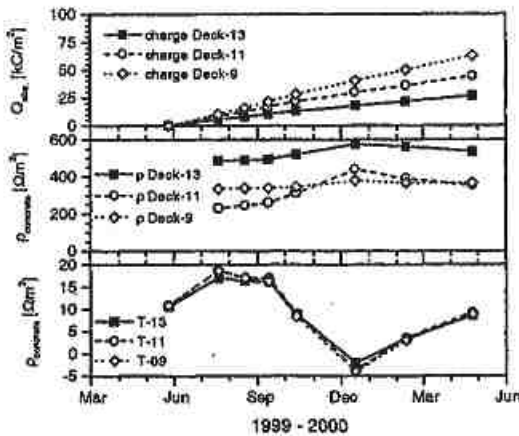


Fig. 2: Total absorbed charge, concrete resistivity and temperature for the three concrete decks at the times of current interruption.

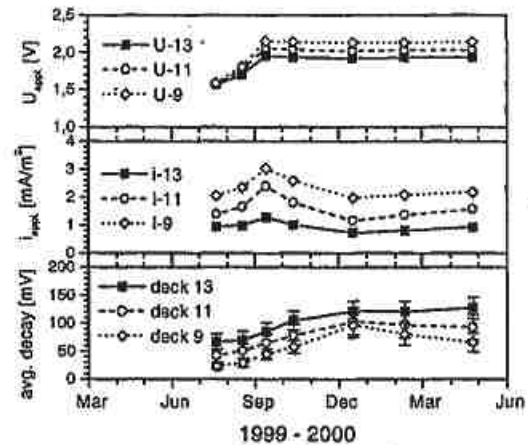


Fig. 3: Applied voltage and current density at the times of current interruption as well as the average of the 24-hour decay values for the three decks.

After one day of current interruption, it was often observed that the reinforcing steel was completely depolarized. Therefore, the static potential measured 24 hours after current interruption was chosen and compared with the static potential measured before the system was energized. It was then observed that the potentials had shifted towards anodic direction. The amount of the potential shift was on the average more than 50 mV after one year of CP (Fig. 4). A positive shift of the static potentials indicate re-passivating effects induced by the CP due to increased alkalinity around the rebars and repulsion of chloride ions from the rebar surface.

By considering the overall corrosion activity in the concrete structure, the same tendency was observed for all the concrete decks. The corrosion current density was calculated by applying eq. 1 for the depolarization measurements and the applied protective current density. The average of the obtained values for each deck was plotted against the time of CP. As shown in Fig. 5, the corrosion activity at the time when the CP was switched off was reduced as a result of the protective system. The overall corrosion current density according to these measurements was reduced by a factor of approximately 5 related to the initial corrosion activity.

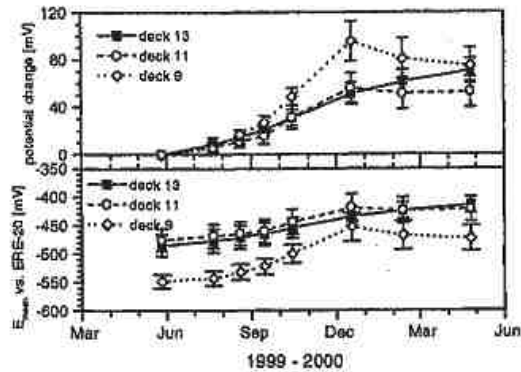


Fig. 4: Amount of the static potential shift for the three decks. Top: relative shift-values, bottom: absolute values.

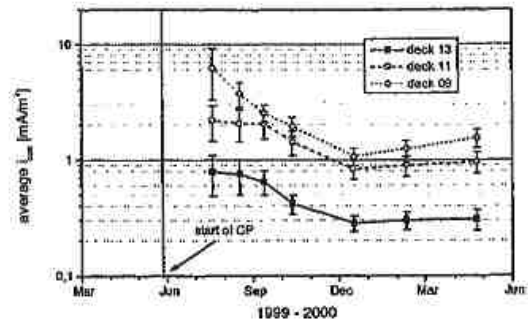


Fig. 5: Change of overall corrosion current density for the three decks with time of cathodic protection.

Both the static potential as well as the corrosion current density showed the same tendency of re-passivation throughout the monitoring period. Comparing the average values of the static potentials with the average values of the corrosion current density gave a relationship as shown in Fig. 6. To a first approximation, the relationship between the corrosion current density the static potentials showed an exponential behavior. The corrosion current density changed by one order of magnitude when the potential was changed by approximately 200 mV.

As already shown, the corrosion activity of the reinforcing steel decreased for increasing amount of absorbed charge. Fig. 7 shows the decrease of the corrosion current density with the amount of protective charge absorbed. In this figure, the values were calculated for standard conditions by converting the protective current density measured at temperature  $T$  in current densities that would be applied at 298 K using the Arrhenius equation:

$$i_{app.}(298K) = i_{app.}(T) \cdot \exp\left[-\frac{E_A}{R} \cdot \left(\frac{1}{T_0} - \frac{1}{T}\right)\right] \quad \text{eq. 2}$$

with:  $E_A$ ..... activation energy for the electrochemical reaction  
 $R$ ..... Gas constant  
 $T$ ..... absolute temperature  
 $T_0 = 298 \text{ K}$

The converted current-time curve was used to calculate the absorbed charge for standard conditions by integration until the time of current interruption.

According to Fig. 7, the corrosion current density decreased with the logarithm of the absorbed protective charge passed through the system. Extrapolation of the measured relationship indicates that after around 500 to 1000  $\text{kC/m}^2$  of charge applied by the

cathodic protection system, the overall corrosion activity was reduced by one order of magnitude. For a moderate current density of around 1.5 to 2 mA/m<sup>2</sup> concrete surface e.g. 2 to 3 mA/m<sup>2</sup> rebar surface, such a reduction of corrosion activity would be expected after 10 years of CP-operation.

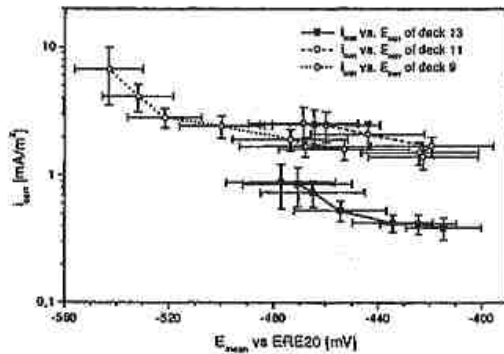


Fig. 6: Relationship between the average of the reinforcement potentials and the overall corrosion current density for the three decks.

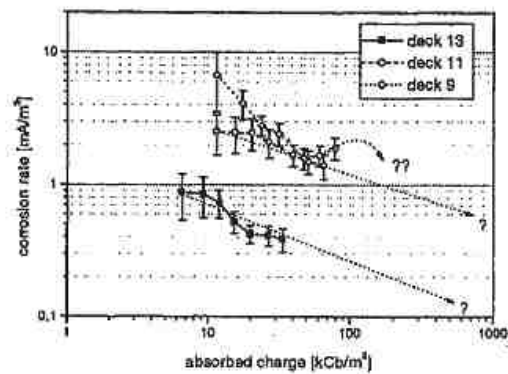


Fig. 7: Expected development of the overall corrosion current density for the three decks with the amount of total absorbed charge (T-corrected).

As clearly demonstrated in the above results, there was a distinct re-passivating effect due to the CP both due to the increased alkalinity and the decreased chloride concentration around the rebar surface. After switching off the CP for current interruption, the oxygen concentration near the rebar surface will increase again. As a result, Fe(OH)<sub>2</sub> will first form as an intermediate stage and then oxidize to magnetite (Fe<sub>2</sub>O<sub>3</sub>). It should be expected, therefore, that after prolonged CP, the layer of magnetite should cover the entire steel surface. Due to the high pH, the surface of the magnetite or hydrated magnetite (Fe(OH)<sub>2</sub>·2FeOOH [6]) will be charged negatively, and this will reduce or hinder a future diffusion of chloride ions towards the inner passive layer [7]. When the re-passivation has reached a sufficiently high degree, the protection of the embedded steel will only need a limited amount of protective current [2].

#### 4. Conclusions

Instead of using the conservative 100-mV criterion only for documentation of the effectiveness of the CP installation, a more complete and thorough evaluation of the measured parameters throughout the monitoring period should be carried out. During current interruption, information on both applied voltage, current density and reinforcement potentials should provide useful indication on the long-term performance and efficiency of the CP installation. As a result, this provides a basis for control and adjustment of the driving voltage or current in such a way that a more optimal utilization and increased service life of the CP installation is obtained. This is particularly important

for CP installations, where a sensitive anode system (conductive synthi paints) at a high current density is applied.

#### 4. Acknowledgment

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#### 5. References

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