

## **Cathodic Corrosion Protection of Steel Reinforced Concrete Structures with a New Conductive Composite Paint System**

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### **Abstract**

Corrosion of steel in concrete is one of the critical problems in civil engineering with regard to the durability of reinforced concrete structures. Cathodic protection (CP) of the steel rebars in concrete structures evolved during the past 25 years as a reliable method to extend the lifetime of reinforced concrete structures. During the CP operation, proportional to the applied protection current, acids are generated at the anode/concrete interface. This effect limits durability and performance of various CP-systems. This contribution describes a newly developed conductive composite paint for use as anode material, characterized by high durability at high current densities and easy applicability, and its practical application for the corrosion protection of a parking deck in Oslo.

**Keywords:** corrosion, cathodic protection

### ***Kathodischer Korrosionsschutz für Stahlbetontragwerke unter Verwendung eines neuen leitfähigen Anstrichsystems***

### **Zusammenfassung**

*Korrosion von Stahl in Beton ist eines der wichtigsten Probleme bezüglich der Dauerhaftigkeit armerter Betonbauten und Tragwerke. Kathodischer Korrosionsschutz (KKS) von Bewehrungsstahl in Betonbauwerken hat sich im Laufe der letzten 25 Jahre als eine verlässliche Methode zur Verlängerung der Nutzungsdauer*

*von Stahlbetonbauwerken etabliert. An der Grenzfläche Anode/Beton bilden sich während des Betriebes des KKS proportional zur Schutzstromdichte Säuren, die die Dauerhaftigkeit und die Effizienz der verschiedenen KKS – Systeme begrenzen. In diesem Beitrag wird ein neuer elektrisch leitfähiger Verbund-Anstrich als Anodenmaterial für den KKS vorgestellt, das durch hohe Dauerhaftigkeit bei hohen Schutzstromdichten und leichte Verarbeitbarkeit gekennzeichnet ist. Die praktische Anwendung für den Korrosionsschutz einer Parkgarage in Oslo wird beschrieben.*

**Stichwörter:** Korrosion, kathodischer Korrosionsschutz



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## 1 Causes for the Corrosion of Steel in Concrete

Reinforcing steel in concrete is usually passivated by the alkaline concrete environment and therefore protected from corrosion. Environmental influences, however, may remove the passivating layer on the steel surface and may induce corrosion and serious damage to civil structures made from reinforced concrete. The most common causes for the depassivation and corrosion of steel in concrete are:

- Carbonation of the concrete overlay: The pH of the concrete in which the rebars are embedded is lowered by taking up atmospheric carbon dioxide, if the pH falls below 11, corrosion may start.
- Chloride ingress into the concrete overlay e.g. from de-icing salts or sea water exposure: The ingress of chlorides may result from direct contact with de-icing salts e.g. on road and highway pavements, on bridge-decks, balconies or through aerosols from roads and bridge decks on nearby civil structures.

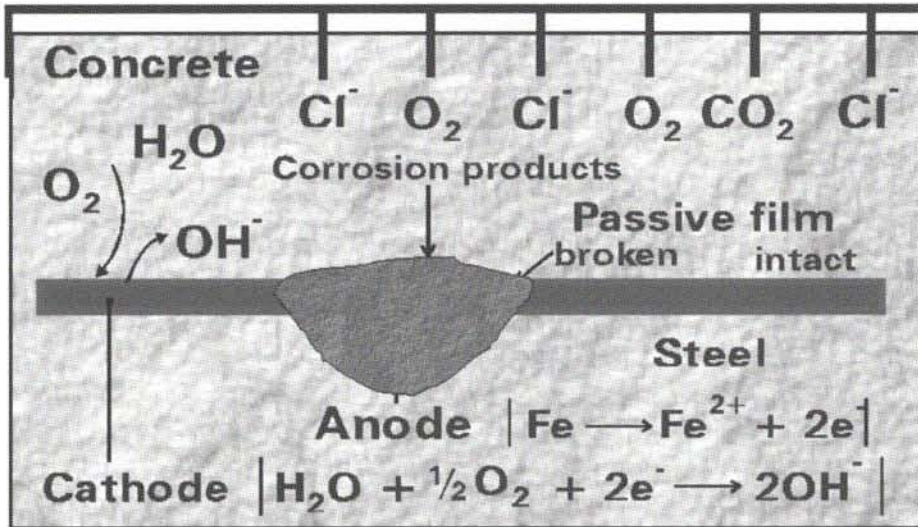
Due to the depassivation of the reinforcing steel a local corrosion cell is formed that functions like a battery (Fig. 1). The depassivated local areas act as anodes and the still passive areas as cathodes. On the anodic sites the iron is oxidised to iron oxides (rust), on the cathodic sites oxygen is reduced to hydroxyl ions. Carbonation induces a uniform corrosion on the steel surface and is a rather slow process, chlorides induce pitting-corrosion that may lead to a rapid local deterioration of the rebars and loss of their integrity. Especially the corrosion induced by carbonation leads to the formation of voluminous corrosion products that cause spalling and cracking of the concrete overlay. Both, the velocity of carbonation and the pace of chloride ingress into the concrete overlay depend mainly on the permeability of the concrete and therefore on the quality of the concrete.

The permeability of the concrete overlay is mainly a function of the porosity of the concrete and hence a function of the water/cement ratio but also a function of the quality of the concrete surface (cement-skin) and therefore of the quality of curing. Environmental factors like humidity, wet/dry cycles, crack-formation by frost damages etc. play also an important role. In some areas the use of chloride contaminated aggregates for concreting in the past poses high risk for corrosion damages to civil structures.

## 2 Repair and Restoration of Concrete Structures Damaged by Rebar Corrosion

Corrosion of steel in concrete is one of the most serious problems with regard to the durability and lifetime assessment of reinforced concrete structures. Enormous resources of capital are and will have to be invested for the repair and restoration of corroding reinforced concrete structures.

## Environment



**Figure 1:** Schematic representation of a corrosion cell [1].

The technical committee 124-SRC "Strategies for concrete structures damaged by reinforcement corrosion" of RILEM (International Union of Testing and Research Laboratories for Materials and Structures) summarized the relevant methods and strategies for the repair and restoration of concrete structures damaged by rebar corrosion in the RILEM-draft paper of 1994 [2].

The three most important repair methods are listed below:

- (i) Repassivation with alkaline mortar or concrete: In the case of chloride induced corrosion, the chloride contaminated concrete has to be removed in all areas in which the critical chloride content has reached the reinforcement independent of the degree of corrosion of the reinforcement. The degree of concrete removal must be sufficient to ensure that a critical chloride level (0.4 - 0.5%) may not reach the reinforcement during the remaining period of service. High-pressure water jetting is required to remove rust and chloride from corrosion pits on the reinforcement. Then an overall alkaline mortar or concrete layer is applied. A chloride impermeable coating on the concrete surface is required to avoid further harmful chloride penetration if further exposure to chloride cannot be prevented. Similar but less stringent requirements have to be met for corrosion induced by carbonation.

- (ii) Corrosion protection by limitation of the moisture content of the concrete: Although there are no long term test results under field conditions, laboratory results have been encouraging: corrosion rates of steel in carbonated concrete are very low if water saturation is excluded. This can be achieved by appropriate surface treatments. Depending on the criticality of the structure, the efficiency of the measure has to be checked either visually or by monitoring with embedded sensors. Monitoring with sensors is absolutely required if corrosion is induced by chlorides.
- (iii) Control of the electrolytic processes by cathodic corrosion protection: The main aim of cathodic protection is to shift the potential difference between the steel and the pore solution towards more negative values, where the corrosion rate is decreased to an insignificant level by applying electric current from an external source. This shift has to be maintained over the remaining lifetime of the structure.

Strategy (i) necessitates the removal and restoration of all concrete parts that are prone to induce further corrosion during the remaining period of use. If done only partially or improperly, local corrosion elements may be created that may even worsen the original situation. Therefore, prior to repair, extensive measurements of chloride penetration and carbonation depth profiles as well as potential mapping are required. Strategy (i) allows a durable restoration of concrete structures damaged by rebar corrosion but requires a considerable amount of time, work and high capital investment.

Strategy (ii) is only advisable for the restoration concrete structures with chloride contamination below the critical chloride level and if the ingress of humidity may be prevented reliably. Damage to the impermeable coating by cracks in the concrete surface or by mechanical impact may induce increased local corrosion. Frequent monitoring is required.

Strategy (iii) is becoming an important, widely accepted and reliable method for fighting reinforcement corrosion with a positive record going back for decades in the USA and Great Britain [3-6]. Cathodic protection (CP) is being applied successfully more recently in Italy [7, 9, 10], in the Netherlands [11] and in Scandinavia. CP has also been applied to new structures in Italy [8, 9] and a jetty deck in the U.K. [2]. An advantage of CP is that removal of chloride contaminated but structurally sound concrete is not necessary. CP has to be applied over the remaining lifetime of the structure, however, there are strong indications that CP applied over longer periods induces a physico-chemical repassivation of the rebars [12]. CP is described in more detail in the next chapter.

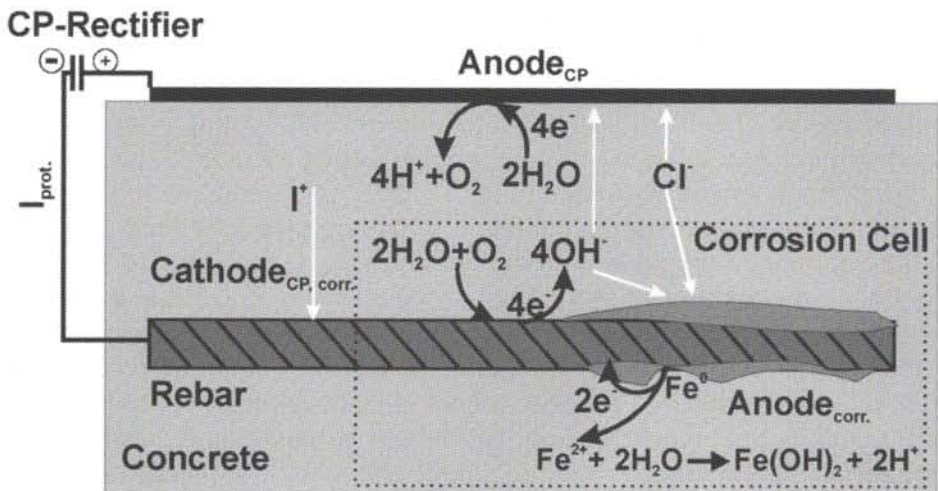


### 3 Cathodic Protection (CP) of Concrete Structures

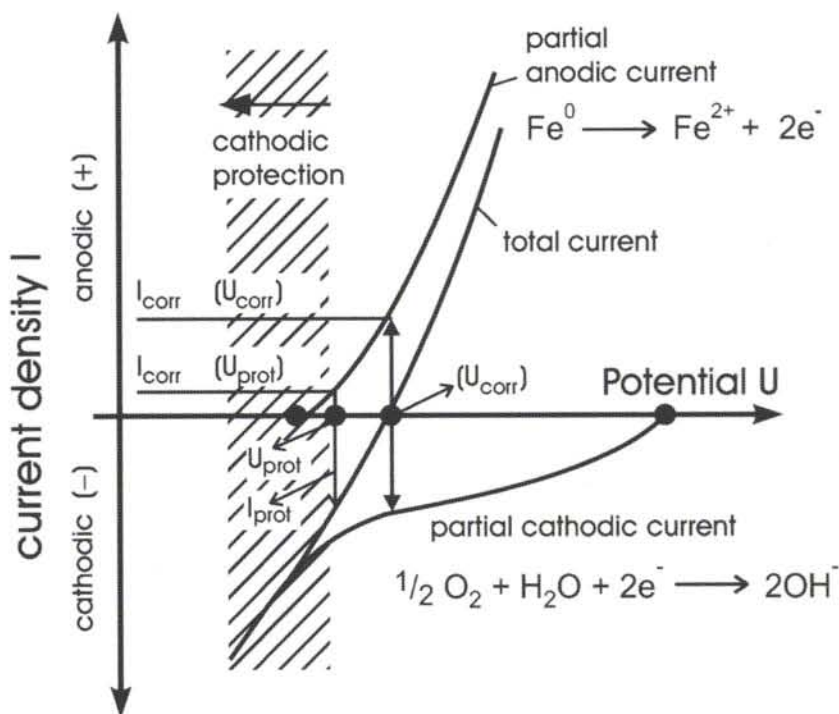
The principle of CP of steel reinforcement in concrete against corrosion is schematically shown in Fig. 2: Reinforcement corrosion occurs due to the formation of a corrosion cell on the rebar surface. On the anodic site of the corrosion cell, simultaneously with the formation of rust ( $\text{Fe}(\text{OH})_2$ ) electrons are injected into the rebar and conducted towards the cathodic sites where these electrons are used to reduce oxygen dissolved in the pore water. CP may be visualized in a very pictorial manner as replacing the anodic sites of the corrosion cells on the rebar surface by an external anode, e.g. placed on the concrete surface (Fig. 2). By supplying external current (protection current,  $I_{\text{prot}}$ ) from the rectifier to the external anode and the rebars, the anodic sites on the rebar surface will become smaller, if sufficient protection current is supplied, the anodic corrosion sites will disappear and no further corrosion will be possible to occur.

Instead of producing corrosion products (rust) on the rebar surface, oxygen will be produced on the external anode (anode<sub>CP</sub>)/concrete interface. If the pH at the external anode/concrete surface is sufficiently lowered due to the acid ( $\text{H}^+$ ) produced at the anode also chlorine may be generated.

In a less pictorial but more accurate technical definition cathodic corrosion protection of steel in concrete is achieved by reducing the corrosion rate (proportional to the corrosion current  $I_{\text{corr}}$ ) by shifting the corrosion potentials of the rebars



**Figure 2:** Schematic presentation of the principle of active CP of reinforcing steel in concrete. Black arrows indicate electrochemical reactions on the anode and cathode surface, white arrows electrolytic currents (electromigration of ions,  $\text{I}^+$ :  $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{Ca}^{2+}$ ).



**Figure 3:** Dependence of the anodic, cathodic partial currents and the total current on the rebar potential  $U$  and the protection current  $I_{\text{prot}}$  in the case of uniform corrosion [13].

( $U_{\text{corr}}$ ) towards more negative values through the application of a cathodic protection current ( $I_{\text{prot}}$ ) from an external DC-power supply (Fig. 3). A sufficient shift of the corrosion potentials of the rebars ( $U_{\text{corr}}$ ) eliminates the local anodic corrosion sites on the rebar surface and reduces therefore the corrosion rates to negligible values.

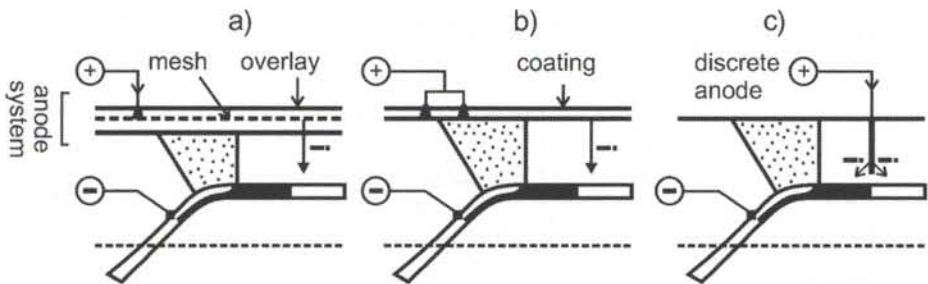
The proper functioning of CP requires sufficient electrolytical conductivity of the concrete overlay, electrical interconnection of all rebars to be protected, and a properly mounted anode. The applied external voltage  $V_{\text{ext}}$  and the ohmic resistance between the anode and the rebars  $R_{A/R}$  is primarily controlling the protection current  $I_{\text{corr}}$ . The ohmic resistance between the anode and rebar  $R_{A/R}$  is the sum of the transfer resistance between the anode and the concrete surface  $R_{A/C}$ , the concrete resistance  $R_C$  and the transfer resistance between concrete and the rebar  $R_{C/R}$ . The transfer resistances of passivated rebars  $R_{C/R}$  are high whereas corroding rebars have negligible transfer resistances in comparison with the concrete resistance  $R_C$ . As the transfer resistance  $R_{A/C}$  of the commonly used anodes is also small compa-

red to the concrete resistance  $R_C$ , the protection current density is primarily a function of the concrete resistance. This implies that the current density distribution may show strong local variations with the concrete resistance.

The current density in areas with low concrete resistance (wet and/or chloride contaminated concrete) may therefore be much higher than in areas of high concrete resistance (dry, chloride free concrete). This induces a stronger cathodic polarisation and therefore a stronger corrosion protection in areas of high corrosive activity and hence an auto regulation. These inhomogeneities induced by the local variations of the concrete resistances have to be taken into account during the planning and monitoring of the cathodic protection system [13].

The principle of cathodic protection using three different types of anode materials is shown schematically in Fig. 4. The principle of a CP-system using a MMO-modified titanium-grid anode is shown in Fig. 4a. MMO signifies "mixed metal oxides", commonly iridium, rhodium or rhenium oxides. The titanium net anode is mounted and fixed mechanically on the concrete surface and then embedded in a mortar layer, on vertical structures it is embedded into shot-crete. The anode and the reinforcement are then connected directly with an external DC-power supply.

MMO-modified titanium grid anodes have a long record of successful functioning in a wide area of applications [4,14]. The anode material itself, the MMO-modified titanium grid, is highly durable and resistant towards the electrochemical processes at the anode surface. The main factor limiting its performance and durability is the quality of the shot-crete in which the anode has to be embedded [4]. Poor quality of shot-creting may lead to the disbondment, anodically produced acid to unpleasant colour changes and/or cracks in the overlay [4,6].



**Figure 4:** Schematic presentation of cathodic protection systems for the corrosion protection of steel rebars in concrete: surface mounted anodes a) MMO-modified titanium mesh and b) conductive coating [2]; c) in concrete embedded discrete anodes.



Local current densities and therefore the rate of acid production on the grid surface may be high, as the anode is not uniformly distributed on the concrete surface [6]. If properly designed, installed, and operated, MMO-modified titanium grid anode systems are highly durable (> 25 years) [4,6]. However, they are expensive [15-16], the fixation on the concrete surface and the embedment into mortar or concrete is labour intensive [4, 6]. In many applications the additional weight and the space loss resulting from the embedding mortar or concrete overlay are not acceptable.

A cathodic protection system using a conductive polymer based coating is shown schematically in Fig. 4b. Conductive coatings as anode materials are used in low risk situations since 1985 in the US and the U.K. [4,6]. The anode is installed by coating the concrete surface with the polymer/graphite dispersion. The conductive coating is termed as secondary anode. The current distribution within the secondary anode is provided by a so called primary anode, made of materials able to resist anodic reactions e.g. platinum clad titanium or copper cored niobium or MMO-titanium that is embedded into the secondary anode at distances of 1 to 2 meters from each other. Conductive coatings are less expensive and very easy to apply [4,6,15,16]. Furthermore conductive coatings may be applied on any shape of concrete structures. Differing from MMO-titanium grid anodes, conductive polymer/graphite coatings are not inert to the anodic reactions. Both, the polymer matrix and the conductive graphite matrix may be degraded by the anodic reactions [4]. The degradation of graphite by anodic oxidation is negligible at sufficiently high loads of graphite powder in the paint (> 60 Vol.%) and may become only serious in an acid environment.

Coatings containing nickel coated graphite fibers are resistant towards oxidation of conductive filler but local acidification might dissolve the nickel coating eventually leading to the anodic oxidation of the graphite fiber. The degradation of the polymer matrix by anodic oxidation may induce embrittlement and may cause loss of adhesion of the coating on the concrete surface. However, the anodically produced acids can be more damaging to the adhesion. At an average protection current density of  $6 \text{ mA/m}^2$  the equivalent of about 0.2 litres of concentrated hydrochloric acid is produced per year. The acid produced at titanium grid anodes is neutralised by the alkaline mortar or concrete, in which the anode is embedded. Conductive coatings do not dispose of such an alkaline buffer capacity. The anodically produced acid should theoretically be neutralized by the hydroxyl ions generated on the cathode (reinforcement). However, in reality the transport rate of hydroxyl ions towards the concrete surface is low at low current densities (1 mm after 10 days at a current density of  $100 \text{ mA/m}^2$ ) [17]. For the neutralization of the anodically formed acid the concrete surface is available only at least during the first few years of CP-operation. The acid attack on carbonated concrete and high local current densities may lead to the deterioration of the concrete surface. The "sandy layer" formed

results in loss of adhesion of the coating to the concrete surface and in the detachment from the concrete surface. Conductive coatings are limited to low current density applications and to low-humidity situations, life-time is expected to be 10 – 15 years [4, 6].

Another type of anode system is shown in 4c: discrete anodes made of inert porous conductive materials (e.g. Ebonex®) are embedded into the concrete. Discrete anodes are especially well suited for concrete members in which the steel reinforcement cannot be protected by surface mounted anode systems like joints in bridge decks.

The application of MMO-titanium grids and of conductive coatings as anode materials for the cathodic protection of rebars in concrete is regulated by the European Standard EN 12696 [18], in Switzerland by the "guidelines of the corrosion commission" [13] and in the USA by the NACE Standard RP0290-90 [14].

## **4 The New CAS Coating**

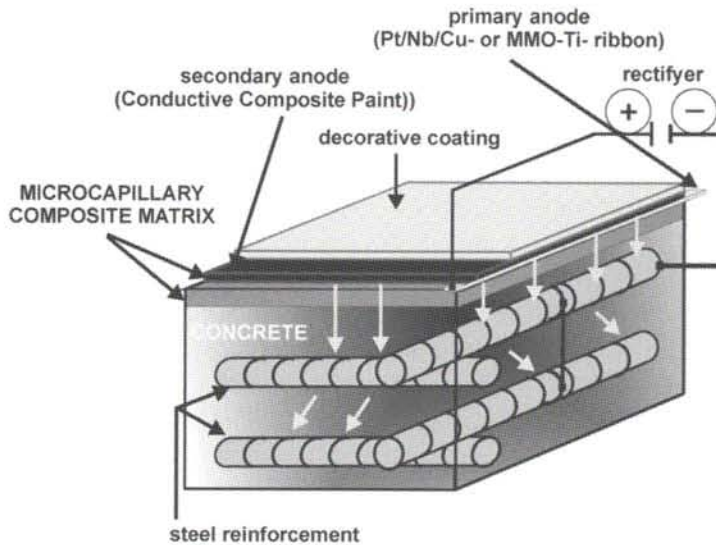
### **4.1 The principle**

The new conductive composite paint is largely inert towards anodic oxidative and acid attack. The paint consists of a two component system that hardens on the concrete surface and in the upper layer of the concrete under the formation of a durable microcapillary polymer/ graphite /alumo-silicate/concrete composite matrix resistant against weak acids (Fig. 5).

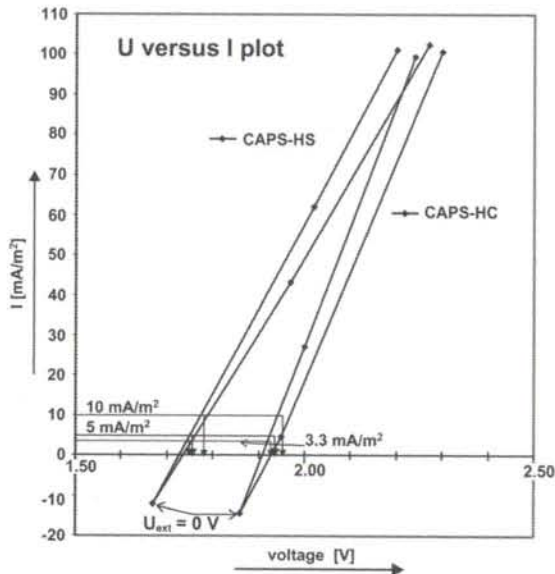
The alumo-silicate/concrete composite matrix strengthens the surface layer of the concrete without increasing the electrolytical concrete resistance. The composite matrix is assumed to promote the transport of the remaining alkalinity and in the long term the transport of the alkalinity produced on the rebar surface from the interior of the concrete towards the concrete surface by capillary suction and inhibits subsequently the acid induced destruction of the concrete surface.

### **4.2 Characterization in the Laboratory**

Laboratory tests were executed on mortar slabs (23x23x4 cm<sup>3</sup>, aggregate 0/5 mm, 400 kg OPC, w/c = 0.50) with a chloride content of 2 - 3 wt.% related to cement calculated as NaCl and with an open porosity of 15 Vol.%. A steel-grid made from reinforcing steel (ø 8 mm, distance 12 cm) was embedded into the mortar slabs; the height of the mortar overlay was 2 cm. The thickness of the conductive composite dry paint was about 200 µm (400 g/m<sup>2</sup> wet paint). The tests and measurements were executed at an ambient relative humidity of 65 to 75%. The conductive composite paint is characterized by low anodic polarization potentials and high current densities at low applied voltages (Fig. 6) due to the low anodic transfer resistance (about 1 Ohm.m<sup>2</sup>) and relatively high conductivity (0.5 to 1 Ohm.cm).



**Figure 5:** Principle of the cathodic corrosion protection of reinforced concrete structures with a conductive microcapillary composite anode (secondary anode), embedded primary anode for the current distribution into the secondary anode and the DC-power supply.



**Figure 6:** Current/Voltage curve of the CAS paint on concrete ([19]).

The CAS-HS is a conductive composite paint with increased pull-off strength and the CAS-P is a high strength conductive composite paint with increased conductivity. To obtain current densities of 5 - 10 mA/m<sup>2</sup> an external voltage of 1.8 to 2.0 V is sufficient. As can be seen from Fig. 6, by turning off the external voltage the current changes its direction that means that the paint becomes the cathode and the reinforcement the anode and the induced current corrodes the reinforcement. Therefore, if the external voltage supply for the CP-system is turned off, it has to be made sure that there are no electrical connections left between the conductive paint and the reinforcement.

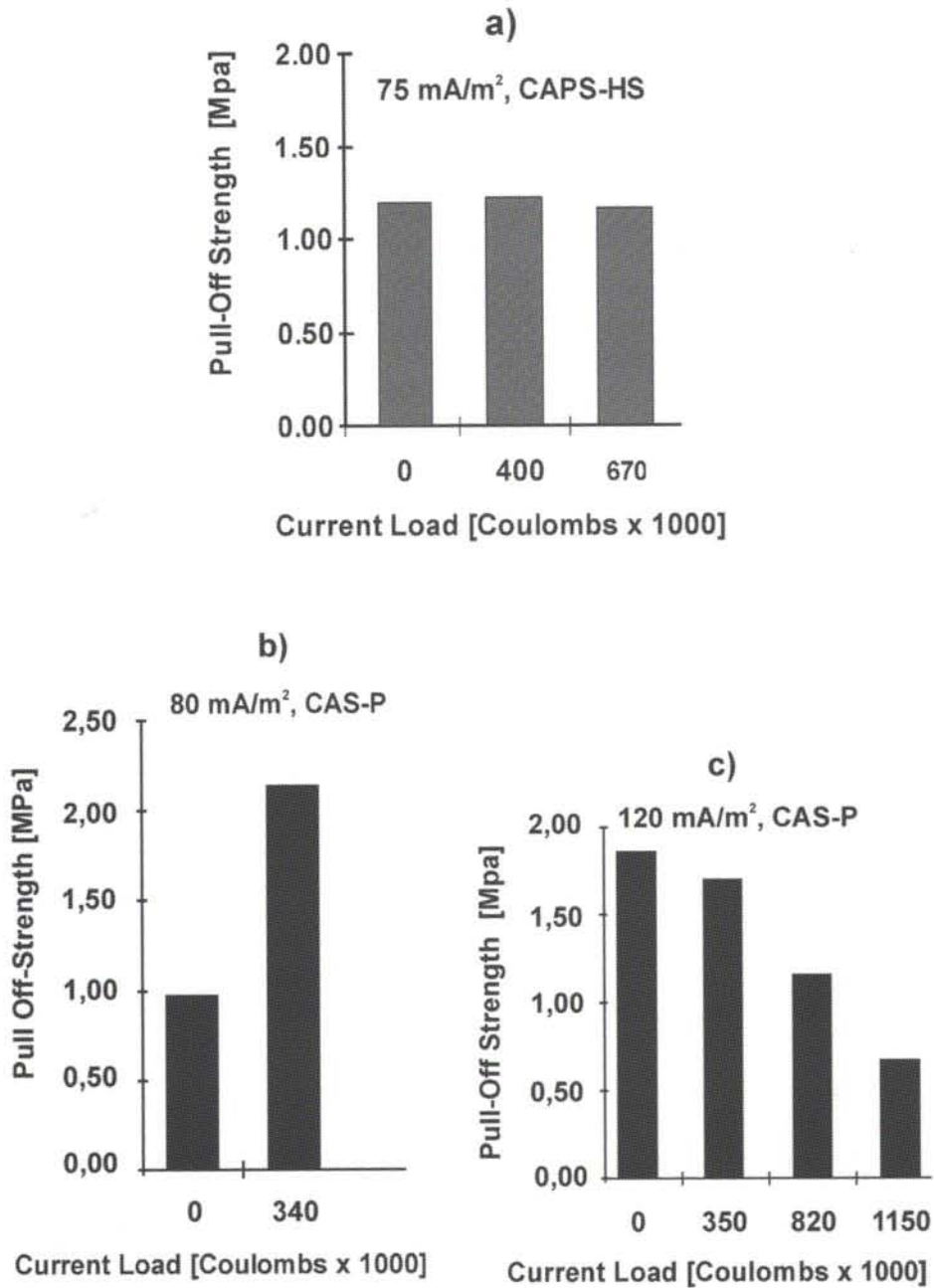
Conventional water-based conductive paints lose their adhesion and can be pulled off by hand from the concrete surface damaged by the acid attack (sandy surface) after passing 40'000-70'000 Coulomb at current densities of 30 to 40 mA/m<sup>2</sup>. The adhesion of the conductive composite paint system is not altered after passing a current of 670'000 Coulomb at current densities of about 75 mA/m<sup>2</sup> (Fig. 7a). The increase of adhesion on a concrete surface of poor quality is due to the fact that the current was turned on about 10 days after applying the paint (CAS-P, Fig. 7b). Adhesion increases within one month due to the formation of the microcapillary matrix.

During pull-off strength tests the cracking occurs in the concrete overlay and not in the paint. The concrete overlay is up to 2 mm from the concrete surface alkaline according to the phenolphthalein test. The pull-off strength decreases at current densities > 120 mA/m<sup>2</sup> but remains acceptable up to a current load of about 800'000 Coulombs (Fig. 7c). The pH of the upper layer of the concrete overlay dropped below 9 under these conditions according to the phenolphthalein test. At standard operating conditions (approx. 3 mA/m<sup>2</sup>), the current consumption during one year corresponds to about 100'000 Coulomb.

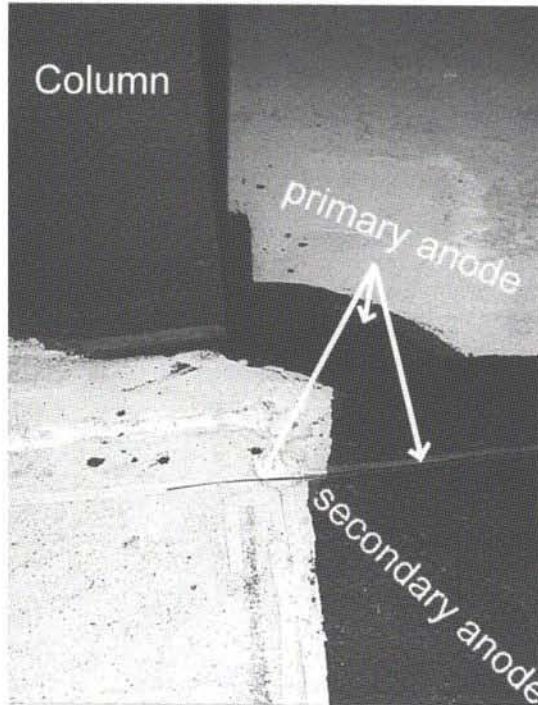
### **4.3 Application principles and procedures**

The composite anode paint system is prepared by mixing two components on site together. The paint is applied on cleaned (by sandblasting, water-jetting, etc.) and dust free concrete surfaces with a thickness of 200 to 300 µm (ca. 450 to 500 g/m<sup>2</sup> wet paint) by means of tools and techniques commonly used for paints and concrete surface coatings. The paint is applied in two layers in an interval of 16 to 24 hours to achieve the necessary thickness of the composite anode coating. Depending on the ambient relative humidity, the paint is wear-proof after about 4 to 8 hours. The pull-off strength is 2 - 3 MPa, depending on the quality of the underlying concrete (pull-off strength > 1,5 MPa), the electrical conductivity ranges from 0.5 to 1.0 Ohm.cm. The cathodic protection system should not be turned on before one month after applying the paint to assure the formation of an adequate composite matrix on and in the concrete surface. Application and hardening of the





**Figure 7:** Influence of current densities (mA/m<sup>2</sup>) and current load (Coulomb/m<sup>2</sup>) on the pull-off strength of conductive composite paint systems.

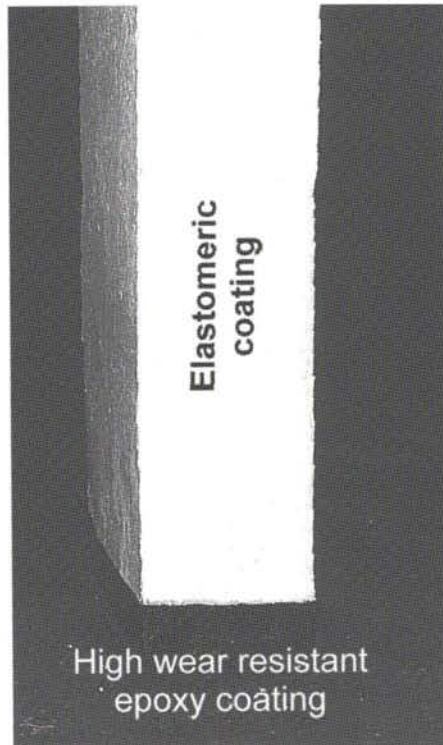


**Figure 8:** Primary anode (platinised niobium ribbon with copper core) embedded into the secondary anode (conductive composite paint).

composite paint system has to take place at ambient temperatures  $> 10^{\circ}\text{C}$ . The relative humidity of the ambient air should allow drying within 24 hours.

The primary anode, a platinised niobium ribbon with a copper core or a MMO-titanium ribbon, is laid into the secondary anode at distances of three to four meters due to the good conductivity of the CAS-paint. The primary anode is glued on top of the first paint layer and then overpainted with the second paint layer (Fig. 8).

The secondary anode is coated with a protective and decorative coating not earlier than one day after applying the last paint layer and after the installation of all necessary electrical connections to the primary anode and to the reference electrodes. For exterior walls of civil structures, pillars of bridges, columns and indoor-walls of parking-decks elastomeric coatings with high impact strength and permeable to water vapour are best suited. With the elastomeric coating any desired colour and appearance may be selected. The CAS-coating on bridge decks and on drive-ways in park-decks is preferably coated with a wear-proof epoxy coating (Fig. 9).



**Figure 9:** Coating of the secondary anode on a column with an elastomer for protection and decoration, and on a drive-way in a parking deck with a high-wear proof epoxy coating.

## 5 Case study

The conductive composite paint was applied for the cathodic corrosion protection (CP) of two parking decks in Oslo (July 1998 in Haugenstua and September 1998 in Ullernbakken). About 1200 m<sup>2</sup> were cathodically protected in each parking deck. The cathodic protection system in the parking deck in Haugenstua is operating satisfactorily since the end of august 1998 and the one in Ullernbakken since the end of September 1998.

In the parking deck in Haugenstua (Fig. 10) two floors with a car-park area of about 1800 m<sup>2</sup> each and 60 columns were repaired. Both, parts of the parking area as well as some of the columns were seriously damaged by corrosion of the steel reinforcement. The corrosion was caused by carbonation of the concrete overlay (carbonation depth 2 - 4 cm) and by chloride ingress (up to 1.8 wt.%/cement weight) from with de-icing salts contaminated spray water from the nearby highway and from de-icing salt carried into the parking-deck by cars.



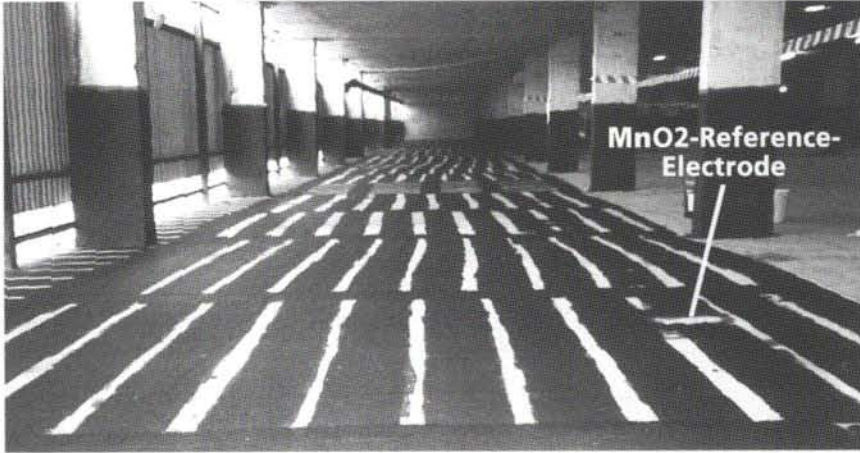


**Figure 10:** Parking deck in Haugenstua in Oslo.

Extensive damage (concrete spalling) were repaired by conventional techniques. Areas that were endangered by corrosion or that corroded without causing yet structural damage to the concrete overlay were cathodically protected from corrosion with the CAS-system (parking-areas and columns of 600 m<sup>2</sup> on each floor). Prior to the application of the CAS-system, the concrete surface was cleaned mechanically. Areas in which the structural integrity of the concrete overlay was insufficient were repaired conventionally, small areas ( $\varnothing < 20$  cm) with polymer modified mortars, larger areas with a rapid hardening mortar with a high electrolytical conductivity.

The conductive composite paint CAS-P was applied on the parking areas to be protected in 25 cm wide stripes, each strip having a distance from each other of about 5 to 10 cm (Fig. 11). The paint was applied in stripes to assure an optimum adhesion of the high-wear resistant overlay towards the paint and concrete-base. The Pt/Nb/Cu-primary anode is embedded in the horizontal painted stripes shown in Fig. 9. MnO<sub>2</sub>-reference electrodes were embedded into the concrete overlay for the control of the efficiency of the cathodic corrosion protection according to EN 12696 [18]. Three days after applying the CAS-system pull-off strengths of  $2.29 \pm 0.73$  MPa on the parking area and  $1.96 \pm 0.15$  MPa on the columns were measured.





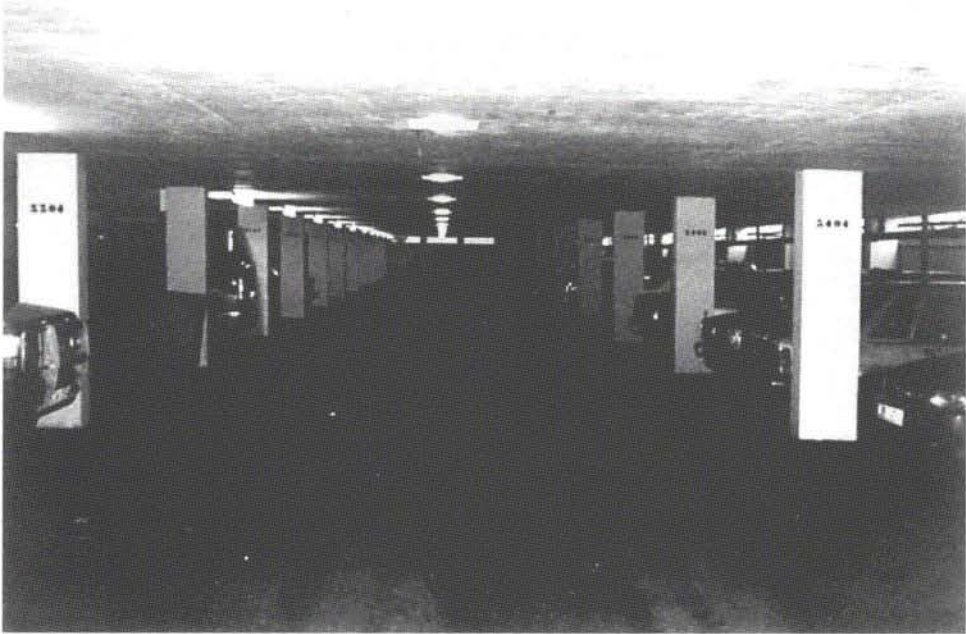
**Figure 11:** Conductive composite paint stripes (two layers,  $400\text{g/m}^2$  fresh paint) on the by corrosion damaged or endangered areas at the parking deck at Haugenstua.

Fig. 12 shows a section of a parking floor after the completion of the restoration and repair works and after turning on the CP-system. The concrete columns were coated with a protective and decorative (white) elastomeric coating, the parking areas with a high-wear resistant epoxy coating.

For the evaluation of local variations in the current densities to be expected, a ohmic resistance mapping is done with a special measuring apparatus three days after applying the composite anode paint. The ohmic-resistance-mapping encompasses the measurement of the electrical resistance between the steel-reinforcement and the conductive composite paint as well as the measurement of the electrical resistance of the conductive composite paint itself between two rollers in electrical contact with the paint at a distance of 10 cm.

Both measurements are used for the quality control and assurance of the CAS system. The measurement of the electrical resistance between the paint and the steel-reinforcement is also used, as mentioned above, for the evaluation of the local variations of the current densities to be expected. The electrical resistance  $R_{A/C}$  varied by a factor of about 3 on the parking areas (40 to 130 Ohm) and by a factor of about 2 on the concrete columns (100 to 180 Ohm) as shown in Fig. 13. From these results maximum local current densities of  $15\text{ mA/m}^2$  are to be expected at an average current density of  $6\text{ mA/m}^2$  in the Haugenstua parking-deck.

The composite anode system is designed for average current densities of 5 to  $35\text{ mA/m}^2$ . Local current densities up to a maximum of  $75\text{ mA/m}^2$  are allowed. Practical experience shows that average current densities of 3 to  $10\text{ mA/m}^2$  are sufficient in most cases to assure satisfactory corrosion protection and to fulfill the 100 mV criterion of the EN 12696 [18] and the NACE-regulation [14].



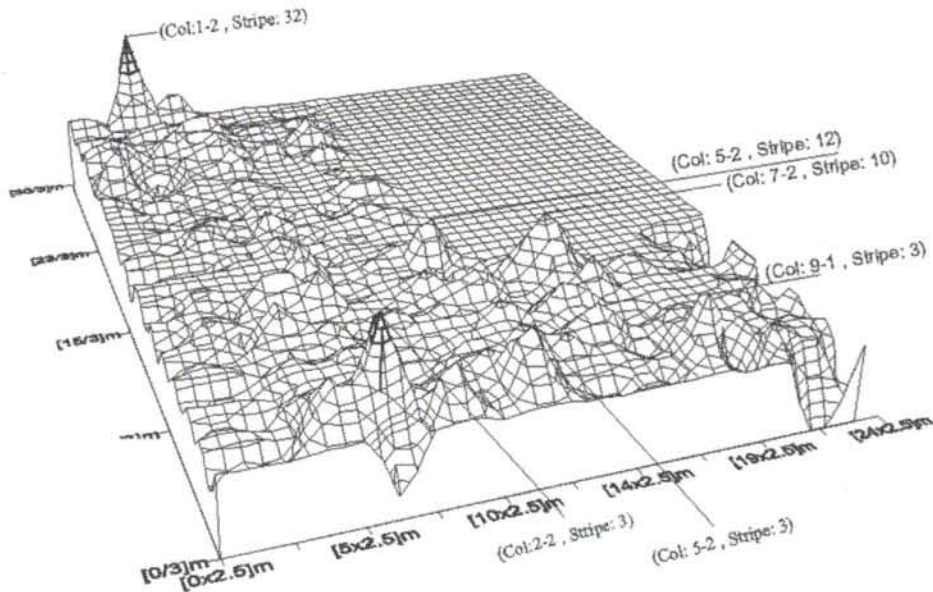
**Figure 12:** Haugenstua parking-deck after completion of repair and restoration works and after putting the CP-system into operation.

## 6 Conclusions

Corrosion of steel in concrete is one of the critical problems in civil engineering with regard to the durability of reinforced concrete structures. Cathodic protection of the steel rebars in concrete structures evolved during the past 40 years as a reliable method to extend the service time of reinforced concrete structures endangered or damaged by steel rebar corrosion. The CP technique with the longest record of reliable performance relies on MMO-titanium grid anodes embedded in concrete as anode material. This technique is comparable to conventional repair techniques that require removal of the concrete overlay and reprofiling with shot-crete if the costs are considered. The CP-technique employing conductive paints as anode materials is highly user friendly at low cost but has limited durability and is restricted to low-risk applications. The main factor limiting its performance is the intrinsic anodic acid production that may lead to the loss of adhesion of the paint to the underlying concrete surface. The novel composite paint system differs from the conventional conductive paint systems by its high durability and by supporting current densities comparable to the MMO-Ti-grid system without loss of adhesion. These properties are assumed to be due to a composite alumo-silicate matrix formed between the paint and the concrete surface. The matrix is resistant against



## Resistance 3D Views of Haugenstua Garage Deck



**Figure 13:** "Ohmic Resistance Mapping" of the electrical resistance between the composite conductive paint (three days after application of the paint) and the steel-reinforcement  $R_{AC}$  (40 - 180 Ohm) on the parking floor 3 of the Haugenstua parking deck.

weak acids and is assumed to promote the transport of alkalinity towards the anode/concrete interface.

### Literature

1. K. Suda, S. Misra and K. Motohashi, *Corrosion Products of Reinforcing Bars Embedded in Concrete*, *Corrosion Science* **35**, 1543 - 1549 (1993)
2. Rilem Draft Recommendation, *124-SRC Repair Strategies for Concrete Structures Damaged by Steel Corrosion*, *Materials and Structures* **27**, 415 - 436 (1994)
3. B.S. Wyatt, *Cathodic Protection of Steel in Concrete*, *Corrosion Science* **35**, 1601 - 1615 (1993)
4. J.P. Broomfield, *Corrosion of Steel in Concrete*, E&FN Spon, London (1997)

5. W.F. Perenchio, U.R. Landgren, R.E. West and K.C. Clear, *Cathodic Protection of Concrete Bridge Substructures*, NCHRP Report 278, 61p (1985)
6. K. Davies, *Impressed current cathodic protection systems for reinforced concrete*, in *Cathodic Protection of Steel in Concrete*, Ed. P.M. Chess, pp 59 – 91, E&FN Spon, London (1998)
7. L. Bertolini, F. Bolzoni, A. Cigada, T. Pastore and P. Pedferri, *Cathodic Protection of New and Old Reinforced Concrete Structures*, *Corrosion Science* **35**, 1633 - 1639 (1993)
8. X: T. Pastore, P. Pedferri, L., Bertolini and F. Bolzoni, *Current distribution problems in the cathodic protection of RC structures*, in *Proceedings RILEM International Conference on the Rehabilitation of Concrete Structures*, Melbourne, D.W.E. Ho and F. Collins editors, pp 189 - 200 (1992)
9. L. Bertolini, F. Bolzoni, P. Pedferri, L. Lazzari and T. Pastore, *Cathodic protection and cathodic prevention in concrete: principles and applications*, *J. appl. Electrochem.* **28**, 1321 – 1331, (1998)
10. P. Pedferri, *Cathodic protection and cathodic prevention*, *Construction and Building Materials* **10**, 391 – 402 (1996)
11. R.B. Polder and R.F.M. Bakker, *Cathodic protection of steel in concrete (Dutch)*, *Cement* 1996, No. 9, 18 - 21
12. W. Schwarz, A. Gerdes, F. Pruckner, G. Nauer and F. H. Wittmann, *Repasivating Effects Induced by Cathodic Protection on Rebars in Concrete Characterised by Electrochemical and Surface Analytical Methods*, in *Werkstoffwissenschaften und Bauinstandsetzen*, F. H. Wittmann und A. Gerdes Herausgeber, Band III, pp 1457 - 1492, Aedificatio Publishers (1996)
13. Korrosionskommission, *Richtlinien für Projektierung, Ausführung und Überwachung des kathodischen Korrosionsschutzes von Stahlbetonbauwerken*, C7d Ausgabe 1991, Schweizerische Gesellschaft für Korrosionsschutz (SGK), Technoparkstrasse 1, CH-8005 Zürich
14. NACE, *Standard Recommended Practice: Cathodic Protection of Reinforcing Steel in Atmospherically Exposed Concrete Structures*, NACE Stand RP0290-90, Item No. 53072, NACE, Houston (1990)
15. P. Lambert, *Economic aspects*, in *Cathodic Protection of Steel in Concrete*, Ed. P.M. Chess, pp 177 – 184, E&FN Spon, London (1998)
16. Society for the Cathodic Protection of Reinforced Concrete (SCPRC), *Cathodic Protection of Steel in Concrete – Status Report*, Report No SCPRC/001.95, SCPRC, PO Box 72, Leighton Buzzard, Bedfordshire, LU7 7EU, UK (1995).
17. J. Miez, *Realkalisierung, Chloridentzug und Kathodischer Korrosionsschutz – Elektrochemische Verfahren zur Instandsetzung von Stahlbetonbauwerken*,



in Korrosion von Bewehrungsstahl in Beton, WTA Schriftenreihe Heft 19,  
pp 165 -182 (1999)

18. *Cathodic protection of steel in concrete – Part 1: Atmospherically exposed concrete*, EN 12696-2000 (March 2000)
19. CAS (Composite Anode System) is a registered trade mark of CAS GmbH,  
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