Paper No.
16712

CORROSION Virtual Conference & Expo April 19-30 2021

AMPP Association for Materials Protection & Performance

Long-term Monitoring Provides Data Required to Predict Performance and Perform Intelligent Design of Galvanic Corrosion Control Systems for Reinforced Concrete Structures

David Whitmore[#] & George Sergi

[#]Vector Corrosion Technologies Ltd. 474 Dovercourt Drive
Winnipeg, MB, Canada R3Y 1G4 Tel:
+1-204-489-6300

Abstract

Long-term monitoring of galvanic anodes installed in reinforced concrete structures has provided the data required to better understand long-term anode performance. Detailed analysis of field and laboratory performance data has identified an aging pattern which follows an exponential decrease in current output similar to a 'half-life' principle where current is halved at constant periods of time. A predictive model has been developed to describe anode current output over time. The predictive model which includes an "aging-factor" can be determined for any galvanic anode. The aging-factor is primarily dependent on the activating chemistry of the anode. The aging-factor also depends on the relative surface area of the anode compared to the surface area of steel wherein the harder an anode works early on in its life the worse its aging-factor becomes.

The predictive model which is based on long-term field data allows galvanic anode systems to be designed to meet any desired performance criteria at any point in time. The model may also be used to design galvanic cathodic protection systems to provide specifiable long-term current density and more controlled polarization to the steel.

Keywords
Galvanic anodes, Corrosion control, Steel reinforcement, Aging-factor

Background

Galvanic anodes for mitigation of corrosion of steel in concrete have now been monitored to various degrees for up to 20 years. A large volume of data exists, which has enabled this detailed analysis. This in turn has allowed a much better understanding of long-term anode behavior and the development of predictive models.

A major finding of this analysis is that the long-term current of a particular anode diminishes in an approximately exponential manner that can be modelled by a "half-life" principle.[1] This was shown by analysis of many sets of current output results which revealed repeated behavior of a slowly decreasing trend consistent with Equation 1.[2]

$$i_t = i_o e^{-\lambda t} \qquad \text{Eq. (1)}$$

Where,
i_t = current density at time, t (mA/m^2)
i_o = initial current density, (mA/m^2)

λ = exponential decay constant,
t = time (years)
The relationship usefully allows an estimation of an aging-factor, that can define the current output capability of the anode at any future time. The value of the aging-factor in years required for halving of the current can be easily determined by inserting the exponential decay constant, λ, as determined in Equation 1, into Equation 2.

$$t_{1/2} = \frac{\ln(2)}{\lambda} \qquad \text{Eq. (2)}$$

Where,
$t_{1/2}$ = the time required for the current density to be halved, and
λ = exponential decay constant, as in eq. (1)

Knowledge of such parameters, describing the long-term behavior of the anodes, allows a better design of the galvanic corrosion control system if it can be shown that it is constant and quantifiable for a particular type of anode based on the zinc activation chemistry, encasement mortar or anode core design.

This paper extends the data analysis to several field studies and lab trials, most already reported in literature, and attempts to elucidate the aging-factor concept and explain the factors that contribute to the aging of galvanic anodes. It further discusses the substantial impact of the aging-factor on the design of long-term galvanic corrosion control and cathodic protection systems.

Field studies
Monitoring of anodes employed for enhancing three different patch repairs on a bridge in Leicester, UK, has been highly successful in revealing the performance of alkali-activated galvanic anodes. The anodes were utilized for preventing incipient anode formation or the ring corrosion effect which ordinary patch repairs have historically suffered from.[3,4] Results from one set of galvanic anodes in a beam, have been reported extensively[1,5] and variation of the current is reproduced in Figure 1.

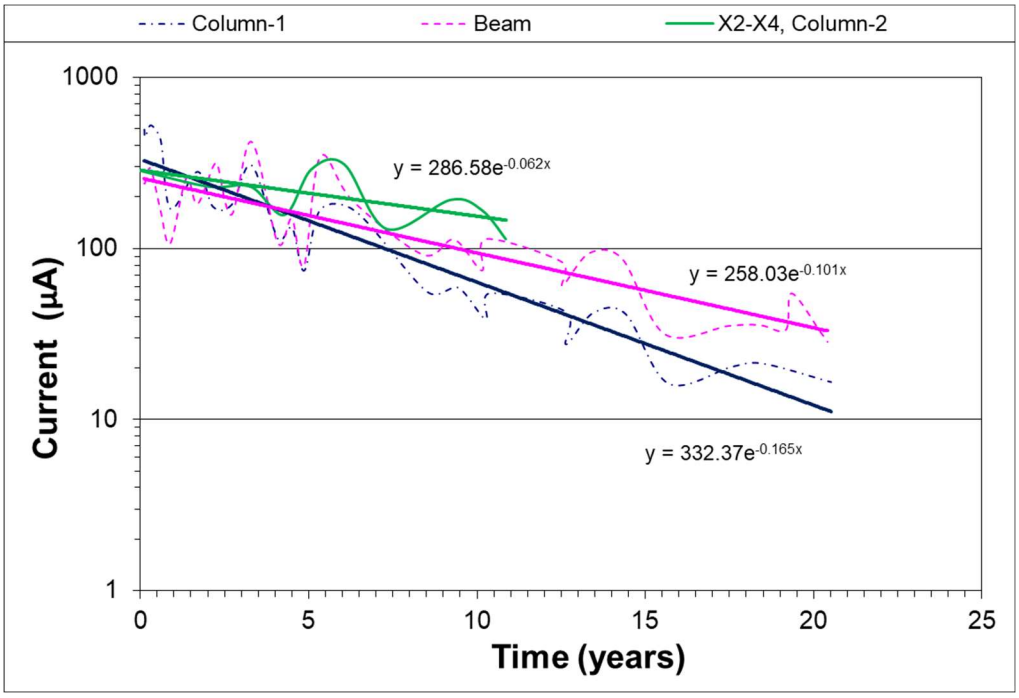

Figure 1 Current reduction with time of three sets of anodes at the same bridge but with differing spacing of anodes: Column-1, 750 mm on center, Beam, 600 mm on center and Column-2, 300 mm on center. Anodes embedded in Column-2 were of a later version and each had either double or four times the zinc surface area than the other two earlier sets.

The variation of the current, experiencing peaks and troughs, is partly caused by the effect of relative humidity, which influences the concrete resistance. It was shown, however, to be particularly sensitive to temperature of the concrete and in this case, as with the anode set in Column-1, which were installed at the same time (Fig. 1), peaks were recorded during summer months and troughs during the winter. The current output is expected to be governed by the Arrhenius equation (Eq. 3). This effect was demonstrated in field tests over a 35º C range[2] and in the laboratory of triplicate galvanic anodes embedded in reinforced concrete slabs and exposed over the range of 8º C and 30º C (Fig. 2). Figure 2 suggests that the current output of the galvanic anodes roughly doubled every 10º C increase in temperature while in the field trial this doubling appeared to occur nearer a 15º C temperature increase.

The apparent difference in current variation with temperature between laboratory-controlled specimens and field tests can be explained by the hysteresis response of temperature gain or loss of the concrete during the daily variations. It can be assumed, to a reasonable degree of accuracy, that the current range over a typical annual temperature range in the UK and across many states in America, if this range is assumed to be ±15º C, that the current output variation could be within a range of half to double the mean.

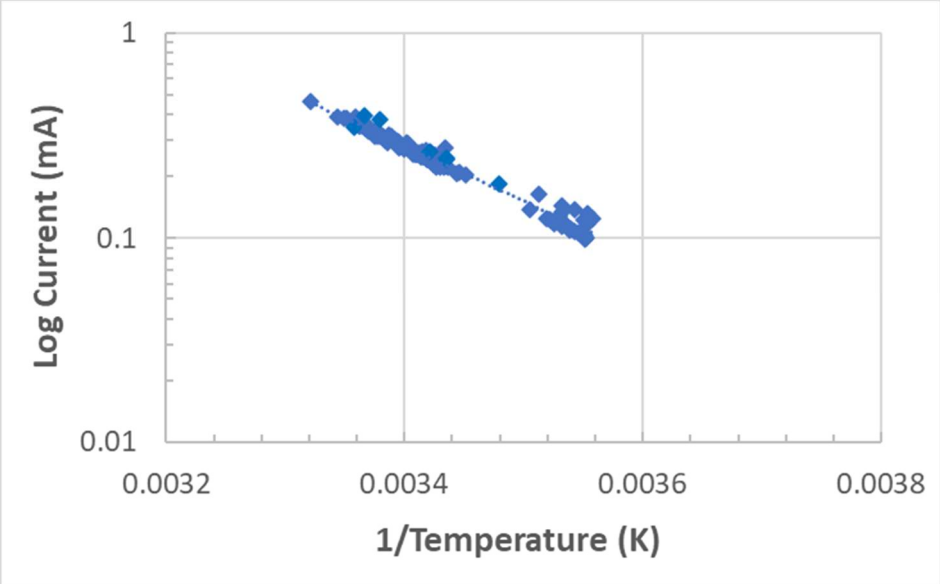

Figure 2 Relationship between the reciprocal of the concrete temperature in K and the logarithm of current output of the anode

$$k = \mathrm{A}e^{-\frac{Ea}{RT}} \qquad \text{Eq. (3)}$$

Where,

k = Rate constant
A = Frequency factor
Ea = Activation energy
R = Universal gas constant
T = Absolute temperature (K)

A form of the equation[6] relates the corrosion rate, i.e. the current output from the zinc, to the reciprocal of temperature (Eq. 4).

$$Logi_{corr} = Log\ A - \left(\frac{\Delta Ea}{2.303RT}\right) \quad \text{Eq. (4)}$$

Where,
i_{corr} = Corrosion current of zinc metal
ΔEa = Apparent activation energy of the corrosion process

What is striking from Figure 1, is the different rates of exponential decay, λ, of the anode sets in the three structural elements. The anodes in the beam and in Column-1 are identical and were installed at the same time yet the aging-factor of each set is very different, the current output halving over a 6.9 year period for the beam but only over a 4.2 year period for Column-1. Concrete quality and steel density are comparable and concrete resistivity and environment have been consistently similar over the whole exposure period, the only difference being the spacing between adjacent anodes. In the beam the anodes were set at a spacing-on-center of 600 mm whereas in Column-1 the spacing was 750 mm. The effect of this spacing can be seen in the early current output of the anodes (Fig. 1). In the beam the first maximum current was of the order of 300 µA but in Column-1 this was in excess of 500 µA. This early high current in Column-1 was induced by the greater steel surface area that each anode in the set was required to protect. As a consequence, the current output diminished more rapidly in Column-1. In an alkali-activating medium, zinc, following its dissolution, exists as soluble zincate ions which are able to migrate within the pore structure of the encasing mortar, precipitating out as zinc oxide when supersaturation of zincate occurs[1,2]. The fast early production of zincate ions in the case of Column-1 would have restricted their migration further into the encasing mortar pores before supersaturation occurred so zinc oxide would have formed close to the zinc/mortar interface reducing the immediate porosity around the zinc metal and slowing down further dissolution of the metal. The lower early current of the anodes in the beam and the gentler zinc dissolution allowed the zinc corrosion products to migrate further into the mortar pore structure allowing a more open path for electrolytic current flow.[2]

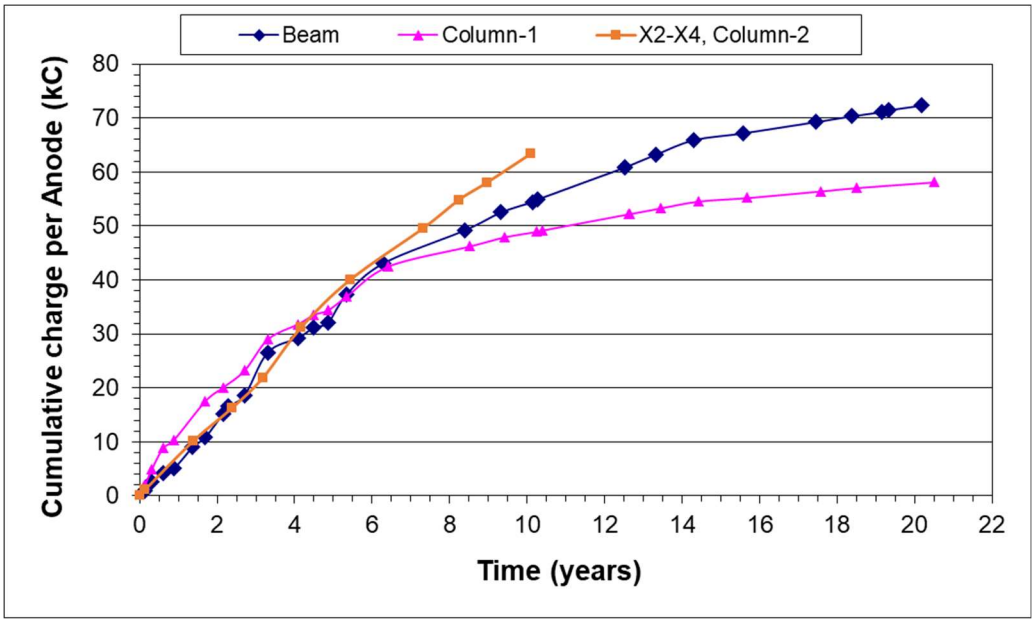

Figure 3 Mean cumulative charge delivered by the anodes in Figure 1 with time

If the accumulated charge with time is studied (Fig. 3), it becomes clear that the long-term ability of the anode to deliver charge to the steel becomes inhibited if it is required to deliver high charge at the beginning. There is clearly little chance that the anodes in Column-1 will deliver as much long-term charge as those in the beam or in Column-2.

This concept becomes even clearer if the results from the third monitored element, Column-2, are analyzed. The aging-factor was shown to be significantly higher, 11.2 years, with the early current output being only slightly higher than that achieved in the beam. These particular anodes were a combination which has double or four-times (X2 & X4) the surface area of the earlier anodes employed for the beam and Column-1 and were placed at only a 300 mm spacing-on-center, in accordance to contemporary practice for the steel density and level of chloride contamination. The lower current requirement placed upon these anodes enabled much-improved longevity.

Table 1 Exponential decay constant, λ, and 'aging-factor', $t_{1/2}$, of alkali-activated galvanic anodes grouped into sizes and types showing also initial anode current and spacing. X1 refers to a standard anode. X2 has double and X4 four times the effective surface area of X1 anode.

Anode type and size	Site Location/ Concrete Element	Initial current per anode (mA)	Anode spacing (mm)	λ	$t_{1/2}$	Mean $t_{1/2}$
X1- Repair	Leicester Crossbeam[1]	0.25	600	0.101	6.9	
X1- Repair	Leicester Column-1[2]	0.50	750	0.165	4.2	5.6
X1- Grid	India Slab[7]	0.62	300	0.118	5.9	
X2- Repair	Leicester Column-2[8]	0.26	300	0.055	12.6	
X2- Grid	India Slab[7]	0.99	300	0.055	12.6	13.0
X2- Grid	M53 Abutment[9]	0.29	300	0.050	13.9	
X4- Repair	Leicester Column-2[8]	0.36	300	0.075	9.2	10.3

X4- Grid	India Slab[7]	2.22	300	0.066	10.5	
X4- Grid	M53 Abutment[9]	0.55	300	0.066	10.5	
X4- Grid	Ivy St. Abutment[9]	0.64	300	0.064	10.8	
Long Rod	Ohio Abutment[5]			0.089	7.8	11.3
Long Rod	North Otter Bridge Deck[2]			0.047	14.7	
Mean all					10.0	

Similar analysis of other sets of alkali anodes has enabled an estimation of the exponential decay constant, λ, and the aging-factor, $t_{1/2}$, in different applications and environments which are summarized in Table 1. The values for the X2 and X4 type anodes in Column-2 were treated separately in order to group anode performance in relation to size.

Accelerated laboratory tests for the long-term prediction of performance have always suffered from this associated reduction in apparent longevity. Figure 3 shows such laboratory test results where X1-type anodes, encased in additional repair concrete material giving a diameter of 60 mm and height of 100 mm were exposed in a sand pit simulating concrete pore solution with 5% chloride addition, each connected to 250 cm^2 of mild steel bar. This highly conductive medium forced the anodes to produce an early current in excess of 600 µA. The exponential decay constant, λ, was calculated to be 0.776 resulting in an aging-factor of only 11 months. Once again, the high current delivery requirement had accelerated the aging of the anodes.

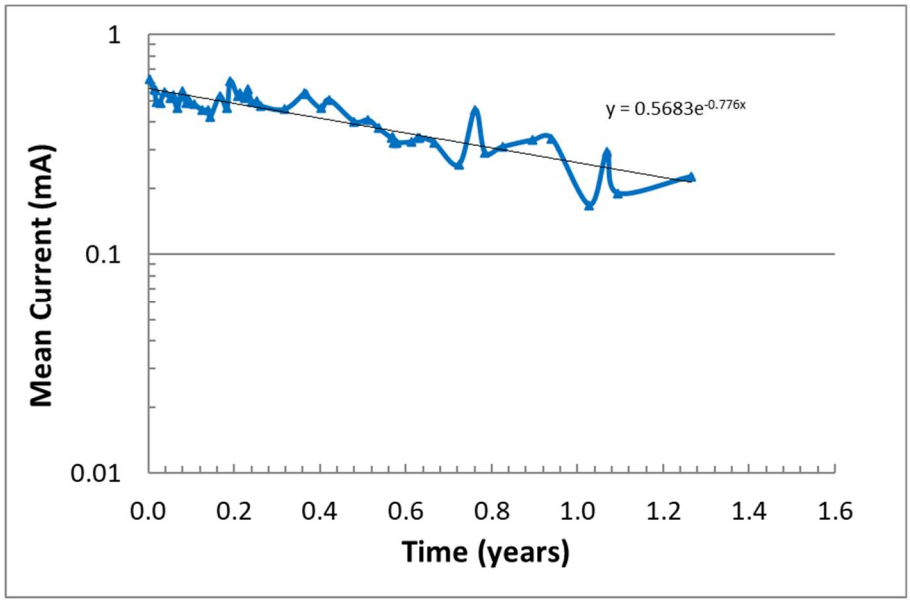

Figure 3 Mean decaying current output of a group of six X1-type anodes in an accelerated laboratory test.

Similar results were obtained by Dugarte & Sagues[10] when they tested anodes of Type X1 in concrete slabs. The early current output of single anodes per slab in their case was of the order of 950-1260 µA resulting in an aging-factor of between 9 months and 20 months. Interestingly, two sets of halide-activated anodes tested in the same way for the same study achieved a mean aging-factor of just 6 months. The same halide-activated anodes in a similarly accelerated test[11] only achieved a mean aging-factor of 5 months, ranging from 4.4 to 6.8 months.

Only two relatively long-term sets of current output results from halide-activated anodes in field studies were identified in the literature.[12,13] The calculated values of λ and $t_{1/2}$ of these two sets of data are shown in Table 2. Both were found to have an aging-factor less than 3 years. This reduced performance is likely associated with the activating medium where zinc corrosion products are quite insoluble in a halide activator and deposit close to the zinc/encasing mortar interface.

Table 2 Exponential decay constant, λ, and 'aging-factor', $t_{1/2}$, of halide activated galvanic anodes from data found in the literature

Anode Type	λ	$t_{1/2}$	Reference
Point	0.237	2.9	Bewley[12]
Point	0.544	1.3	Bennett & McCord[13]

Intelligent Design

Knowledge and understanding of the long-term behavior of anodes can be intelligently used to design long-lasting and controlled protection of steel reinforcement with the use of galvanic anodes. In its simplest form, a minimum current density can be chosen for a particular period of time, e.g. minimum current 2 mA/m^2 over a 20 year design life. To achieve the specified minimum current density over the specified design life and knowing the aging-factor of the anode to be used, it is possible to calculate the initial current density required and the correct spacing of the anodes to achieve the specified criteria. An example of this is given in Figure 4 where the mean aging-factor of the X2-type alkali-activated anode and the mean aging-factor of a halide-activated anode is shown.

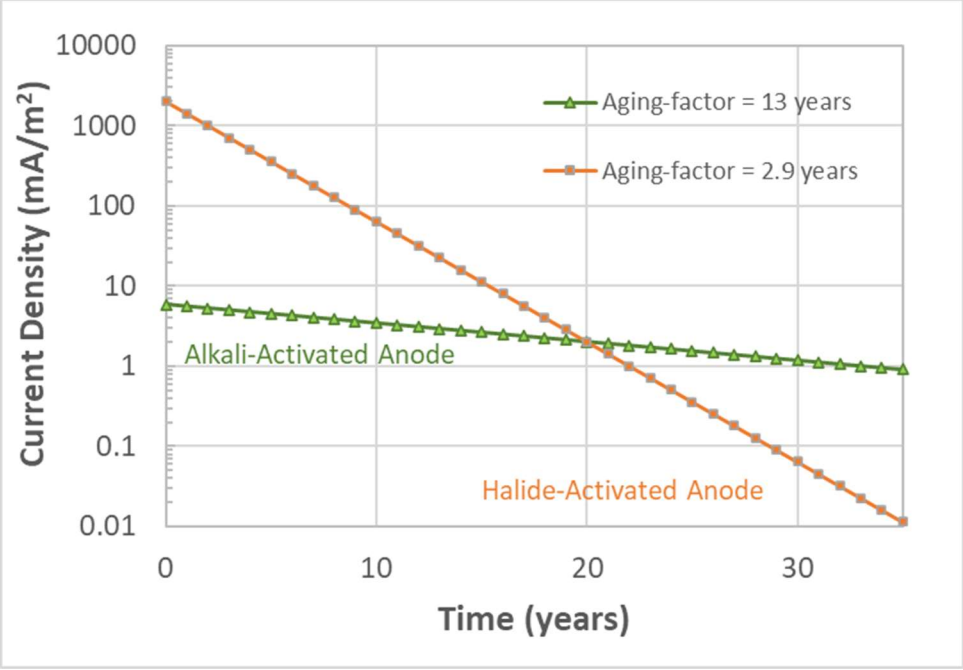

Figure 4 Plot of anode current density vs time for two types of anodes with different Aging-factors such that both anodes provide a current density of 2 mA/m^2 at 20 years.

Both sets of anodes can theoretically achieve the specified minimum current density over 20 years. The anodes with the longer aging-factor of 13 years are clearly more suitable as the initial current density only needs to be an achievable 5.8 mA/m^2 while that of the shorter aging-factor anodes require an initial current density of nearly 2,000 mA/m^2.

As stated above, it is important to consider the current output over time and to avoid making decisions based solely on the initial current output. Figure 5 below shows the current output over time of alkali-activated anodes and halide-activated anodes as illustrated above where the anodes are spaced to give an initial current density of 2mA/m2. Although both sets of anodes provide the same initial current density, the anodes with the shorter aging-factor decay quickly and will provide little benefit after a short period of time.

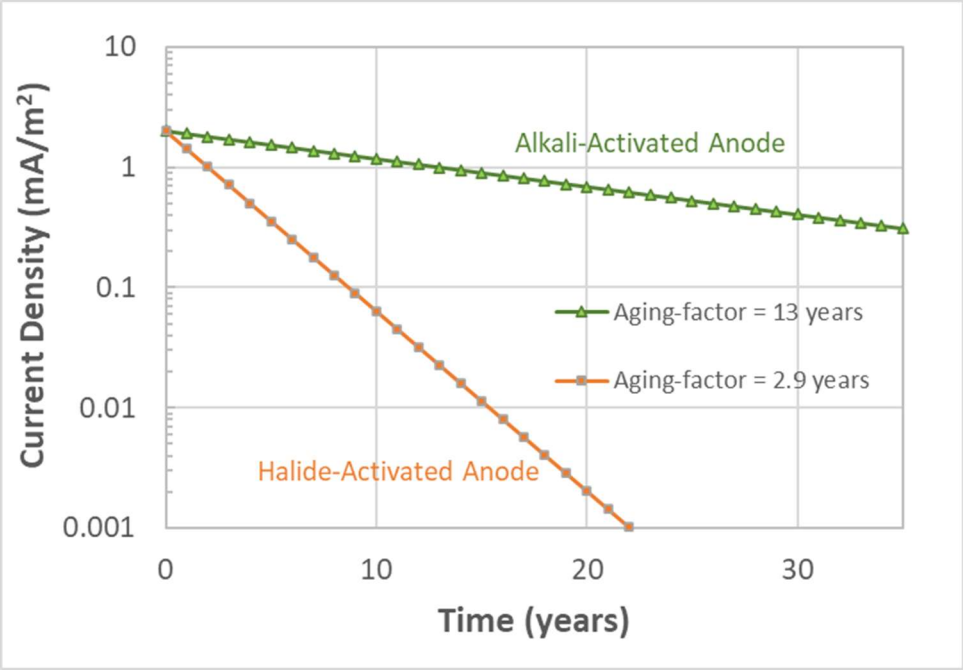

Figure 5 Current density vs time for two types of anodes with different Aging-factors both of which start with a current density of 2 mA/m^2.

A complete design should also consider temperature variation and its effect on current output. Anode performance data should, include the initial current output, the average annual temperature and the aging-factor. This is important since a certain anode could be applicable for a given structure in the UK with an annual mean temperature of 12.5 ºC whereas a larger anode would be required for the same structure in a more tropical environment such as Florida where the mean annual temperature is over 21 ºC. These adjustments allow performance-based design of galvanic anode systems for reinforced concrete structures to be tailored to the needs of different environments.

Conclusions

Study of long-term galvanic anode performance has enabled better understanding of anode capability. Analysis of data has revealed an approximate exponential current reduction with time which simulates a 'half-life' principle and allows an aging-factor to be calculated.

The aging-factor was shown to be dependent on the activating medium. In the case of alkali-activated zinc anodes, it was also shown to be controlled by the initial current output requirement placed on the anode, a gentler early current for a specific, extended aging-factors as zinc corrosion products are able to dissipate more freely within the pore structure of the encasing mortar and reduce the restriction of ionic current paths.

Current output was also seen to be related to temperature and be governed by the Arrhenius equation. The temperature and aging-factor controlling components can be easily factored into a more intelligent predictive design process for galvanic corrosion control systems.

References

1. Sergi, G., Seneviratne, G., & Simpson, D. "Monitoring Results of Galvanic Sacrificial Anodes in Steel Reinforced Concrete over 20 Years", Submitted, *Constr. Build. Mater.* (2020)
2. Sergi, G., Seneviratne, G. "Improved Design Considerations for Steel Reinforcement Corrosion Control with Galvanic Anodes Following Performance Evaluation from Analysis of Site Data", Submitted in *Structural Faults & Repair,* Edinburgh (2021)
3. D. P. Barkey, "Corrosion of steel reinforcement in concrete adjacent to surface repairs" ACI Mater. J. 2004, 101, 266.
4. S. Soleimani, P. Ghods, O.B. Isgor & J. Zhang, "Modeling the kinetics of corrosion in concrete patch repairs and identification of governing parameters" Cem. Concr. Compos. 2010. 32, 360.
5. Sergi, G. "Ten-year results of galvanic sacrificial anodes in steel reinforced concrete", *Mater. Corros.* (2011), **62,** 2 pp. 98-104
6. Emran, K. M. "Effects of concentration and temperature on the corrosion properties of the Fe–Ni–Mn alloy in HCl solutions", *Research on Chemical Intermediates* (2015) 41, pp. 3583–3596
7. Kamde, D., Krishnan, N., Pillai, R., Sergi, G., Shah, D., & Velayudha, R., "8-year performance of cathodic protection systems in reinforced concrete slabs and life-cycle cost benefits", Proc. Int. Conf. on Sustainable Materials, Systems and Structures, Durability, Monitoring and Repair of Structures, 20-22 March 2019 – Rovinj, Croatia, pp. 611-618
8. Sergi, G. & Seneviratne, G. "Extending residual service life of steel reinforced structures by the use of galvanic anodes", Proc. Concrete Solutions, 5th Int. Conf. on Concrete Repair, Queens University, Belfast, UK, 1-3 September 2014
9. Rathod, N., Slater, P., Sergi, G., Seveviratne, G. & Simpson, D. "A fresh look at depolarisation criteria for cathodic protection of steel reinforcement in concrete" MATEC Web Conf. 289, 03011, 2019, Concrete Solutions
10. Dugarte, M.J. & Sagüés, A.A. "Sacrificial Point Anodes for Cathodic Prevention of Reinforcing Steel in Concrete Repairs: Part 1—Polarization Behavior" *CORROSION*, 70, 3, pp. 303-317
11. Berke, N. S., Ade, K. M., Nemunaitis, B. & Hanford, W. "Evaluation of Embedded Sacrificial Anode Probe for Use in Concrete Repair" NACE Corrosion 2019, Paper 13097

12. Bewley, D. “High-power, low-maintenance, hybrid corrosion protection”, Bridge construction and repair, *Concrete*, Oct 2016, pp. 25-27
13. Bennett, J. E. & McCord, W. T. “Performance of zinc anodes used to extend the life of concrete patch repair”, NACE Corrosion 2006, Paper 06331