

REPAIR AND MAINTENANCE OF STEEL REINFORCED CONCRETE STRUCTURES BY SIMULTANEOUS GALVANIC CORROSION PROTECTION AND CHLORIDE EXTRACTION

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SUMMARY

The efficiency of the galvanic corrosion protection (GCP) of the steel reinforcement of a novel Embedded Zinc Anode (EZA) is evaluated on three types of civil structures – abutment of a road bridge in the Styrian Alps in Austria, concrete abutments of a steel bridge and support-beams for the bearings of a road bridge in the Netherlands. The EZA is applied to the surface of concrete members whose steel is to be protected from corrosion by embedding a zinc mesh into a proprietary binder matrix. The efficiency of the GCP was monitored with embedded reference cells, concrete resistivity - and macro cell sensors. Data collected over a period of up to nearly 5 years show that the EZA protects the steel reinforcement efficiently and reliably. Based on these data, estimation of expected service time is discussed. Data from a pilot study are presented that indicate an efficient migration of chloride ions towards the anode and their chemical immobilization in the binder matrix.

Keywords: *corrosion of steel reinforcement, galvanic corrosion protection, zinc mesh anode, chloride extraction, cathodic protection*

1. INTRODUCTION

Galvanic corrosion protection of steel in concrete is based on the formation of a galvanic element if a metal less noble than cast iron steel, in direct contact with the concrete overlay, is electrically connected to the steel rebars. The reinforcing steel is protected from corrosion as long as sufficient galvanic current flows between the galvanic anode and the steel reinforcement. Most commonly, zinc is used as the sacrificial anode material. The galvanic element formed corresponds to a conventional zinc/air battery that is becoming popular again as an alternative source of energy.

Galvanic corrosion protection was first employed to protect a bridge deck in Illinois in 1977 within the cooperative highway research program, with mixed results [1]. A problem with the initially applied sacrificial anodes was that their protection current decreases with time, and they eventually become passive, so most systems had a relatively short useful life [2].

In the 1990's, sacrificial anode systems based on sprayed zinc anodes, zinc foil glued to the concrete surface (zinc hydrogel system), zinc mesh pile jackets around bridge columns filled with sea water were starting to be evaluated and used for the protection of bridge structures [2-5]. To a limited extent, zinc anodes embedded into the concrete overlay, are used to protect the steel reinforcement especially accompanying concrete repair.

The efficiency of galvanic corrosion protection depends on the lasting activity of the zinc anode. Deposition and agglomeration of the anodic products like zinc hydroxide and zinc hydroxychlorides or contact with calcium hydroxide in the pore solution may passivate the zinc anode surface.

Service time of the zinc anode may be limited by self corrosion that increases with the activation of the zinc anode and may reach up to 70% of the zinc consumed during operation.

The driving voltage is set by the properties of the anode, the interface of the anode to the concrete and by the electrolytic conductivity of the concrete over-layer. Sprayed zinc anodes require sufficient humidity and high chloride contents to operate satisfactorily [6]. Galvanic systems are not suitable for the protection of steel in carbonated concrete members. Experience showed that most failures of galvanic systems occurred due to the failure of the adhesion of the anode to the concrete overlay and due to passivation of the anode exposed to frequent wet dry cycles or due to loss of alkalinity of the embedding mortar. Zinc-Hydrogel anodes are especially sensitive to exposure to high humidity with subsequent delamination.

A novel galvanic zinc anode system, composed of a zinc mesh embedded into a proprietary mortar that solidifies into a solid electrolyte, was developed by CAS. The solid electrolyte of the embedded zinc anode system (EZA) is based on a tecto-alumosilicate-binder containing additives that prevent passivation of the zinc anode, assure high and durable galvanic activity of the zinc anode and high and durable adhesion towards the concrete overlay.

The efficiency of the galvanic corrosion protection (GCP) of the steel reinforcement with a novel embedded zinc anode (EZA) is evaluated on three types of civil structures – a road bridge (cantilevers, part of the underside the bridge deck and an abutment) in the Styrian Alps in Austria, concrete abutments of a steel bridge and support-beams for the bearings of a road bridge in the Netherlands.

2. DESCRIPTION OF THE SYSTEM

The galvanic EZA system is composed of a zinc mesh embedded into the proprietary solid electrolyte (figure 1). The TASC binder matrix is formed by the hardening of the hydraulic binder containing tecto-alumosilicate-cement. The TASC binder matrix function as a solid electrolyte, that ascertains an optimum electrolytic contact between the zinc anode and the concrete overlay, it prevents the self passivation of the zinc anode and therefore assures an optimum and reliable protection of steel reinforcement endangered by, or already damaged by chloride induced corrosion.

The EZA is placed on the surface of the concrete member in which the steel reinforcement is to be protected from corrosion: The concrete surface has to be prepared with the standard procedures for placing coatings on concrete surface (preferably sand blasting, high-pressure (400 bar) water jetting, etc.). Adhesion strength after 24 hours is in the range of 0.6 – 1.0 MPa, after 7 days > 2 MPa and after 28 days about 2.5 – 3.0 MPa.

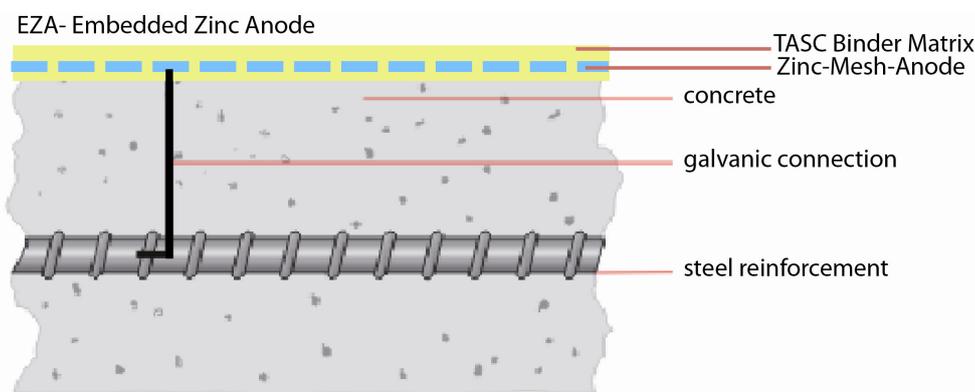


Fig. 1 Embedded galvanic zinc anode (EZA): zinc mesh embedded into the EZA binder matrix.

The efficiency of corrosion protection by the EZA may be evaluated according to the procedure described in EN 12696 – the 24 h depolarisation criterion. To monitor the efficiency of the installed EZA systems, reference cells, macro-cell-, concrete resistivity, temperature and humidity sensors were installed and monitored with an automated monitoring system.

3. FIELD INSTALLATIONS

3.1 Alpine Road Bridge

For the evaluation of the efficiency and durability of the EZA system, a road bridge in an alpine region of Styria (Austria) was chosen (figure 2) for the following reasons:

The bridge is located in the Styrian Alps in an altitude of 1000 m above sea level. The climate in that region is characterized by rapid wetting and drying cycles with large temperature differences in the summer including temperature changes crossing the thaw point and by frequent frost-thaw cycles with high exposure to deicing salt during winter.



Fig. 2 County road bridge “Alplgrabenbrücke” in the Styrian Alps on the county road B72.

3.1.1 Description of Bridge Condition

The bridge structure showed visible concrete damages – cracks, spalling and corrosion - near the abutment “Birkfeld”. Water and saltwater during wintertime penetrated the bridge deck through cracks due to the bridge deck bumping against the abutment. Chloride contents of 4.0 – 5.6 wt. % / cement weight down to a depth of 2 cm were measured in the areas that were frequently wetted. In the less frequently wetted areas, the chloride content was in the range from 0.5 – 0.9 wt. % / cement weight, carbonation depth was ≥ 4 cm.

Therefore one has to assume high corrosion activity of the steel reinforcement of the concrete members with the risk of significant loss of cross section of the steel reinforcement in the future.

3.1.2 Installation of the EZA – System

The EZA system for the galvanic corrosion protection (GCP) of the steel reinforcement in the concrete members of the county road bridge “Alplgrabenbrücke” was installed in September 2007 on 50 m² of concrete surface.

Concrete members were protected that were particularly endangered and/or damaged by the corrosion of the steel reinforcement: the abutment, the bridge deck underside near the abutment and the adjacent cantilevers. The EZA system was put into operation on 1 November 2007. Operational and performance data were presented at the ICCRRR [8]. The data proved that the steel reinforcement is reliably protected from corrosion by the EZA system. The owner of the bridge – the Styrian department of bridge construction and repair – decided during the general bridge repair,

executed from 21 June until 21 August 2012, to take over the EZA on the abutment. To assure frost thaw salt resistance and to increase performance, especially with respect to the galvanic chloride extraction, the EZA was coated with an elastic acrylic coating. In an area of about one m^2 , the EZA was renewed by embedding a zinc mesh into the EZA binder on top of the existing EZA (figure 3).



Fig. 3 View on the EZA installed on the abutment of the Alplgrabenbridge

3.1.3 Data of Operation of the EZA – system

The operating data of the EZA-system over a period of nearly six years (1 November 2007 – 19 April 2013), outlasting six alpine winters, were evaluated and analyzed with respect to stability, performance and durability: The course of the galvanic current of the EZA-system show that the initially high galvanic currents decreased during the first three months continuously and stabilized after about 2 years (Figure 4).

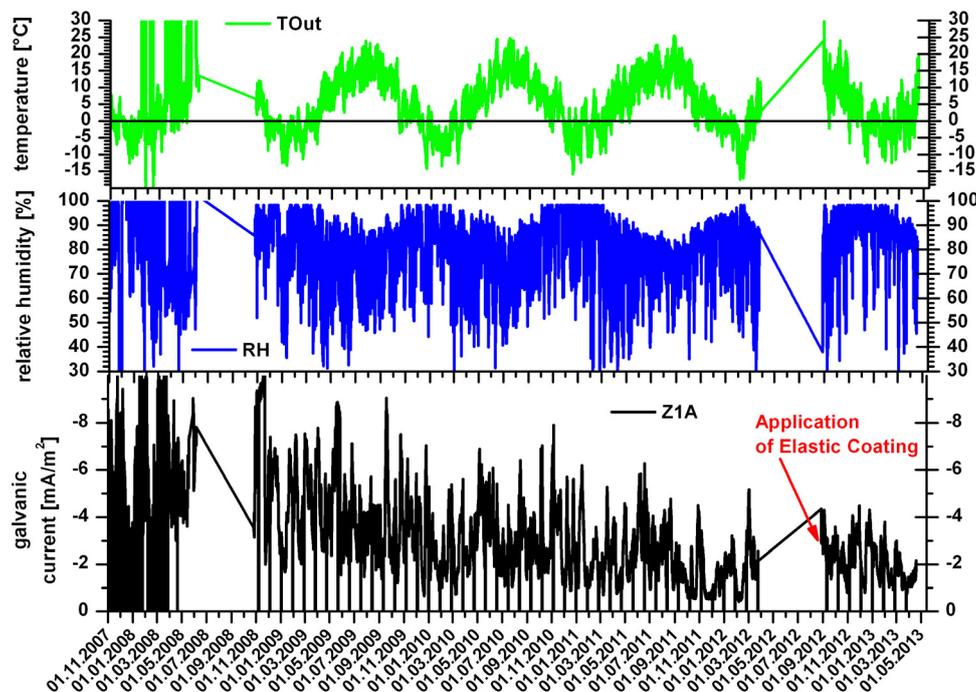


Fig. 4 Galvanic Current of the EZA-System in comparison with the ambient relative humidity (RH) and temperature (T_{out}). Data from 1 November 2007 till 19 April 2013.

The galvanic current decreased at dry ambient air ($RH < 50\%$) and temperatures below freezing but increased immediately if humidity levels and/or temperature increased again to the values previously measured at the corresponding humidity and/or temperature levels. The application of a water vapour permeable elastic coating in August 2012 decreased the influence of the ambient humidity significantly and resulted in relatively high galvanic current at temperatures significantly below freezing. During the time period of observation the EZA system passed six alpine winters without measurable loss or decrease in performance. Furthermore, the numerous wet/dry and freeze/thaw cycles did not affect the long-term performance of the EZA-system.

The efficiency of the corrosion protection of the GCP systems was verified by depolarization measurements according to EN 12696 [7, 8]. The EZA system is fully functional after nearly five years of operation enduring six alpine winters. The galvanic zinc anode protects the steel reinforcement reliably and durable from corrosion.

Delamination of the surface layer of the solid EZA electrolyte has been observed in areas which were soaked thoroughly with de-icing salt solution during winter time. However, the zinc anode mesh was not laid open due to the delamination of the surface layers. Drilled cores showed that in areas where the EZA was soaked with de-icing salt solution from the inside through cracks across the bridge deck, the compound between the EZA mortar and the concrete remained fully intact. The galvanic corrosion protection was therefore guaranteed in all areas in which the EZA anode is installed. The application of the elastic acrylic coating protected the EZA reliably from frost-thaw salt damages during the exceptionally long and hard winter 2012/2013.

From the charge passed during the operation of the system and based on samples of the zinc mesh drawn from various areas, a service time of about 15 years is estimated.

3.2 De Meernbrug Steel Bridge

The De Meernbrug Steel Bridge (figure 5) project in Utrecht, The Netherlands, was realized 2010 due to reinforcement corrosion in the concrete front wall of both abutments of the steel “De Meernbrug” bridge over the Amsterdam-Rijn canal. Reinforcement corrosion was initiated due to high levels of penetrated chloride readily available from de-icing salts from the overlying road. Over 1% mass of chloride by mass of cement was present at the rebar level in the damaged areas. Undamaged concrete showed high levels of chloride as well, but were slightly lower as in the damaged areas. During repair works a decision was made to change traditional repair work to cathodic protection.



Fig. 5 De Meerenbrugg steel bridge in Utrecht with concrete abutments

The three main reasons were: reduction of direct costs due to the fact that traditional repair conforming to EN1504-standards would mean excessive removal of chloride contaminated concrete while cathodic protection would mean limited repair of delaminated and disintegrated spots; reduction of risks for future development of concrete damage on the none repaired locations and reduction of over-all execution time of the work being done.

In total some 200 m² of traditional reinforced concrete was cathodically protected. For the protection, some minor surface repairs were performed, after which a zinc mesh with a total amount of 4 kg zinc per m² of concrete surface was applied. The amount of zinc relative to the amount of steel surface to be protected (relative steel density was well below 1 m² steel per m² concrete) showed a theoretical lifetime expectancy of more than 15 years.



Fig. 6 De Meerenbrug steel bridge in Utrecht with concrete abutments

The zinc mesh was embedded in the non-cementitious TASC-binder which forms the core of the system's performance. The system of cathodic protection as applied was finalized with an aesthetic coating system based on the Sika Decadex system (figure 6). This is a typical installation of an "install and forget" system as there is no need for a power supply on this remote site and no need for extensive monitoring and control as the system is always "on". Both issues were demands made by the department responsible for the future maintenance of the bridge. As inspected in 2012 the system's performance is up to the industry's standards.

3.3 'Hubertusviaduct' in Den Haag

This 2008 project in The Hague was initiated by the municipality. During damage assessment of a large fly-over junction 'Hubertusviaduct,' with 4 abutment walls, there was a chloride induced reinforcement corrosion problem in the concrete just beneath the expansion joints. During the repair works, all expansion joints were replaced with new, water-tight rubber joints. The concrete damage was re-paired and the abutment was cathodically protected.

In total 90 m² was covered with zinc mesh with a total of 2 kg per m² of concrete (figure 9). Considering the low reinforcement density, a lifetime of over 10 years is expected. A total area of 90 m² of concrete was protected on 4 different locations, divided into 5 separate zones. Each zone was installed with a decay-probe (activated titanium Ti*) and a reference-electrode (manganese dioxide MnO₂-type). All connections within a zone to the reinforcement, the zinc-anode, the decay-probe and the reference-electrode were made in a connection box. The entire surface was coated with the Decadex coating system.



Fig. 6 EZA installed on the beams supporting the bearings of abutments of the Hubertus viaduct in The Hague

Performance of the system has been monitored with respect to the EN12696 standard. Visual inspection showed no signs of aging, deterioration or failure, despite the fact that leakage from the joints above was abundant and water load was permanent on the horizontal parts of the installation. The protective current density was typically 2 mA/m^2 concrete after 3 years of operation. The depolarization of the cathodic protection system in 24 hours was well above the EN12696 criterion of 100 mV. A typical depolarization measurement result from 30 June 2011 is given in Table 1.

Table 1 Verification of the effectiveness of the GCP by the EZA by 24 h depolarisation measurements according to ISO EN 12 696. Potential values in mV

Cell	Reference Cell Type	On-potential	Instant-off	1h off	24h off	24h Depolarisation
Re1	MnO ₂	547	457	386	288	169
DP2	Ti*	366	278	183	91	187

Already after a few years, the joints had started to leak again and the EZA was exposed to deicing salt solution during wintertime. The EZA has outlasted five winters, three of them were harsh. Performance has been above expectation in the first 5 years. The system is capable of withstanding water load, deicing salts, proves to be frost-thaw-resistant and shows no signs of aging.

4. Service Time Expectations & Galvanic Chloride Extraction

The maximum expected service time of galvanic systems is usually calculated according to Faradays law from the measured galvanic current integrated over time. The current is usually measured over a relatively large area. Currents may vary strongly locally depending on the humidity, chloride content and on the density of the reinforcement in the concrete overlay. From zinc-mesh samples drawn in August 2012 from the EZA installed on the Alplgraben bridge it is estimated that currents vary by a factor of up to 2,2. Highest current consumption and therefore zinc consumption will occur at areas of high chloride content, high humidity and high density of reinforcement – areas in which corrosion protection is most required. From an mean galvanic current of $3,6 \text{ mA/m}^2$ one would expect a service time of 36 years. Considering the local variation of current densities one may estimate the service time of the EZA of 16 years. Therefore, the service time of the EZA, containing 2 kg Zinc/m^2 , is estimated to be about 15 years.

An important aspect with regard to the service time of zinc based galvanic anodes and the durability of corrosion protection of steel in concrete is the “galvanic chloride extraction”. Migration leads to an accumulation of anions, especially of chloride ions, at the anode and a depletion of chlorides near the steel rebar surface. Migration is counterbalanced by diffusion. Once the rate of diffusion of chloride ions accumulated at the anode into the concrete cover is equal to the rate of migration towards the anode then no net movement of chloride ions and therefore no further chloride ex-

traction will occur. Differing from all other anode systems used for CP or for chloride extraction, chloride ions are chemically immobilized near the zinc anode by reacting with anodically formed zinc hydroxide as zinc-hydroxychlorides - zinc-hydroxychlorides are nearly insoluble in water [9]. This “one-way” transport of chlorides towards the galvanic zinc anode results in an efficient chloride extraction of chlorides from the concrete cover. This chloride immobilization mechanism is especially efficient in the EZA system [8]. Therefore one may expect that chloride is efficiently removed from the concrete cover at the end of the service time of the EZA provided that the EZA is coated with an elastic membrane impermeable to liquid water.

5. Conclusions

The performance of the novel EZA galvanic corrosion protection system, consisting of a zinc mesh embedded into a proprietary non-cementitious binder matrix was evaluated on the abutments of three different civil structures – an alpine road bridge in Austria, a steel bridge in Utrecht, NL and a viaduct in The Hague, NL. Measurements according to ISO EN12696 and with macro cell sensors over a period of up to nearly 6 years show that the EZA system has protected the steel reinforcement of the concrete members reliably from corrosion. Coating of the EZA with an elastic membrane reduces the influence of ambient humidity and temperature significantly and assures frost-thaw salt resistance. Calculated from the galvanic currents integrated over time and from zinc mesh samples drawn from an EZA field installation, service time of the EZA containing 2 kg zinc/m² is estimated to be about 15 years. Results indicate that within the expected service time, galvanic chloride extraction and immobilization in the EZA will be efficient enough to prevent renewed corrosion of the steel after the end of service time.

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