"An Approach For the Evaluation of Performance of Point Anodes for Corrosion Prevention of Reinforcing Steel In Concrete Repairs" A.A. Sagüés, V. Balakrishna and R.G. Powers, pp. 35-41, Proceedings of ***fib*** Symposium "Structural Concrete and Time", La Plata, Argentina, Sept. 28-30, 2005, A. Di Maio and C. Zega, Eds., ISBN 987-21660-1-3.

AN APPROACH FOR THE EVALUATION OF PERFORMANCE OF POINT ANODES FOR CORROSION PREVENTION OF REINFORCING STEEL IN CONCRETE REPAIRS

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ABSTRACT

Repair of chloride contaminated concrete with fresh concrete passivates the steel in the repair region, but that also elevates the steel potential in the surrounding, still contaminated concrete. Thus, the risk of corrosion increases in the surrounding region. Sacrificial anodes are being promoted as a means to avoid this risk by cathodically polarizing the steel in the repair and surrounding region. An approach to evaluate candidate anodes for this application is presented. The galvanostatic operation history of the anode is used together with independent steel polarization data to forecast the performance of the anode-reinforcing steel system under diverse application scenarios. Examples of experimental and analysis methods developed for this purpose are presented along with initial results.

RESUMEN

Las reparaciones de hormigón contaminado con cloruros por medio de hormigón nuevo repasivan el acero embebido en la zona de reparo, pero también elevan el potencial del acero en la zona alrededor, incrementando ahí el riesgo de corrosión. Para evitar ese riesgo, se ha propuesto el uso de ánodos de sacrificio que polarizan catódicamente el acero en la zona de reparo y sus alrededores. Se presenta aquí un método para evaluar ese tipo de ánodo. Se usa la historia galvanostática operacional del ánodo para pronosticar su comportamiento bajo varios escenarios de aplicación. Se presentan también ejemplos de métodos de análisis y resultados iniciales.

INTRODUCTION

Chloride-induced corrosion of reinforcing steel in concrete creates expansive corrosion products that crack the concrete cover. Repair often consists of removing the cracked concrete and replacing it with chloride-free concrete. It takes only a small amount of corrosion penetration (e.g. ~0.1 mm (0.004 in)) of the reinforcing steel bar (rebar) to develop concrete cracks, so sometimes rebar replacement may not be needed as the remaining steel cross section may be still adequate. Patch repair limited to the portion of the structure showing conspicuous cracking may have detrimental consequences however if, as is often the case, zones adjacent to the patch have already experienced substantial chloride contamination.

The problem stems from the electrochemical nature of corrosion of steel in concrete, which starts when the chloride concentration at the rebar surface has exceeded a critical value known as the chloride corrosion threshold (C_T). The value of C_T depends not only on variables such as the rebar material or the pH of the concrete pore water, but also on the electrical potential E of the steel with respect to the surrounding concrete. The evidence available to date suggests that if all other factors remain the same, C_T tends to increase by a large factor (e.g. one order of magnitude or more) when E decreases from ~-100 mV in the Copper/Copper Sulfate Electrode (CSE) scale to ~ -0.7 V CSE (Presuel et al 2005b).

The value of E for a short isolated rebar segment is determined by the interplay between electron-consuming reactions (principally reduction of dissolved oxygen in the pore water) and electron-producing reactions (such as the dissolution of iron from the rebar in the corrosion process). Steel that is in the passive condition (that is, before C_T was exceeded) in atmospherically exposed concrete tends to develop E~-100 mV CSE, while steel that is corroding actively in chloride-contaminated concrete often shows E values in the ~-300 mV CSE to -600 mV CSE range. If the segment is not isolated but part of a larger rebar assembly, then because of electrochemical coupling the local value of E is elevated or decreased if the potential in the surrounding zones is high or low respectively. This *macrocell* coupling effect is stronger if the concrete electric conductivity is high (low resistivity).

An important consequence of macrocell coupling is that passive steel surrounding an actively corroding spot may develop E values significantly more negative than if the rebar assembly were discontinuous. As a result, the value of C_T in that surrounding steel is increased and active corrosion does not take place there even if chloride contamination at the rebar depth is already substantial. In effect, the rebar at the corroding spot is preventing the initiation of corrosion in the surrounding region – an instance of a situation generally named *cathodic prevention* (Pedeferri et al 1996). The detrimental effect of patching indicated earlier stems from the steel at the former corroding spot becoming passive, so that its potential increases and the cathodic prevention effect on the surrounding zone subsides. The newly lowered value of C_T in the surrounding zone then may be less than the existing chloride concentration, and active corrosion could promptly start, leading to a *ring* or *halo* corrosion damage effect around the patch.

To forestall the ring effect, small anodes are available commercially, intended to be cast in the repair patch (Whitmore and Abbott 2003, Sergi and Page 2001). The anodes usually consist of a zinc alloy piece with connecting wires, embedded in a mortar disk. Electronic connection is made by tying the wires to the rebar in the patch. The mortar around the zinc alloy is formulated to obtain high pore water pH to promote a regime where zinc is in the active condition. In that condition, the isolated (open circuit) value of E for Zn is highly negative (~-1 V CSE). Macrocell coupling with the rebar in the patch and the surrounding zone then could allow for appreciable lowering of E and restoration of a cathodic prevention regime to values comparable to or greater than those existing before the repair. The mortar formulation may also include humectants to promote retention of pore water to sustain active corrosion of the anode. Proprietary patch concrete mixtures are also marketed to increase the conductivity around the anode and maximize macrocell coupling with the ring zone

An ongoing research program is evaluating the performance of commercially available point anodes. A newly initiated research program at the University of South Florida, sponsored by the U.S. Federal Highway Administration, is assessing the durability and efficiency of these anodes by determining their potential-current operating function, and its dependence on time and integrated charge delivery as well as the mechanisms responsible. The operation history of the anode is then used together with independent steel polarization data to forecast the performance of the anode-reinforcing steel configuration system under diverse application scenarios. This paper describes the evaluation approach and presents early results of the investigation.

EVALUATION APPROACH

The investigation aims to characterize anode performance by determining the potential/current delivery function (PCF) of the anode, and its dependence on relevant service variables (e.g. moisture content and alkaline content of surrounding concrete) and on service time. Implicit in this approach is determining the ability of the anode metal to remain in the active condition over long periods of time, as well as the cumulative capacity of the anode (total usable charge delivered) and associated ultimate service life capability.

The PCF and its time dependence determined by testing can then be contrasted with known reinforcing steel polarization parameters to determine the ability of the anodes to achieve cathodic prevention over a usable distance (throwing power) under realistic service conditions which may include, for example, high performance concrete with high electric resistivity.

Figure 1 shows the concepts involved and their application. Consider an anode being evaluated when initially placed in service. The anode is expected to develop under open circuit (OC) condition, a potential in the order of -1V CSE. If placed in contact with a passive rebar assembly, the anode delivers current and polarization causes the anode potential (as measured against a reference electrode placed in close proximity to the anode) to become less negative than in the OC condition. The polarization should be larger the larger the current demand, as described by Curve 0 which is effectively the PCF of the anode at the beginning of its service life. Curve 0 would also result from joining the locus of separate points corresponding to a number of similar newly placed anodes acting independently at different current demands. If current delivery of each anode were kept constant for a long time, the anode performance is expected to degrade somewhat from causes such as zinc consumption (with consequent decrease in effective surface area) and accumulation of corrosion products that may impede the passage of ionic current or even promote passivation of the anode surface. The manifestation of such degradation would be a shift to more positive values in the anode potential, likely to a greater extent at longer services times and higher currents, as illustrated by PCF Curves 1 (time = t_1) and 2 (time = $t_2 > t_1$) . Those curves can be obtained experimentally by operating the anodes while connected to an external galvanostatic circuit. Both the ability of the anode to remain active and the cumulative capacity of the anode can then characterized from the curves at each current regime.

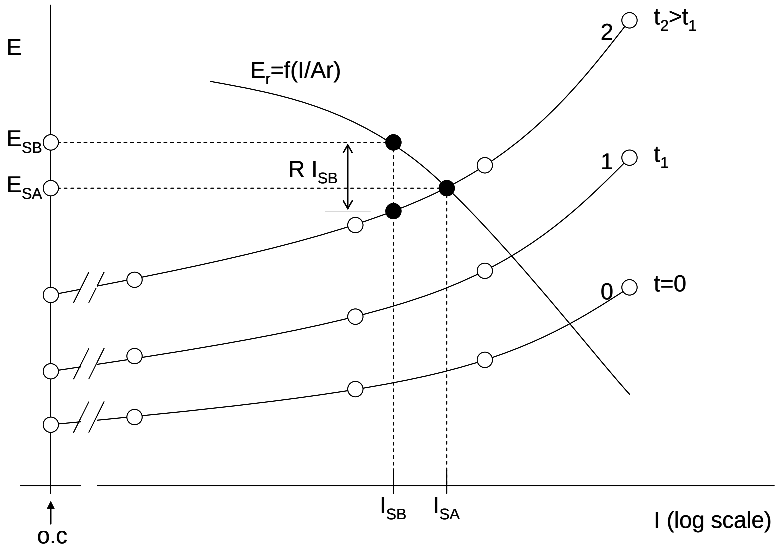

Fig. 1. Idealized diagram of the evaluation approach.

A diagram thus obtained (family of PCF curves as function of time) for a given anode type and environment, including mortar type and humidity condition, can serve as a standardized descriptor of the anode performance for those conditions. This procedure eliminates variability that appears when evaluating anodes, as it is often done (Sergi and Page 2001), by coupling to a passive rebar assembly embedded in the same mortar or concrete. The variability in such cases stems from the current demand by the rebar assembly, which may sometimes be sustained at high levels for long periods of time, or drop rapidly early in the life of the test depending on the initial condition of the steel surface or small variations in the pore water composition or concrete moisture.

The potential-current trajectory described as time progresses for an anode in actual service is always more complicated than a vertical line in a PCF diagram, which would correspond to the way in which the data are obtained under galvanostatic conditions. Nevertheless, the curves in the diagram may be used to obtain a bounding indication of how much protective action may be expected from a rebar assembly for which there is information on its polarization characteristics. As an illustration, the polarization information can take the form of the long term potential-cathodic current density polarization curve E_r=f(i) for the reinforcing steel, determined by prior measurements. Thus if the anode placement density is such that each anode is to protect an area A_r of rebar surface area, the curve E_r=f(I/A_r) describing the polarization characteristics of that area (Sagüés et al 2003) can be superimposed directly on the PFC diagram to determine how much rebar polarization may be achieved at different aging conditions. If the resistivity of the concrete path between anode and rebar is very small, the rebar receives a current I_{SA} and is polarized down to potential E_{SA}, which may then be compared with the minimum requirements for corrosion prevention in the specific application considered. E_{SA} is the best polarization level to be expected; if concrete resistivity is finite so an effective circuit resistance R applies, the current is less (I_{SB}) and the rebar polarization is only down to E_{SB}. The amount of polarization is proportionally less if the area to be polarized is greater, as the effect is the same as moving the rebar polarization curve to the right. This type of analysis to project the extent of useful anode action based on the results of the test can be extended to more complex system geometries by appropriate current distribution modeling (Presuel-Moreno et al 2005a, Sagüés et al 2003).

EVALUATION IMPLEMENTATION EXAMPLE

The program is evaluating two types of commercially available anodes, both using a small mass (e.g. ~ 30 g) zinc alloy anode embedded in a highly alkaline mortar pellet ~30 mm thick and with circular/rectangular shape ~ 70 mm diameter/wide. The mortar in one of the anode types contains admixed humectant. The connection to the zinc is provided by carbon steel tie wires protruding from sides the mortar pellet. Those wires are intended to be tied to the adjacent reinforcing steel in a typical repair application.

The basic test specimen arrangement (Figure 2) consists of a prism 20 cm x 20 cm x 10 cm) with a test anode placed near the center. An embedded activated titanium rod (ATR) reference electrode (Castro et al 1996) (periodically calibrated against a Copper Sulfate Electrode (CSE)) is placed against one of the external mortar faces of the anode. Alternatively, an externally placed CSE is used with appropriate compensation for electrolyte resistance if potential measurements are done with current on. An activated titanium mesh of the type used for impressed current cathodic protection of steel in concrete is cast underneath one of the main faces of the prism. Connecting wires from anode and mesh are connected to a galvanostatic circuit. Two cementitious media are used for the prisms: a specialty polymer modified cementitious repair mortar extended with ~1cm size limestone coarse aggregate, and an ordinary repair concrete (w/c=0.41, silica sand and ~1 cm size limestone as fine and coarse aggregates respectively). Test currents are 0 (OC), 30, 100, and 300 μA, bracketing typical expected service conditions (Sergi and Page 2001). Exposure is in chambers of nominal 90% and 65% relative humidity (RH) at room temperature (22 +- 2C). Test duration is scheduled to be at least one year. All test conditions are evaluated in triplicate, except when specimen potential exceeds +200 mV CSE at which time the test for that specimen is terminated and subsequent results are averaged for the remaining peer specimens only.

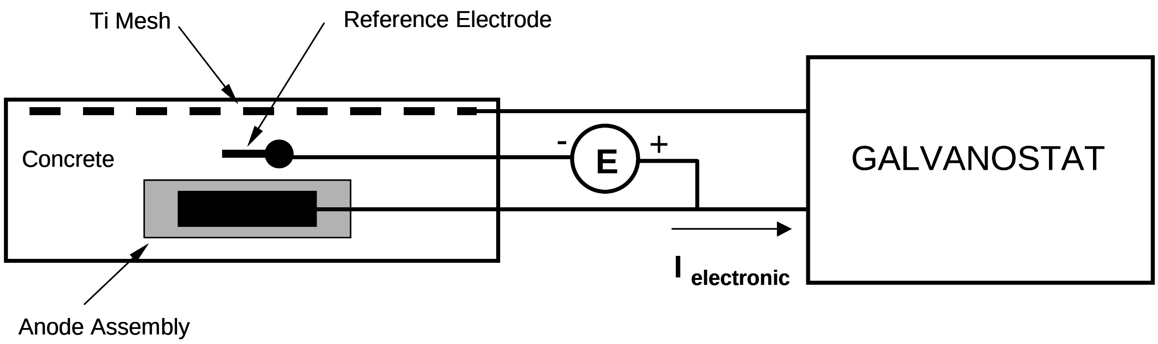

Fig. 2: Anode Test Arrangement (Idealized-Actual Placement May Vary)

Figure 3 exemplifies preliminary results of ongoing testing for one of the anode types being evaluated at 90% RH, embedded in the specialty repair material. Results reported are the average of triplicate tests. Initial OC potential, ~-0.9 V CSE was in the expected range (although anodes embedded the ordinary repair concrete tended to have initial OC potential ~-0.8 V CSE). As exposure time increased, the OC potential became less negative, possibly reflecting intrinsic anode consumption as well as dilution of alkaline species from the anode pellet mortar into the surrounding embedding mortar. On-potential was corrected for ohmic potential drop. Anodes subject to 30 μA drain behaved similarly to the OC anodes, but anodes subject to the higher current levels developed proportionally more positive potentials and faster aging, as expected.

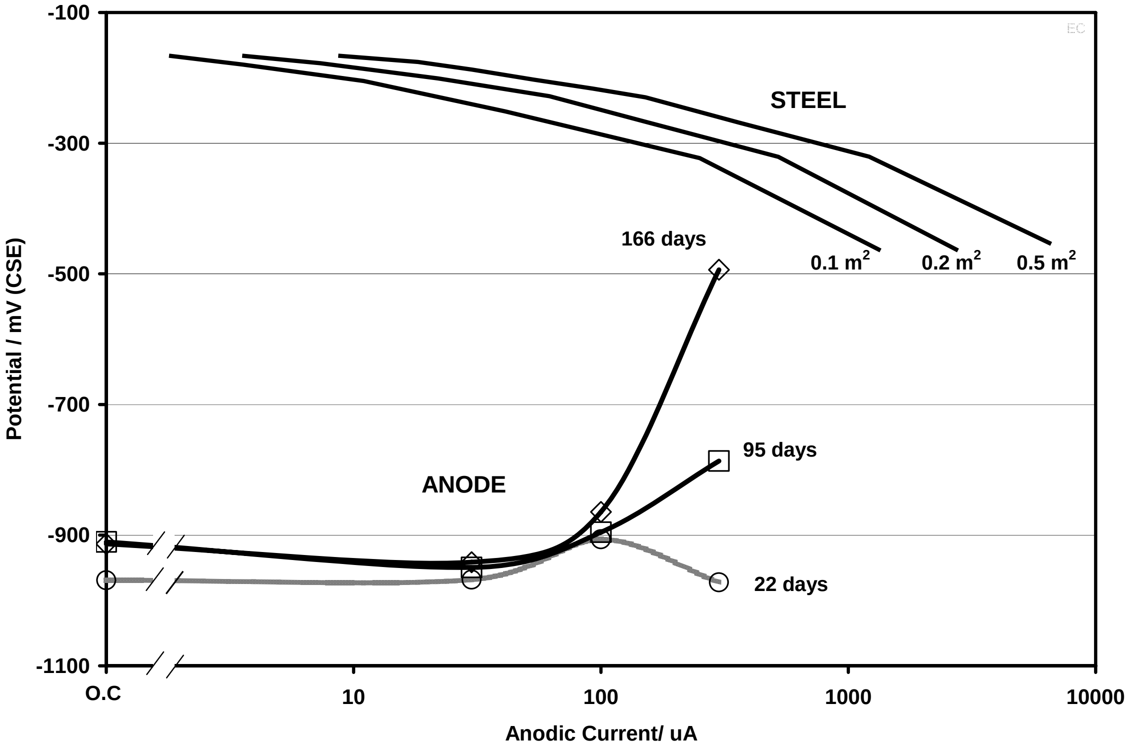

Fig. 3: Illustration of preliminary findings for one of the anode types investigated, with superimposed abstracted cathodic polarization behavior of passive rebar (Sagüés et al 2003), adjusted for total steel area as indicated. Times indicated are since first energizing the system.

As outlined in the previous section, superimposed in the same plot are polarization curves representing the cathodic behavior of a passive rebar assembly with a total steel area of 0.1, 0.2 and 0.5 m^2. The steel areas correspond to typical practical anode to anode spacing values ranging from ~0.3 m to ~ 0.70 m if a steel area/concrete area ratio of 1:1 is assumed. The curves have been abstracted from long-term polarization data of passive steel in laboratory concrete columns not saturated with water (Sagüés et al 2003) , adjusted for the total area represented. The OC potential of the passive rebar was ~ -0.15 V CSE. As can be seen, none of the PFC anode curves obtained during the test period intersect the assumed rebar polarization regimes. However, if a plausible effective cementitious path resistance R= 1 Kohm is assumed, the graphic construction shown in Figure 1 indicates that the anode aged for 5.5 months could cathodically polarize the 0.1 m^2 and 0.5 m^2 assemblies by ~0.18 V and ~0.1V respectively below the steel OC potential. The corresponding extent of cathodic prevention achieved by those polarization levels may vary from substantial to modest, pending further interpretation of the limited available information on the efficiency of this mode of protection (Presuel-Moreno et al 2005a, Presuel-Moreno et al 2005b, Pedeferri 1996,)

It is emphasized that the results shown in Figure 3 are presented only as an illustration of the testing approach introduced here, applied to early experimental findings. An overall assessment of the performance of the specific anode types being investigated needs to await the development of a broader data set as time progresses. The ongoing tests have served also to reveal areas needing improvement in implementing this test method on large test arrays. In particular, electric instabilities inherent to the use of galvanostatic control in anodes that may be prone to passivation have been observed in some cases. Modification of the test instrumentation to include potential control beyond a certain level, and alternative potentiostatic operation, are being explored.

CONCLUSIONS

An approach to evaluate candidate anodes for patch repair applications was developed and its feasibility demonstrated applying the experimental and analysis methods to actual commercially produced anode samples. The operation history of the anode under galvanostatic control can be used together with independent steel polarization data to aid in forecasting the performance of the anode-reinforcing steel system under various application scenarios.

ACKNOWLEDGEMENT

This investigation is supported by the Florida Department of Transportation and the U.S. Federal Highway Administration. The findings and opinions presented here are those of the authors and not necessarily those of the funding agencies.

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