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Long-term experience with cathodic protection of reinforced concrete structures

Felix Wenk

Helbling Beratung + Bauplanung AG, Hohlstrasse 614, Zurich, Switzerland
felix.wenk@helbling.ch

Daniel Oberhänsli

Helbling Beratung + Bauplanung AG, Hohlstrasse 614, Zurich, Switzerland
daniel.oberhaensli@helbling.ch

Abstract
The use of the cathodic protection system for degraded reinforced concrete structures allows infrastructures to be repaired without eliminating the concrete contaminated with chloride or the carbonated concrete in the area of the reinforcement. This is particularly interesting when the excessive elimination of concrete resulting from mechanical removal or from high pressure water blasting may endanger the structure. Repair cost, time and noise emissions as well as the limited closing time of the infrastructure restored using the cathodic protection technique are substantially reduced. Compared to conventional repair methods, rebar corrosion is completely stopped on a long-term basis. The service life and durability of the infrastructure is thus improved and surface protection systems such as hydrophobic treatments and coatings can be minimized, or completely avoided. Since 1988, around twenty reinforced concrete structures in Switzerland have been repaired and protected using the cathodic protection method. Corrosion protection of the rebar material is continuously monitored. As a result, it is possible to control and increase the service life of the repaired infrastructure by adjusting the electrical parameters, such as the current appropriately. Rebar depolarisation after switching off the rectifier is an important criterion for corrosion protection. If service life is to be increased, however, experience has indicated that the current density on the rebar and on the anode as well as the off potentials may be important parameters for long-term corrosion control. Furthermore, homogeneous distribution of the current and the distribution of the test coupons within the structure are important parameters for the correct evaluation of corrosion protection. Items of infrastructure, such as bridges, tunnels and parking lots, which have been protected for years in aggressive environments using the cathodic protection system, has enabled us to gain wide experience of the technical benefits offered by this method of corrosion protection.

Keywords: cathodic protection, reinforced concrete

1 Introduction

The use of cathodic corrosion protection (CP) on reinforced concrete structures is particularly meaningful in the case of structures contaminated by chloride. As the use of CP does not usually require the removal and replacement of concrete contaminated with chloride, there is a clear reduction in the following problems in comparison to conventional repair:

- Weakening of the structure, risk of cracks during the repair (Fig. 1)
- Bond problems between old and new concrete (Fig. 2)
- Macro element formation between the reinforcement in old and new concrete (Fig. 3)

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Fig. 1: Support during the repair

Fig 2: Bond problems

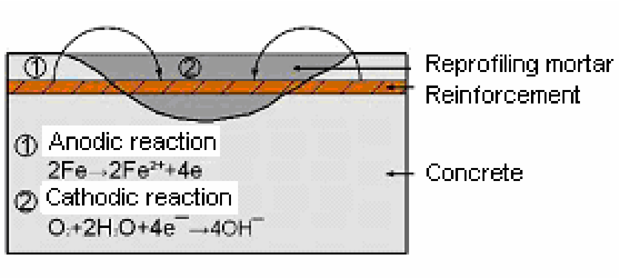

Fig 3: Macro-element

As concrete contaminated by chloride needs not be removed at all and corroding reinforcement rarely needs to be exposed, the flow of forces in the structure is barely affected. Costly and time-consuming scaffolding structures are thus not usually required. Chlorides in the concrete are, however, removed slowly from the reinforcement and the concrete is realkalised in the area of the reinforcement. The passive layer on the surface of the steel is restored. As a result of these processes, corrosion is not only temporarily reduced as is the case with other methods of repair, but stopped permanently.

A further benefit of CP is that the condition of the structure can easily be measured over its entire surface at any time by means of measuring devices integrated into the system without any need to carry out new potential mapping surveys or chloride analyses. When the CP process is used, there is also a reduction in noise emissions due to the smaller amount of concrete that has to be removed. Restrictions in use and construction times are lower than is the case when conventional methods of repair are employed. Due to the long service life achieved by the use of CP repair, the periodic measures required by other methods of protection and repair (e.g. the renewal of surface protection) can be dispensed with. In the case of traffic structures, in particular, this results in a reduction in off-periods.

Where construction costs are concerned, CP is already worthwhile when the depth of removal is more than two to three centimetres. Taking the service life of the repair into account, CP is at least equal if not even substantially less expensive. Operating costs are also relatively low. The annual cost of electrical energy amounts to less than € 0.05/m^2. To ensure that the protective process is effective, it is essential that the power sources operate without any major interruptions. Monthly checks on this can, however, be carried out by the owner's own staff. At an interval of 1 to 5 years, potential and depolarisation measurements have to be carried out by a specialist company. Thanks to the progress in communication technology, this maintenance and checking on correct operation as well as the regulation of the system can be handled conveniently and fairly inexpensively by means of a remote system.

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2 Applications

In Switzerland, over 20 structures have been repaired using CP in the last twenty years by the authors’ company. The most important structures are listed in the table below with the relevant CP-related data.

Table 1: CP projects in Switzerland

 *Fig 4: Bridge in Rodi-Fiesso*	**Structure:** Bridge in Rodi-Fiesso **Commissioning:** 1988 **Under protection:** Abutments and supports **Surface area protected:** 287 m2 **Number of supply zones:** 7 **Voltage supply:** 3.8 V **Average protective current density:** 11 mA/m2 concrete **Average anode current density:** 44 mA/m2 **Reference electrodes:** 7 holes for CSE **Test coupons:** 7 **Power source:** 12 V/8.3 A (output regulated)
 *Fig 5: Segelhof in Dättwil*	**Structure:** Segelhof office building in Dättwil **Commissioning:** 1991 **Under protection:** Façade supports **Surface area protected:** 185 m2 **Number of supply zones:** 4 **Voltage supply:** 2.4 V **Average protective current density:** 6 mA/m2 concrete **Average anode current density:** 23 mA/m2 **Reference electrodes:** None **Test coupons:** None **Power source:** 48 V/3 A (output regulated)
 *Fig 6: Römerstrasse covered parking lot*	**Structure:** Römerstrasse covered parking lot in Baden **Commissioning:** 1991 **Under protection:** Supports **Surface area protected:** 237 m2 **Number of supply zones:** 4 **Voltage supply:** 2.2 – 3.1 V **Average protective current density:** 2 mA/m2 concrete **Average anode current density:** 8 mA/m2 **Reference electrodes:** None **Test coupons:** None **Power sources:** 12 V/10 A (output regulated)

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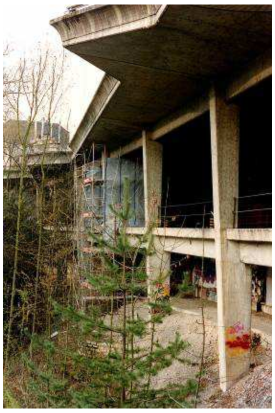
 *Fig 7: Office building in Zurich*	**Structure:** Hohlstrasse office building in Zurich **Cause of damage:** Chlorides from mineral wood flooring **Commissioning:** 1992 **Under protection:** Ceiling structure **Surface area protected:** 399 m2 **Number of supply zones:** 2 **Voltage supply:** 2.8 V **Average protective current density:** 2 mA/m2 concrete **Average anode current density:** 9 mA/m2 **Reference electrodes:** 4 holes for CSE **Test coupons:** None **Power source:** 24 V/25 A (output regulated)
 *Fig 8: Supports at the station square*	**Structure:** Station square in Baden **Commissioning:** 1992 **Under protection:** Supports **Surface area protected:** 97 m2 **Number of supply zones:** 3 **Voltage supply:** 3.3 V **Average protective current density:** 8 mA/m2 concrete **Average anode current density:** 30 mA/m2 **Reference electrodes:** 6 holes for CSE **Test coupons:** None **Power source:** 12 V/10 A (output regulated)
 *Fig 9: Intschi bridge near Amsteg*	**Structure:** Intschi bridge near Amsteg **Commissioning:** 1993 (not in use since 1999, trial) **Under protection:** Support **Surface area protected:** 180 m2 **Number of supply zones:** 3 **Voltage supply:** 1.2 V **Average protective current density:** 2 mA/m2 concrete **Average anode current density:** 7 mA/m2 **Reference electrodes:** 10 (Ag/AgCl) **Macrocells:** 6

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 *Fig 10: Saline bath in Regensdorf*	**Structure:** Fitness park in Regensdorf **Commissioning:** 1993 (conversion in 2004) **Under protection:** Supports in the saline bath **Surface area protected:** 6 m2 **Number of supply zones:** 1 **Voltage supply:** 1.6 V **Average protective current density:** 3 mA/m2 concrete **Average anode current density:** 13 mA/m2 **Reference electrodes:** None **Test coupons:** None
 *Fig 11: Eich tunnel near Eich*	**Structure:** Eich tunnel near Eich **Commissioning:** 1994 **Under protection:** Tunnel walls **Surface area protected:** 2,500 m2 **Number of supply zones:** 12 **Voltage supply:** 1.1 to 1.7 V **Average protective current density:** 3 mA/m2 concrete **Average anode current density:** 12 mA/m2 **Reference electrodes:** 24 (Ag/AgCl) **Test coupons:** 12 **Power sources:** 12 V/10 A (output regulated)
 *Fig 12: Gotthard tunnel entrance*	**Structure:** Gotthard tunnel entrance near Göschenen **Commissioning:** 1995 **Under protection:** Tunnel walls, supports **Surface area protected:** 2,860 m2 **Number of supply zones:** 8 **Voltage supply:** 1.1 to 2.9 V **Average protective current density:** 3 mA/m2 concrete **Average anode current density:** 13 mA/m2 **Reference electrodes:** 50 (Ag/AgCl) **Test coupons:** 28 **Power sources:** 12 V/10A (voltage regulated)

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 *Fig 13: Parking garage in Baden*	**Structure:** Römerstrasse covered parking lot in Baden **Commissioning:** 1995 **Under protection:** Parking deck **Surface area protected:** 903 m2 **Number of supply zones:** 7 **Voltage supply:** 1.1 V **Average protective current density:** 4 mA/m2 concrete **Average anode current density:** 16 mA/m2 **Reference electrodes:** 7 (Ag/AgCl) **Test coupons:** 7 **Power sources:** 12 V/10 A (output regulated)
 *Fig 14: Office building in Zurich*	**Structure:** Hohlstrasse office building in Zurich **Cause of damage:** Chlorides from mineral wood flooring **Commissioning:** 1996 **Under protection:** Ceiling structure **Surface area protected:** 380 m2 **Number of supply zones:** 2 **Voltage supply:** 3.3 V **Average protective current density:** 1 mA/m2 concrete **Average anode current density:** 3 mA/m2 **Reference electrodes:** 4 (Ag/AgCl) **Test coupons:** 4 **Power source:** 12 V/10 A (output regulated)
 *Fig 15: A5 highway tunnel*	**Structure:** Highway tunnel near Auvernier **Commissioning:** 1997 **Under protection:** Tunnel walls **Surface area protected:** 2,500 m2 **Number of supply zones:** 12 **Voltage supply:** 2.5 to 3.5 V **Average protective current density:** 9 mA/m2 concrete **Average anode current density:** 35 mA/m2 **Reference electrodes:** 25 **Test coupons:** 15 **Power sources:** 12 V/10 A (voltage regulated)

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 *Fig 16: Drinking water containerin Arnen*	**Structure:** Drinking water container in Arnen near Kerzers **Commissioning:** 1998 **Under protection:** Ceiling **Surface area protected:** 77 m2 **Number of supply zones:** 2 **Voltage supply:** 1.9 V **Average protective current density:** 9 mA/m2 concrete **Average anode current density:** 36 mA/m2 **Reference electrodes:** 4 (Ag/AgCl) **Test coupons:** 4 **Power sources:** 12 V/2 A (potentiostatically regulated)
 *Fig 17: Siggern bridge near Attiswil*	**Structure:** Siggern bridge near Attiswil **Commissioning:** 2003 **Under protection:** Abutments, truss heads and lane intersection **Surface area protected:** 280 m2 **Number of supply zones:** 10 **Voltage supply:** 1.4 V **Average protective current density:** 5 mA/m2 concrete **Average anode current density:** 21 mA/m2 **Reference electrodes:** 8 (titanium) **Test coupons:** 8 **Power source:** 12 V/2 A (potentiostatically regulated)
 *Fig 18: Rheumatism clinic in Zurzach*	**Structure:** Rheumatism clinic in Zurzach **Commissioning:** 2003 **Under protection:** Ceiling of the heat storage basin **Surface area protected:** 150 m2 **Number of supply zones:** 1 **Voltage supply:** 1.4 V **Average protective current density:** 12 mA/m2 concrete **Average anode current density:** 48 mA/m2 **Reference electrodes:** 2 (titanium) **Test coupons:** 2 **Power source:** 12 V/2 A (output regulated)

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Fig 19: Palestra Polisportiva</td>
<td>Structure: Palestra Polisportiva in Lugano
Commissioning: 2004
Under protection: Hurdis ceiling
Surface area protected: 175 m2
Number of supply zones: 3
Voltage supply: 2.5 V
Average protective current density: 3 mA/m2 concrete
Average anode current density: approx. 25 mA/m2
Reference electrodes: 6 (titanium)
Test coupons: 6
Power source: 12 V/10 A (output regulated)</td>
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<td>
Fig 20: Bridge over the river Emme near Aefligen</td>
<td>Structure: Bridge over the river Emme near Aefligen
Commissioning: 2006
Under protection: Truss heads, lane intersections and kerbstones
Surface area protected: 122 m2
Number of supply zones: 8
Voltage supply: 1.4 to 2.0 V
Average protective current density: 10 mA/m2 concrete
Average anode current density: 50 mA/m2
Reference electrodes: 8 (titanium)
Test coupons: 10
Power source: 12 V/2 A (potentiostatically regulated)</td>
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<td>
Fig 21: Apartment building in Adliswil</td>
<td>Structure: Apartment building in Adliswil
Commissioning: 2007 (currently being processed)
Under protection: Covered passages
Surface area protected: 60 m2
Number of supply zones: 3
Reference electrodes: 3 (titanium)
Test coupons: 3
Power source: 10 V/10 A (voltage regulated)</td>
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<td>
Fig 22: Airport parking garage</td>
<td>Structure: Parking garage P6 at Zurich Airport
Installation: 2007 (currently being processed)
Under protection: Parking deck
Surface area protected: 770 m2
Number of supply zones: 3
Reference electrodes: 6 (titanium)
Test coupons: 6</td>
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Alongside classic infrastructures such as bridges, tunnels and parking garages, other structures contaminated by chloride such as swimming pools and saline baths as well as chemical premises have also been repaired using CP. Following a period of stagnation between 1995 and 2002, i.e. during the marked spread of conventional methods of repair, there has been renewed interest in CP in recent years. Major potential has been identified in parking garages, in particular. Conventional maintenance work carried out using water under high-pressure results in serious restrictions where building usage is concerned due to the large amount of water and noise emissions involved. Together with lengthy construction times, this can lead to a significant loss of earnings.

3 Experience using cathodic corrosion protection

Experience gained over the last 20 years is given below.

Power sources

Output regulated rectifiers were mainly used in connection with the structures treated. Occasional use was also made of voltage or potentiostatically regulated power sources. No serious problems have been encountered with all pieces of equipment. If the resistance in the concrete increases due to its age or due to the season, the protective current falls correspondingly. If several areas are supplied by one rectifier, the difference in protective current requirements must be regulated by additional, adjustable resistances on the anode side. Current-regulated rectifiers are not recommended as they do not take into account the differences in protective current requirements caused by temperature and resistance. Potential-regulated power sources regulate the potential in respect of a reference electrode. Regulation is inadequate when the reference electrode is faulty or its surroundings are not representative of the entire area being supplied.
The location of the power source is decisive for the length of the cables. Cable costs can be disproportionately high in the case of large structures with a large number of areas being supplied. It may be better in such cases to install the power sources including the measuring equipment decentrally for the zones to be supplied and to arrange for the controlling and monitoring system to be remotely controlled.

Anodes

Following an unsuccessful attempt with a Ferex anode at it was called at the end of the 1980s, only anodes made of oxide-activated titanium were used. Experience gained up to now with these is basically good. Installing the mesh is, however, very time-consuming and has to be done with care as the edges are very sensitive to touch. Together with the above-mentioned sensitivity to touch, the flexural stiffness and the slight curve of the mesh lead to the mesh having to be attached to the concrete subsurface with a fairly high number of plastic fasteners

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(approx. 10 to 20 pcs per m2). The occasional undulations of the mesh also mean that the layer of mortar in which it is embedded has to have a fairly high thickness of between 15 and 20 mm. Mesh that has been rolled flat is an improvement as it allows the number of fasteners and the thickness of the layer to be reduced. Material costs for the anode mesh account for up to 50% of the entire cost of an installed CP system (excluding any preparation of the concrete surface and the embedding mortar). For the competitiveness of CP compared with conventional repair methods, it would also be a major benefit if anodes were cheaper.

In contrast to other mesh anodes, there are no problems with the supply points on titanium mesh. These are usually spotwelded to the mesh using titanium strips and guarantee a controlled and lasting supply of current. The criteria of redundance, voltage drop and possibly efficiency when there is any fault location are decisive for the number of supply points. At least two supply points should be carried out per supply zone.

The checks in respect of any electrical short circuits between anode and cathode (=reinforcement) are highly decisive for the successful implementation of a CP system. Prior to the application of the mesh, the concrete surface must be examined for potential contact points at least visually or even better using a spark-testing unit. The latter must be totaly eliminated. For example, the corresponding electrically conductive parts can be removed or a highly resistive coating applied to the spot. If necessary, the anode mesh can also be cut out locally. Before the mortar is applied, it is important to ensure again that there is no short circuit by taking resistance and potential measurements between anode and cathode. The subsequent location and remedying of short circuits is very time-consuming. Short circuits can also arise later on. In the past 20 years, four cases have occurred. In one tunnel, plugs were put into the walls years after the commissioning of the CP system. One plug then touched both the anode as well as the reinforcement. In another case, an attachment element of a subsequently installed suspended ceiling triggered off a short circuit. Alongside potential and resistance measurements, infrared photographs can also be used to locate short-circuit spots.

<u>Mortar/concrete</u>

EN 12696 [1] and Swiss guideline C7 [2] mainly address the issue of the mortar and give less consideration to the existing concrete. In practice, however, it is mainly the electrical resistance of the existing concrete that is responsible for the supply voltage. Normally, the titanium mesh is attached directly to the concrete surface. Consequently, there is usually around 5 mm of mortar and approx. 2 - 4 cm of existing concrete between the anode and the reinforcement. The specific resistances calculated in practice from supply voltage and protective current usually amount to between 15 to 25 kΩm, which is clearly above the permissible values for the mortar ([1]: max. 1 kΩm, [2]: max. 0.5 kΩm after 56-days of storage). Despite these high values, the cathodic corrosion protection applied to the corresponding structures functions perfectly.

In the evaluation of the mortar, cementitious mortars with low plasticiser additive were preferred in each case. However, investigation have shown that standard plasticised cementitious mortars are also no problem where electrical resistance is concerned [3]. It was also noted that the ranking of resistances measured initially is often not decisive (see Diagram 1).

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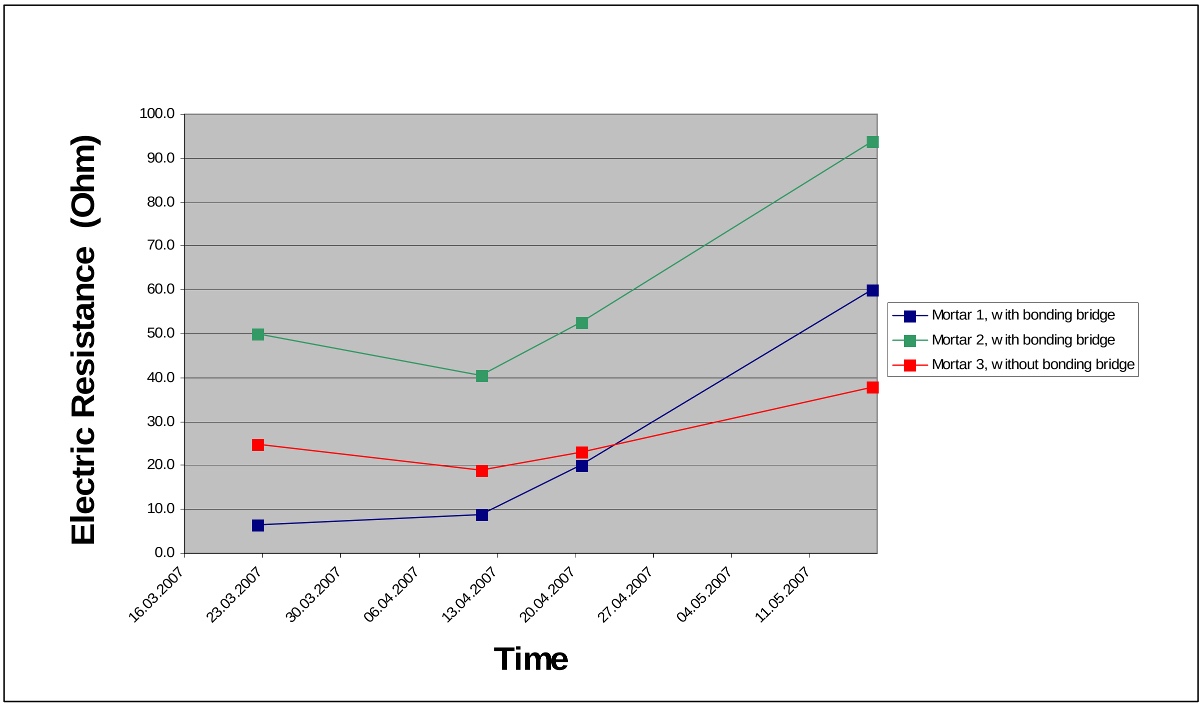
Diagram 1: Development of overall electrical resistance between anode and cathode (in situ)



On some structures, the recommended maximum off-potential of the anode (+1.0 V CSE) was exceeded. The localised acidification round the anode in the mortar caused no damage there even after 10 years, all the more so since the average anode current densities never amounted to more than approx. 50 mA/m2.

<u>Reference electrodes</u>

So far, the reference electrodes permanently installed have been silver/silver chloride electrodes or electrodes made of oxide-activated titanium. On several occasions, holes have also been drilled into the structure to the depth of the reinforcement layer in order to measure the potentials or the depolarisation using mobile copper/copper sulphate electrodes. Basically, the reference electrodes used up to now have not presented any substantial problems. Even after more than 10 years, permanently embedded reference electrodes continue to perform their intended function. While the electrodes made of oxide-activated titanium do not show a constant potential, they are, however, less expensive and easy to use. However, they meet requirements as the relative potential (drop in potential, rise in potential) is more important in the cathodic protection of reinforced concrete structures than the absolute potential. Some problems were noted when measuring depolarisation with mobile copper/copper sulphat electrodes in existing holes. It appears that drying out or minor displacements caused by vibrations while taking measurements can lead to changes in potential that cause problems (see Diagram 2).

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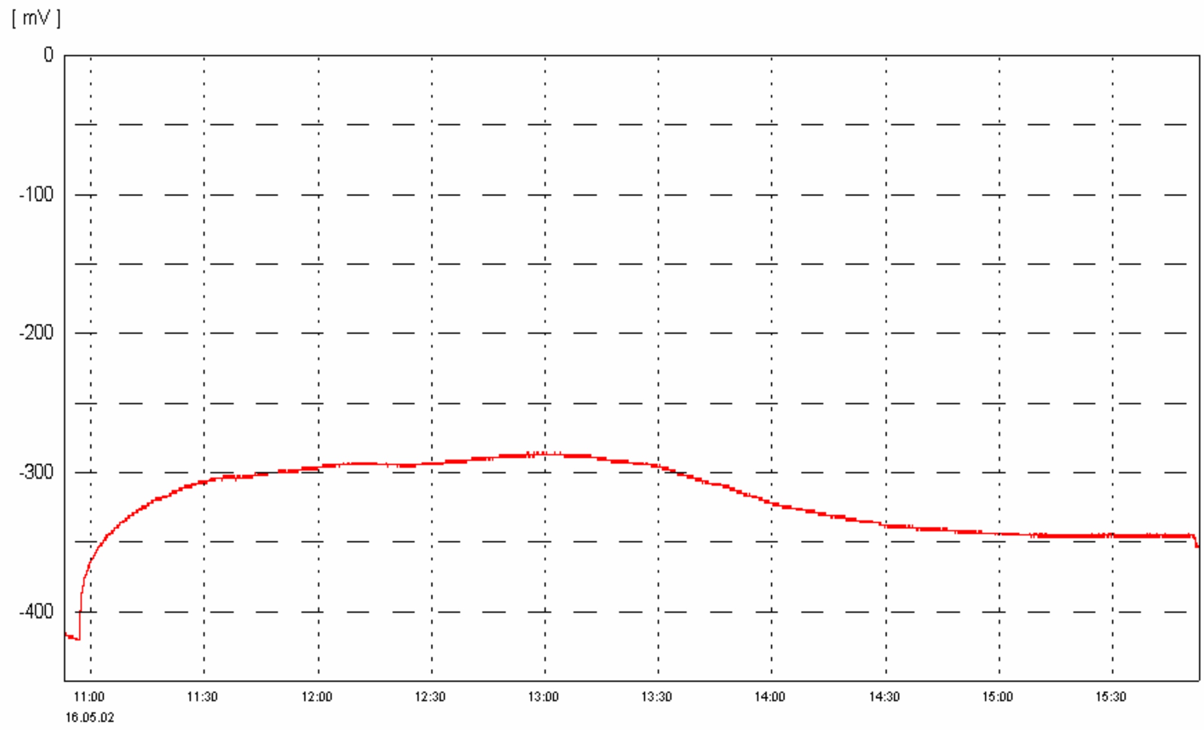
Diagram 2: Measurement of depolarisation with mobile copper/copper sulphate electrodes



The largest possible number of reference electrodes is desirable for statistical reasons. The cost of the delivery and installation of reference electrodes is also modest (approx. € 170). However, the cost of the cabling and monitoring is much greater. [1] states a minimum number of 2 units per supply zone. The location of the reference electrodes is best determined based on a potential mapping survey, which will determine the areas with high protective current requirements (high humidity, high chloride content) and with low protective current requirements (low humidity, low chloride content).

Test coupons

For the measurement of local current densities, test coupons with defined steel surfaces were installed in most structures. They were offset at the level of the front or the rear reinforcement layer. As an alternative, existing reinforcement components were also separated and connected to the system. The benefit of this alternative is that the enveloping concrete is established and thus representative of the reinforcement to be protected. In the case of new test coupons, the reprofiling mortar can seriously distort local current densities. Among other things, the reasons for this are to be found in the initially high humidity of the mortar or in any existing hollow areas. Measurements show that local current densities can be more than 10 times greater or smaller than average current densities. As time goes by, however, experience shows that these differences decline. They also decline with the distance to the anode. However, this means that hydrogen is formed locally on the reinforcement and leads to acidification near the anode despite a fairly low average level of protective current. The former must be taken into account particularly with structures containing prestressed steel.
The rear reinforcement is also protected by the conductive connection. The current densities measured on the test coupons clearly show the influence of the wall thicknesses. On a 40 cm thick concrete wall the current density on test coupons at the level of the rear reinforcement amounts to approx. 1 - 15% of that of the front test coupons or approx. 10 – 20 % of the average current density. On a ceiling that is around 20 cm thick, the current density on a specially prepared steel measuring probe fixed to the undersurface of the ceiling amounts to approx. 50% of that of the front probe. A temporal increase in current density was not

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observed. Additional information is given in the bibliography [2], [4]. The current densities that reach the rear reinforcement are difficult to calculate as they depend on different factors, such as the thickness of the wall, the resistance of the concrete, reinforcement content at the front and at the back. If complete protection is also required for the rear reinforcement, an infeed test on a representative area can provide more accurate information on this.
Concerning their number, their location and their costs, the test coupons are to be treated like the reference electrodes.

Protection criteria

The following protection criteria are given in the literature [5]:

- -720 mV potential level ref. Ag/AgCl
- 300 mV polarization shift
- 100 mV/150 mV decay shift

The -720 mV – criterion can only be achieved with very high current densities on most structures, which leads to the local development of hydrogen on the surface of the reinforcement and to acidification on the anode. The criterion can best be used on very damp structures. It is not used for the structures mentioned in chapter 2.
The 300 mV polarization shift criterion is achieved to a better degree on most structures. However, the protective current density is much higher than the one required for the third protection criterion, this being the rise in potential criterion. Instead of a rise in potential of approx. 100 mV, more than 200 mV was frequently measured after four hours.
The most feasible protection criterion at present is the 100 mV or 150 mV rise in potential criterion. It is/was used on all the structures described in chapter 2. It can also be maintained on most structures. However, there are some structures on which the criterion is not fulfilled everywhere. An increase in protective current is not always rewarded with the desired success. Often, smaller depolarisation values have even been measured at higher protective current densities. Depolarisation depends on different factors such as temperature, the dampness of the concrete, equalising currents and, in particular, on the post-diffusion of oxygen [6]. These must be taken into account when assessing the rise in potential measured. High temperatures usually lead to low depolarisation values. The same applies to the slower post-diffusion of oxygen, such as, for example, due to the increasing period of protection.

4 Outlook

Based on 20 years' experience with more than 20 protected structures, it can be stated that cathodic corrosion protection applied to steel-reinforced structures is highly suitable as a lasting method of repair. Particularly, in the case of chloride-contaminated steel-reinforced concrete structures, it is a competitive method of repair in every respect, which has clear benefits in different points compared with conventional processes. In theoretical respect, the subject of protection criteria, in particular, must be gone into in greater depth. Where technical equipment is concerned, there is still a need for optimisation in the application of the anode mesh. The ideal solution would, of course, be an inexpensive anode that could be sprayed on or rolled up and which would only degrade over a period of 30 to 50 years to the extent that the system's ability to function remained unaffected. Efficient and economic remote control systems with the corresponding visualisation systems can also greatly simplify the functional checks and evaluations that are fairly complex due to the large number of data to be acquired and can also provide rapid indications of the effect of any subsequent regulation of the protective current. In material respect, it is to be hoped for the spread of CP that the prices of anode mesh fall and that more companies will take an interest in the implementation of CP systems and address its possibilities.

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