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

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ABSTRACT: A novel galvanic zinc anode system, composed of a zinc mesh embedded into a proprietary binder that solidifies into a solid matrix with ion exchange properties, was developed by CAS. The solid matrix 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 four 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 four viaducts in the Netherlands and a parking deck in Switzerland.
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 6 years show that the EZA protects the steel reinforcement efficiently and reliably. Based on these data, estimation of expected service time is discussed. Data indicate an efficient migration of chloride ions towards the anode and their chemical immobilization in the binder matrix.

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 (Kepler et al. 2000). 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 (Virmani & Clemena 1998).
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 (Virmani & Clemena 1998, Kessler et al. 2002, Szabo & Bakos 2006, Bullard et al. 2009). 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.
Sprayed zinc anodes require sufficient humidity and high chloride contents to operate satisfactorily (Bäßler et al. 2006). 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 binder that solidifies into a solid matrix 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 four types of civil structures – a road bridge in the Styrian Alps in Austria, concrete abutments of a steel bridge, support-beams for the bearings of a road bridge in the Netherlands and a parking deck in Saas Fee in Switzerland.

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.

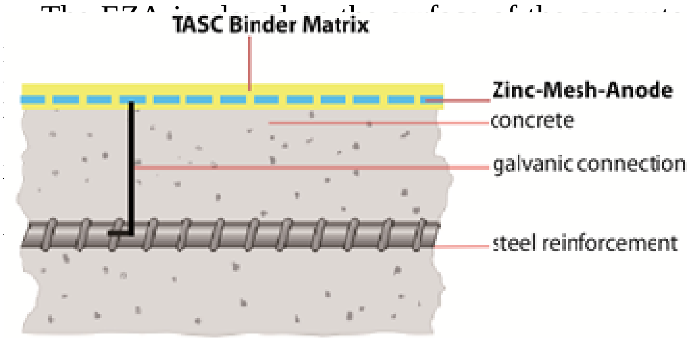

Figure 1. Embedded galvanic zinc anode (EZA): zinc mesh embedded into the EZA binder matrix

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.

Figure 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 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 m2, the EZA was renewed by embedding a zinc mesh into the EZA binder on top of the existing EZA (figure 3).

Figure 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 more than six years (1 November 2007 – 19 December 2013) 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).

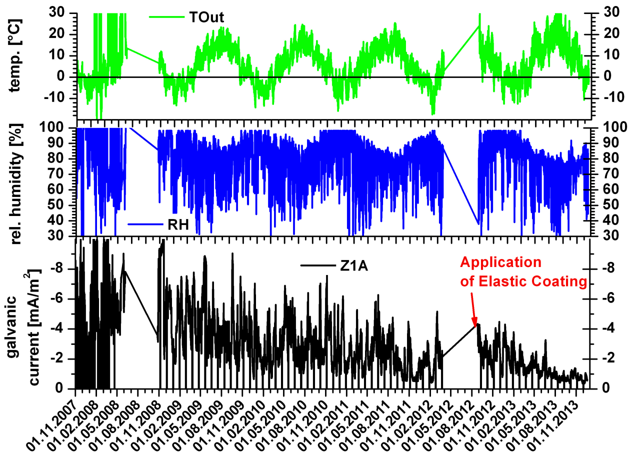

Figure 4. Galvanic Current of the EZA-System in comparison with the ambient relative humidity (RH) and temperature (Tout). Data from 1 November 2007 till 19 December 2013.

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. Furthermore, the numerous wet/dry and freeze/thaw cycles did not affect the long-term performance of the EZA-system. The galvanic zinc anode protects the steel reinforcement reliably and durable from corrosion.

The efficiency of the corrosion protection of the GCP systems was verified by depolarization measurements according to EN 12696 (Schwarz et al. 2011, Schwarz et al. 2012). The EZA system is fully functional after seven years of operation enduring seven alpine winters.

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. 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 over the Amsterdam-Rijn canal (figure 5) project in Utrecht, The Netherlands, was realized 2010.

Figure 5. De Meerenbrugg steel bridge (top) in Utrecht with concrete abutments (bottom)

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.

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. 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 on a total of 200 m2 concrete surface. The EZA system as applied was finalized with an aesthetic coating system based on the Sika Decadex system (figure 5). 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 2013 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 m^2 was covered with zinc mesh with a total of 2 kg per m^2 of concrete (figure 6 & 7). Considering the low reinforcement density, a lifetime of over 10 years is expected. A total area of 90 m^2 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 MnO_2-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.

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

Each zone was installed with a decay-probe (activated titanium Ti*) and a reference-electrode (manganese dioxide MnO_2-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.

Figure 7. EZA installed on the beams supporting the bearings of the Hubertus viaduct in The Hague

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, measured on beams shown in figure 6.

Date of meas.	**Ref. Cell Type**	**On-potential**	**Instant-off**	**4h off**	**24h off**	**24h Depol.**
30 June 2011	MnO_2	-547	-457	-386	-288	**169**
	Ti*	-366	-278	-183	-91	**187**
30 July 2013	MnO_2	-551	-499	-404	-245	**254**
	Ti*	-356	-314	-237	-70	**244**

Table 2. 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, measured on beams shown in figure 7.

Date of meas.	Ref. Cell Type	On-potential	Instant-off	4h off	24h off	24h Depol.
30 July 2013	MnO_2	-559	-507	-466	-327	**-180**
	Ti*	-288	-245	-194	-115	**-130**

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 six winters, four of them were harsh. Performance has been above expectation in the first 6 years. The system is capable of withstanding water load, deicing salts, proves to be frost-thaw-resistant and shows no signs of aging.

3.4 *'Parking Deck in Saas Fee*

The parking garage in Saas Fee is designed to take in all cars of tourists and inhabitants of Saas Fee – Saas Fee is car free. The parking deck was erected 1979/80 and extended with a new section 1980/81, offering 2900 parking lots (figure 8).

Figure 8. Central parking deck in Saas Fee, Switzerland

The concrete overlay of the decks are impregnated with chlorides ranging from 0,5 – 3,0 wt.%/wt% cement near the loose steel reinforcement. The decks are reinforced with unbonded post-tensioned tendons. Conventional techniques would require the removal of with chloride contaminated concrete, coating of the steel reinforcement and refurbishment with repair mortar or concrete. This procedure would be highly delicate with regard to the unbonded tendons in the parking deck – damage to these tendons has to be avoided under any circumstances. With regard to the pre-stressed tendons and the risk of CP induced hydrogen embrittlement, galvanic corrosion protection offers a safe and reliable remediation technique. In July 2011, on a parking booth, the EZA system was installed on 30 m^2 concrete surface. The EZA system has been coated with a tough elastic, static crack-bridging waterproofing and wearing surface layer of broadcast total solid epoxy Sikafloor-390, covered by a high abrasion resistant sealcoat of total solid epoxy Sikafloor-354 (figure 9).

Figure 9. EZA-installation in one parking booth

The EZA is now in operation since August 2011, exposed to the harsh alpine conditions in 1880 m above sea level. Data show that it is protecting the steel reinforcement reliably and safely with 0-maintenance expenditures.

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 mA/m2 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/m2, 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 ac-

cumulation 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 (Clever et al. 1992). This "one-way" transport of chlorides towards the galvanic zinc anode results in an efficient chloride extraction of chlorides from the concrete cover and subsequentely, leads to the repassivation of the steel reinforcement confirmed by rest potential and macro-cell current measurements. This chloride immobilization mechanism is especially efficient in the EZA system (Schwarz et al. 2012). 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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