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**Galvanic corrosion protection of steel in concrete  
with a zinc mesh anode embedded into a solid  
electrolyte (EZA): Operational Data and Service Time  
Expectations**

# Galvanic corrosion protection of steel in concrete with a zinc mesh anode embedded into a solid electrolyte (EZA): Operational Data and Service Time Expectations

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**ABSTRACT:** 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 – 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. The EZA is applied to the surface of concrete members whose steel is to be protected from corrosion by embedding a zinc mesh (2 – 4 kg/m<sup>2</sup>) into a proprietary mortar that hardens to a solid electrolyte. 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.

## 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 have 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, Powers & Lasa 2004; Szabo & Bakos 2006, Bullard, Cramer & Covinho 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.

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 overlay. Sprayed zinc anodes require sufficient humidity and high chloride contents to operate satisfactorily (Bäßler et. al.). Galvanic systems are not suitable for the protection of steel in carbonated concrete members.

For the galvanic systems evaluated so far, efficient corrosion protection for steel in concrete has been provided. Expected service times are in the range of 40 years and more.

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. Zinc-Hydrogel anodes are especially sensi-

tive 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. The results of the evaluation of the performance and estimation of the service time of the galvanic anodes system are presented.

## 2 DESCRIPTION OF THE SYSTEM

The galvanic EZA system is composed of a zinc mesh embedded into the proprietary solid electrolyte (figure 1) that ascertains an optimum electrolytic contact between the zinc anode and the concrete overlay.

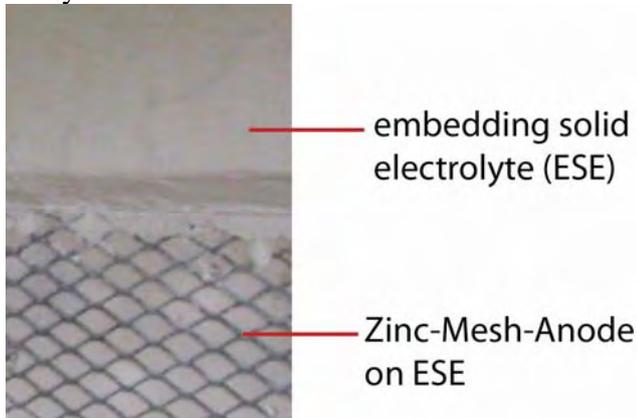


Figure 1. Embedded galvanic zinc anode (EZA): zinc mesh embedded into the TASC mortar from which the embedding solid electrolyte forms.

The solid electrolyte, based on a tectoalumosilicate cement (TASC), 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 zinc anode, a zinc mesh, is embedded into the proprietary solid electrolyte that ascertains an optimum electrolytic contact between the zinc anode and the steel reinforcement.

Unlike impressed current CP systems, hydrogen evolution is not possible on an EZA. The EZA is es-

pecially suited for the corrosion protection of prestressed concrete structures.

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 (high-pressure water jetting, sand blasting, 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.

The efficiency of corrosion protection by the EZA may be evaluated according to the procedure described in EN 12696 – the 24 h depolarisation criterion. For that purpose, the installation of into the concrete overlay embedded reference cells and an automated monitoring and control system is required.

## 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 shows 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 were in the range from 0.5 – 0.9 wt.%/ cement weight, carbonation depth was  $\geq 4$  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, possibly leading to structurally unsafe conditions.

### 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 from 17 to 27 September 2007 on 50 m<sup>2</sup> of concrete surface.

Concrete members were protected that were particularly endangered and/or damaged by the corrosion of the steel reinforcement: abutment “Birkfeld”, the bridge deck underside near the abutment and the adjacent cantilevers (figure 3).



Figure 3. View on the GCP zones after completion of the installation.

### 3.1.3 Data of Operation of the GCP Systems

The operating data of the GCP systems over a period of nearly five years (1 November 2007 – 25 March 2012), outlasting five alpine winters, were evaluated and analyzed with respect to stability, performance and durability: The course of the galvanic current of the GCP systems show that the initially high galvanic currents decreased during the first three months continuously and stabilized after about 1,5 years (Figure 4). The galvanic currents decreased and approached in some zones zero 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. During the time period of observation the GCP systems passed five alpine winters without measurable loss or decrease in perform-

ance. Furthermore, the numerous wet/dry and freeze/thaw cycles did not affect the long-term performance of the GCP systems.

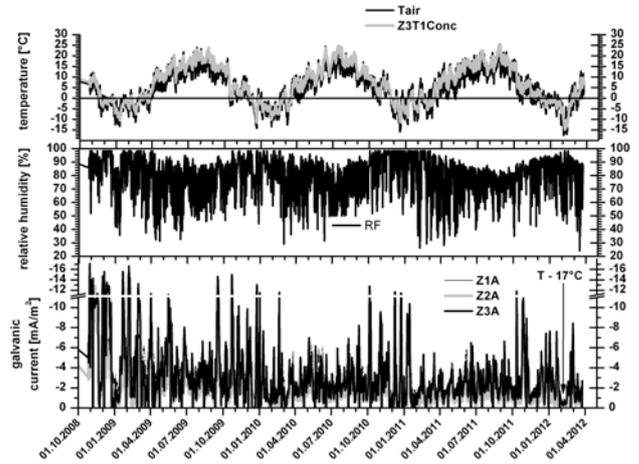


Figure 4. Galvanic Currents of the GCP Systems in comparison with the ambient relative humidity (RH) and temperature (ambient temperature  $T_{out}$ , concrete temperature BT1 - 1 cm below the concrete surface, BT2 - 3 cm below the concrete surface). Data from 1 November 2007 till 25 March 2012.

The efficiency of the corrosion protection of the GCP systems was verified by depolarization measurements according to EN 12696 (Schwarz, Müllner & den Hondel 2011).

The EZA system is fully functional after nearly five years of operation enduring four 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 deicing 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.

### 3.1.4 Expectations on Service Time and Durability

The maximum expected service time of galvanic systems is usually estimated from the consumption of the zinc anode, calculated according to Faradays law, based on the average galvanic current measured. Calculated from the galvanic currents integrated over time, between 3% and 9.0% of the zinc anode (2000g/m<sup>2</sup>) were consumed (Table 4) during the period of operation from 1 November 2007 – 25 March 2012. Using the mean galvanic current values and assuming that a minimum of 70% of zinc will be available for galvanic protection, one obtains maximum life time expectancies of a minimum 30 years.

These calculated maximum expected service time is based on the assumption that (1) average currents remain stable and sufficiently high over the time pe-

riod the system is expected to operate efficiently, (2) the current distribution over the surface of the galvanic anode is homogenous and (3) self corrosion of the galvanic anode is negligible.

Table 1 – Anode material consumed from 1 Nov. 2007 until 25 March 2012 and service time expectancy of the GCP systems

Zone	Z1	Z2	Z3	Z4
Charge passed in Coulombs	498.453	360.124	533.154	179.181
% of zinc anode consumed according to Faraday law	8,4%	6,1%	9,0%	3,0%
Calculated service time- expectancy in years *	36	50	34	101
Mean current mA/m <sup>2</sup> (01/11/07 - 25/03/12)	3,59	2,60	3,50	1,29

\* Service time expectancy calculated for 70% (1400g/m<sup>2</sup>) zinc as available during service time

Ad 1): During the start up of galvanic corrosion protection systems, the initial galvanic currents are usually high and decrease during operation over time. To assure reliable corrosion protection, the galvanic protection currents have to attain and remain stable over the expected service time of the galvanic protection system.

The galvanic currents of the EZA system decrease over a time period of about 1,5 years (Figure 4) towards nearly stable values. The galvanic currents of the EZA, as an open surface anode system exposed to weathering, are strongly influenced by temperature and relative humidity of the ambient air as shown in figure 4. Due to the high sensitivity to weathering conditions, short term evaluation of the galvanic currents does not allow a reliable evaluation of their stability over time. If one compares galvanic currents averaged over similar time periods, e.g. the month of March of each year, then the stabilization of the galvanic currents after 2 years of operation becomes evident (figure 5).

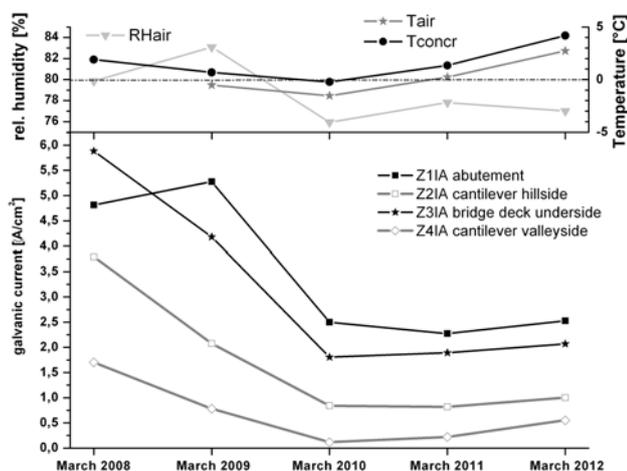


Figure 5. Galvanic currents ZxIA, ambient (Tair) and concrete temperature (Tconcr) and ambient humidity (RHair) averaged over 1 – 26 March of each year.

The month of March was chosen as it was the last period of time of observation. Figure 5 demonstrates that even after prolonged dry periods, the EZA system attains its original activity if humidity increases to normal values.

Ad 2): Cores were taken on 18 Mai 2011 from areas of the EZA placed on concrete with high chloride content (up to 5,6 wt%/ wt. cement) and frequently exposed to frost/thaw salt solution during winter and frequently wetted during summer (abutment, zone 1). Evaluation of the loss of diameter of the zinc mesh in these areas by optical microscopy revealed that up to 40% of the cross section of the zinc wires was lost in these “hot spots” during the operation of the EZA anode. Comparing the amount of current required to dissolve 40% of the zinc with the average current density during the time period from 1 November 2007 – 18 Mai 2011, one obtains a current ratio of 4,8: In these hot spots, locally about 5 times higher currents flow than the average current measured over the whole area. Comparing the average current (4,37 mA/m<sup>2</sup>) up to the time when the core was drawn with the average current density (2,56 mA/m<sup>2</sup>) during stable operation (average current in march 2012) then one obtains an minimum expected service time in the “hot spot” area of 12,8 years, assuming that in these areas 100% zinc is available.

Ad 3): Self corrosion of the zinc mesh exposed to 100% relative humidity was determined to be < 0,1 mm/year. Self corrosion of the EZA anode during galvanic operation proved to be negligible. For that reason, EZA systems shall be put into operation no later than 3 weeks after installation. The service time calculation in ad 2) includes eventual self corrosion of zinc. If exposure to chloride salt solution and liquid water is prevented by coating the EZA surface with an appropriate coating, then one may safely assume a service time expectancy of a minimum 15 years even at the “hot spots” of the concrete members.

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”. Chloride ions move in the electric field generated by the current, flowing between the galvanic anode and the cathodic steel, analogously to the electrochemical chloride extraction and to cathodic protection (CP) with impressed currents (Castellote et al. 1999, Buenfeld et al. 1998, Eichler et. al. 2010). 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 extraction 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. This “one-way” transport of chlorides towards the galvanic zinc anode results in an efficient chloride extraction of chlorides from the concrete cover. This immobilization mechanism is especially efficient in the EZA system.

In a previously executed performance study of the 3M zinc-hydrogel anode (W. Schwarz 2003), it was documented that in the concrete cover of a test specimen prepared with cement containing 4 wt.% / cement weight of chloride, approximately 50% of the chloride was extracted by the galvanic zinc anode within one year of operation (Figure 6). Due to the chemical immobilization of the chloride ions near the anode, chloride ions are depleted at the concrete/anode interface, indicating that the rate of migration of chloride ions is faster near the anode than near the steel rebar.

One explanation for that observation might be that chloride ions are competing with hydroxyl ions transporting negative charges towards the anode. Near the steel rebar, hydroxyl ions are produced cathodically and will be present in increasing concentration.

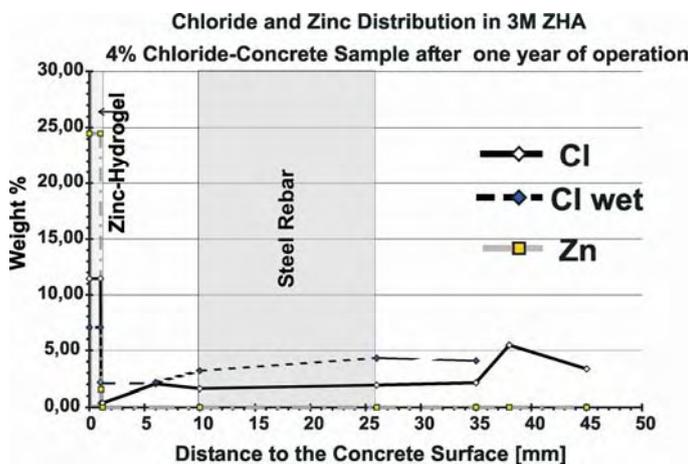


Figure 6. Chloride migration in the concrete cover of a concrete specimen loaded with 4% chloride/ cement weight towards a 3M zinc hydrogel anode mounted on the concrete surface after one year of operation. Cl, Zn... chloride and zinc concentration determined between steel rebar and Zn-anode by EDX, Cl wet... chloride concentration determined in a concrete core with a diameter of 10 cm by wet chemical analysis.

Near the anode, hydroxyl ions will be neutralized by the anodically produced acid, as a result hydroxyl ion concentration will be lower near the anode. Consequently, the rate of chloride ion transport will be highest near the anode, leading to the observed depletion of chloride ions near the anode.

Stoichiometrically, the chloride binding capacity of the anodically formed zinc hydroxide is approximately 2:1 per weight. In the present case, in which 2 kg zinc mesh is applied on the concrete surface, the chloride binding capacity of the galvanic zinc anode is 1 kg chloride/ m<sup>2</sup> concrete surface. Assuming e.g. a concrete cover of 2 cm then the galvanic zinc anode has a maximum capacity to immobilize 2 wt.% chloride/wt. concrete. Chloride concentrations in concrete contaminated with chlorides from sea water or from de-icing salt solutions seldom exceed 0,5 wt.%/ wt. concrete.

Thus, the chloride binding capacity of galvanic zinc anodes is high enough to extract chlorides from the concrete cover and immobilize them near the surface almost entirely. Therefore, one may expect that after the expected service time of a minimum of 15 years, the chloride level in the concrete near the rebars is sufficiently low and the alkalinity level near the rebar is high enough to prevent any renewal of steel corrosion.

### 3.2 De Meernbrug Steel Bridge



Figure 7. De Meerenbrug steel bridge in Utrecht with concrete abutments.

This 2010 project in Utrecht, The Netherlands, was initiated 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 deicing 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.

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.

In total some 200 m<sup>2</sup> 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 m<sup>2</sup> of concrete surface was applied.



Figure 8. One of the abutments of the De Meerenbrug steel bridge in Utrecht protected with the EZA system.

The amount of zinc relative to the amount of steel surface to be protected (relative steel density was well below 1 m<sup>2</sup> steel per m<sup>2</sup> concrete) showed a theoretical lifetime expectancy of more than 15 years.

The zinc mesh was embedded in non-cementitious TASC-mortar 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. 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 2011 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 repaired and the abutment was cathodically protected.

In total 90 m<sup>2</sup> was covered with zinc mesh with a total of 2 kg per m<sup>2</sup> of concrete (figure 9). Considering the low reinforcement density, a lifetime of over 10 years is expected. A total area of 90 m<sup>2</sup> 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<sub>2</sub>-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.



Figure 9. Support for the bearings on one of the abutments of the Hubertus viaduct in The Hague.

The entire surface was coated with the Decadex coating system.

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<sup>2</sup> concrete after 3 years of operation.



Figure 10. EZA protected with an acrylic coating (Decadex) exposed to de-icing salt solution from a leaking joint of the Hubertus viaduct in The Hague.

The depolarization of the cathodic protection system in 24 hours was well above the EN12696 criterion of 100 mV, averaging 174 mV depolarization in 24 hours. A typical depolarization measurement result from 30 June 2011 is given in Table 2.

Table 2 – Verification of the effectiveness of the GCP of the EZA by 24 h depolarisation measurements according to EN 12 696. Potential values in mV

Cell	Type	On-potential	Instant-off	1h off	24h off	24h Depolarisation
Re1	MnO <sub>2</sub>	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 (figure 10). The EZA has outlasted three winters, two of which were harsh. The Decadex coating protected the EZA efficiently from damage.

Performance has been above expectation in the first 3 years. The system is capable of withstanding water load, deicing salts, proves to be frost-thaw-resistant and shows no signs of aging.

#### 4 CONCLUSIONS

The performance of the novel EZA galvanic corrosion protection system, consisting of a zinc mesh embedded into a proprietary non-cementitious mortar that hardens to a solid electrolyte, was evaluated on concrete members of three different civil structures – an alpine road bridge in Austria, abutments of a steel bridge in Utrecht, NL and on the abutments of a viaduct in The Hague, NL.

Measurements according to EN12696 and with macro cell sensors over a period of up to nearly 5 years show that the EZA system has protected the steel reinforcement of the concrete members reliably from corrosion.

During very dry seasons (RH < 50%) and under freezing conditions (T < 5°C), galvanic currents decrease towards zero values but return to normal if humidity and/or temperature increase again. Frost-thaw salt resistance may be obtained by covering or impregnating the TAS-EZA with a water impermeable frost thaw salt resistant coating.

Calculated from the galvanic currents integrated over time, a maximum of 7 wt.% of the zinc-anode was consumed during the initial three years of operation. Considering self corrosion and local variations of the current flow, a service time expectancy of minimum 15 years, including “hot spots” – areas of high chloride content and humidity - may be safely assumed for a EZA containing a zinc mesh with 2 kg/m<sup>2</sup>., results indicate that, provided the EZA is covered with a protective coating, 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.

#### 5 ACKNOWLEDGEMENTS

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