LONG-TERM PERFORMANCE OF GALVANIC ANODES FOR STEEL REINFORCED CONCRETE

George Sergi[a], Peter McCloskey[a], Dave Simpson[a]

[a] *Vector Corrosion Technologies, georges@vector-corrosion.com*

Background

The first protected structure to have galvanic anodes installed is now coming up to 25 years. The performance of these anodes has been monitored throughout. The results revealed the mechanism underlying the continued performance of the anodes and proved that a highly alkaline porous encasing mortar was able to maintain a suitable environment for long-term activation of the zinc core. It also allowed the migration of the soluble zincate corrosion products away from the zinc/mortar interface. The gradual build-up of corrosion products diminished the current output of the anodes proportionately in a predictable way that allows a good design methodology to be implemented. The analysis of the results has also enabled the development of a whole new range of anodes, suitable for many applications from the corrosion prevention around patch repairs to the complete arrest of corrosion in large areas of structures. This paper follows the history of the development of galvanic anodes and speculates on their future as a system for prolonging the use of buildings and infrastructure in a sustainable way.

Trial Results

Current output of galvanic anodes was monitored over nearly 25 years and indicated a gradual decline in the level which could be approximated by an aging factor, $t_{1/2}$, whereby the current is shown to be halved at regular time intervals [1,2].

[1] Sergi, G., Seneviratne, G. & Simpson, D., "Monitoring results of galvanic anodes in steel reinforced concrete over 20 years" Construction & Building Materials, 269 (2021) 121309

[2] Whitmore, D. & G Sergi, G., "Long-term monitoring provides data required to predict performance and perform intelligent design of galvanic corrosion control systems for reinforced concrete structures" Corrosion 2021, AMPP, Paper No. 16792

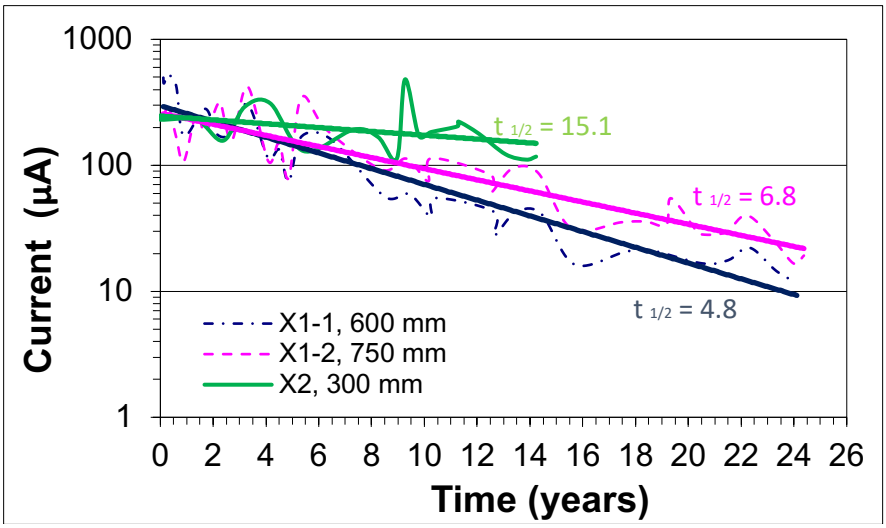

Figure 1 Current output of sets of galvanic anodes at three different spacings on centre with time indicating a consistent reduction in current output, described by an aging factor, $t_{1/2}$.

These anodes were employed as enhanced patch repairs in a bridge substructure in the UK. The two original and identical anodes were positioned at a spacing on centre of 600 mm and 750 mm. They were designed for a service life of 10 years but were providing useful current output for at least 15 years and continued to deliver a diminished level of current until now. Careful analysis of the results, including an autopsy of several removed anodes, indicated three deterioration mechanisms, vis, reduction in cross sectional area with time, decreasing level of activator, and pore blocking around the metal/ mortar interface from corrosion products. The latter mechanism was exacerbated by the large spacing of the anodes, which required them to work too hard at the beginning and restricted the initially soluble corrosion products from migrating away from the metal/ mortar interface.

Improved design of subsequent anodes, which included a larger proportion of activator in the encasing mortar and hence greater porosity around the interface from its consumption, as well as shorter spacing between anodes laid out in the structure, resulted in a much better performance of the anodes (X2 compared to X1 in Fig. 1). The aging factor increased from 4.8 years and 6.8 years to 15 years, with an expectation for the current output of the new anode to halve every 15 years. The discovery that current output with time is predictable led to improved design parameters based on a target current density at the end of the design period.

Further Development of Anodes

Understanding the properties of galvanic anodes and assessing their limitations led to new ideas and products. A major development was based on the understanding that it is possible to arrest corrosion of the steel reinforcement within a short period of weeks to months by applying a relatively high cathodic current density to steel of the order of 30-80 mA/m^2 [3]. Once arrest is achieved, only prevention of further corrosion is necessary at a current density in the region of 0.4-1.6 mA/m^2. A single dual-stage anode was developed that could provide both the high early current by an ICCP component and the subsequent cathodic prevention by an in-built galvanic anode (Fig. 2).

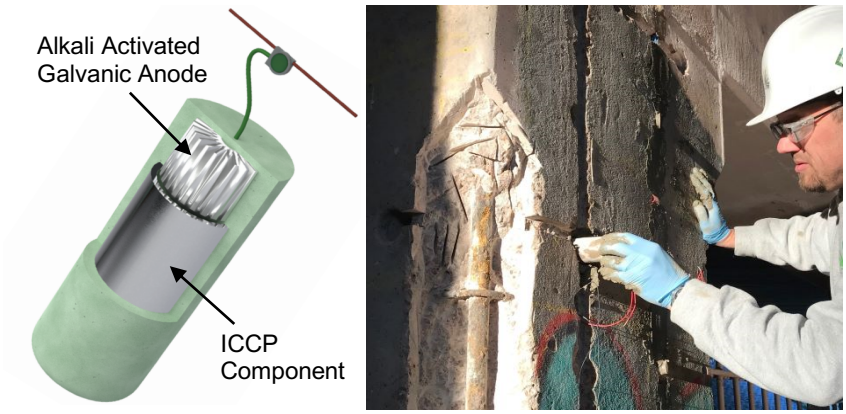

Figure 2 Dual-stage anode consisting of ICCP and galvanic anode components and example installation.

This Dual-stage anode system has now been used in several structures including in an aquarium in Genoa Italy. Another structure in Wales was also repaired using the Dual-stage technique [4]. Two piers and a crossbeam of a bridge had suffered from corrosion from chlorides in excess of 2% by weight of cement with cracking and spalling. Chains of up to 20 anodes were installed in several zones. The anodes were spaced out at 500 mm on centre in a grid configuration, designed to deliver a minimum of 300 kC/m^2 of charge during Stage-1. This was achieved over a period within 100 days. The current density was 30-80 mA/m^2. The high current density resulted in depolarised potentials during Stage-1 of the order of 180-230 mV, well above 100 mV suggested by the standards for cathodic protection. The high current density was required to achieve passivation of the steel which was achieved within Stage-1 with 24-hour depolarised potentials considerably higher than -150 mV vs silver/silver chloride, 0.5 M KCl (Fig. 3).

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[3] Rathod, N., Slater, P.R., Sergi, G., Seneviratne, G. 2018. “A suggestion for a two-stage corrosion mitigation system for steel reinforced concrete structures”. Proc. EUROCORR 2018, 102036, Kraków, Poland, 9 September 2018 https://research.birmingham.ac.uk/en/publications/a-suggestion-for-a-two-stage-corrosion-mitigation-system-for-stee

[4] Sergi, G., Seneviratne, G. and Simpson, D. 2022. “Long term control of corrosion of steel reinforcement by a two-stage cathodic protection method”. Concrete Solutions, MATEC Web of Conferences 361, 0 https://doi.org/10.1051/matecconf/202236102004

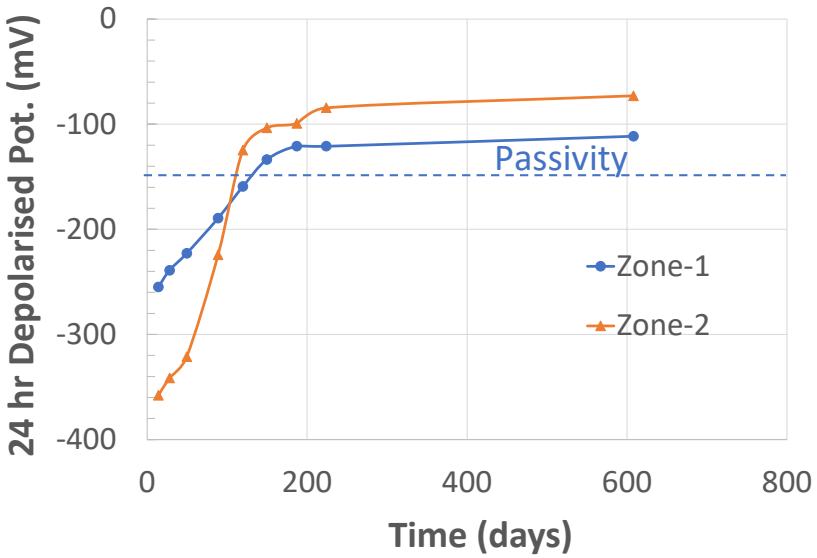

Figure 3 Change in the mean depolarized potential of the steel in two different zones, as recorded 24 hours after disconnection of the anodes.

Surface Applied Anodes

A galvanic anode up to 1 m long was developed initially for cases where extensions to structural elements were constructed and protection of the existing part was required, especially if some repairs were necessary owing to chloride contamination. The anodes were cast into the new concrete element and attached to the old steel reinforcement. It soon became clear that the high current output of these large anodes would have been very useful for protection applications where the anodes could be positioned on the surface of the structure. A surface anode was, therefore, developed which was contained in an impermeable casing in order to avoid drying of the anode. The system has now been installed in several structures in USA, UK and Italy with great success [5].

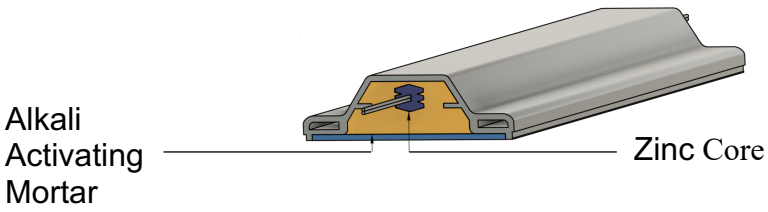

Figure 4 Schematic of a surface applied anode

The Future of Cathodic Protection

Judging by advancements in the last 5-10 years, it is inevitable that further developments will occur in the field of cathodic protection of steel reinforcement. It is likely that reliable and greatly simplified cathodic prevention systems will become more of a norm in new construction where corrosion prevention would be considered more desirable and cost-effective than eventual corrosion mitigation and repair or even replacement of the structure.

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[5] Sergi, G., “Life extension of existing steel reinforced structures by simple cathodic protection techniques for sustainable durability”. Life Cycle of Structures and Infrastructure Systems, Biondini & Frangopol (Eds), 2023, ISPN 978-1-003-32302-0, Open Access: https://www.taylorfrancis.com CC BY-NC-ND 4 license.

Considerably less power would be required to drive cathodic prevention systems as the current density does not need to exceed 1-2 mA/m^2 but more importantly, disruptions and added expenses for subsequent repair can be eliminated. Such low levels of current density can be easily achieved by well-designed galvanic anode systems. Furthermore, intelligent monitoring systems may be set up to predict when steel reinforcement corrosion initiation risk increases and activate an already installed cathodic prevention system. A move in that direction will be driven by the requirement for more environmentally acceptable procedures for structure management.

The replacement of existing structures, buildings and infrastructure in general, is environmentally very costly, so maintenance of existing structures and their conversion to new use is likely to become standard practice. For steel reinforced structural elements, extensive repairs to reinstate corroded areas would have to be reduced and cathodic protection would be a prime candidate for maintaining the structure to a safe condition with minimal repairs. For the same environmental reasons, low emission power generation will start to proliferate and self-powered localised CP systems, i.e. driven by solar and wind energy or rechargeable components, will likely become the norm.

The concept of cathodic protection would likely also evolve as a two-stage process similar to what was described above. Allowing a higher than what is currently considered to be a normal long-term cathodic current density of less than 10 mA/m^2 will inevitably arrest corrosion owing to the rapid build-up of alkali ions and the depletion of the aggressive chloride ions after which cathodic prevention would again be viable.

The continual development of galvanic anodes would likely increase the Aging Factor to well beyond 20 years by a combination of better design of the metallic sacrificial element and of the encasing activating mortar. This would allow a much longer service life of galvanic anodes at designable current densities for specific environmental conditions and particularly, ambient temperature.