TAKING CONTROL OF CORROSION MANAGEMENT DECISIONS

BY GRAEME JONES

It is generally understood that structures decline in performance over time. This is often due to the availability of oxygen and the ingress of moisture with aggressive agents, resulting in the subsequent initiation and then propagation of corrosion of the reinforcement steel or structural steel frame. This structural decline has significant implications to safety and inherent value of the asset, whether privately owned or publicly managed.

Planned and timely intervention in the corrosion processes as they develop is both wise maintenance management and economically sensible. Often, however, the owner waits until damage to the concrete cover or masonry façade is visually obvious, or worse, palpable, which is the point when costs can spiral out of control and options to mitigate the damage diminish. While budgetary constraints are understandable, the solution should always suit the problem; thus, understanding the basis of the problem is essential to designing a solution to provide the anticipated service life for the structure and meet cost expectations.

There are many mitigation options available, depending on the timing of the identification of problems, including galvanic cathodic protection (GCP), surface-applied corrosion inhibitors (SACIs), and impressed current cathodic protection (ICCP). These take many forms.

An emphasis on where and when to choose corrosion inhibitors as one mitigation option and managing expectations is discussed in detail herein. In many instances, they may not be relevant or may be used in tandem with other techniques at different locations within the same structure.

The cost of this solution is relatively low, yet structure managers and owners are reluctant to truly embrace this technology. Some studies have indicated mixed success when measuring performance, whereas others have shown impressive results. Specifiers are still often confused by the emerging picture.

In this article, field experiences will be used to lay the foundations for understanding the use of corrosion mitigation. It is not suggested that these be used as a replacement for good practice in concrete repair methods. If the concrete is cracked or spalled, then repair should occur, as would be expected in accordance with industry best practices.

SACIs may not be a panacea for corrosion problems, but considered use with performance monitoring and management may be the key to providing durability for many structures and infrastructures.

SACIs

SACIs are a generational development for reinforced concrete structures arising from more recognized use in industries such as oil and gas, electronics, and transportation.

Their development in the construction sector can be tracked back to the 1950s with a patent for the use of sodium benzoate held by the Thames Water Board in the UK.

In broad terms, SACIs offer a low-cost option in the tool kit of corrosion prevention techniques. At around a \$1.00 to \$1.50/ft^2 (U.S.) installed cost they are by far a better cost option than using ICCP systems that may cost as much as \$15 to \$30/ft^2. With the value of the investment, however, comes an evaluation of the certainty of performance, and it should be no surprise that a well-designed, properly installed ICCP system offers controlled performance for a longer time period than SACIs, often in harsher environments.

It is reasonable to expect that inhibitors cannot compete with the exertions expected of ICCP systems, but properly chosen in terms of material and the application situation, SACIs can offer mitigation of corrosion in a great deal of structures. It is with the management of expectations and appropriate targeting of SACIs that good and sustainable results can be achieved.

What follows may provide perspective on the background to making the decision to use SACIs and the use of management tools by which to gauge performance and reapplication decisions.

MECHANISMS OF PROTECTION

By definition, a corrosion inhibitor is a chemical that, when introduced in low concentrations, actively reduces the rate of corrosion by direct action at the metal surface.[1] In the same textbooks, corrosion inhibitors are classified in three ways:

anodic, cathodic, and ambiodic (mixed) because they act on anodic, cathodic, or both sites on the steel surface. The impact on the corrosion rate is largely the same in all three classifications because a reduction compared with pretreated levels can be anticipated. The effect on corrosion potential, however, is very different.

The Evans Diagram in Fig. 1 demonstrates this in schematic form of potential (V) versus current (I) for ambiodic inhibitor action.

Figure 1 shows the mechanisms of operation for each classification and the means of managing expectations through the correct monitoring of performance. If the corrosion inhibitor can bond to the steel surface after penetrating through the concrete cover, then the corrosion rate reduction in all three classifications can be anticipated.

Potential change, however, occurs only in anodic (positive shift) and cathodic (negative shift) types. Ambiodic or mixed inhibitors in themselves cause no discernible change to corrosion potential, as they act equally on both anodic and cathodic sites (refer to Fig. 1). This does not mean that potential will not change, as effects from the environment (moisture, oxygen, and temperature) can still result in a measured change in value.

The choice of whether inhibitors are the wisest protection measure for a structure depends on its current corrosion condition, quality of cover, level of free chloride, extent/depth of carbonation, existing corrosion product, and accessibility to the structure in the future. All of these factors are usually determined by performing a visual and condition survey. Inhibitors can be very effective in treating carbonation but, again, caution is given to the extent to which corrosion products have already grown on the steel surface.

Clearly, if corrosion growth is too far advanced, it will cause the cover to crack, and it should be repaired in the usual manner. However, where propagation has begun but is insufficient at the time to cause cracking or spalling, then the inhibitor may take more time to permeate the cover and rust layer to arrive at the steel surface to cause a measured reduction in the corrosion rate.

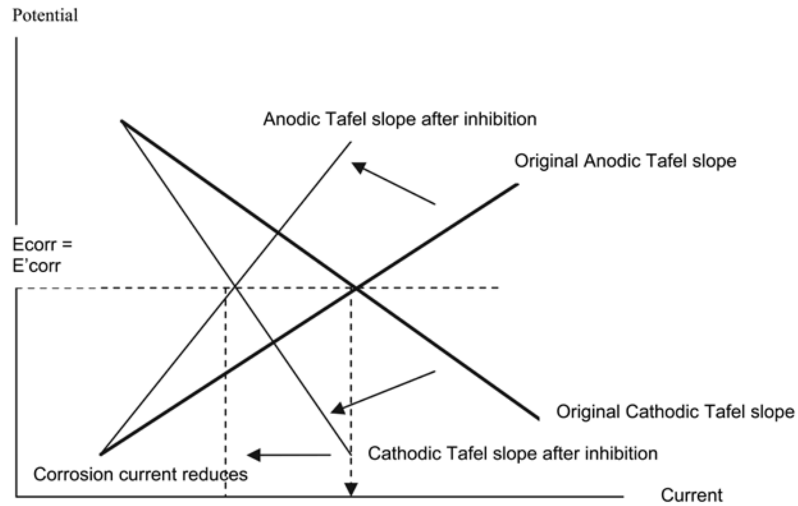

Fig. 1: Evans Diagram for ambiodic inhibition

It is important to stress that the diagram considers performance on an ionic or molecular scale; therefore, less than a micron of corrosion product is sufficient to introduce a time constant to the transport mechanism for the inhibitor. This is important for engineers reporting to the owner on performance, given that as much as 9 months to 1 year can pass before discernible corrosion rate reduction can be witnessed (refer to Fig. 2). In terms of management of the process, the decision would still be to adopt its use but understand what to expect from performance.

Monitoring performance trends is the key to knowing whether the inhibitor is having any specific effect on the surface corrosion processes

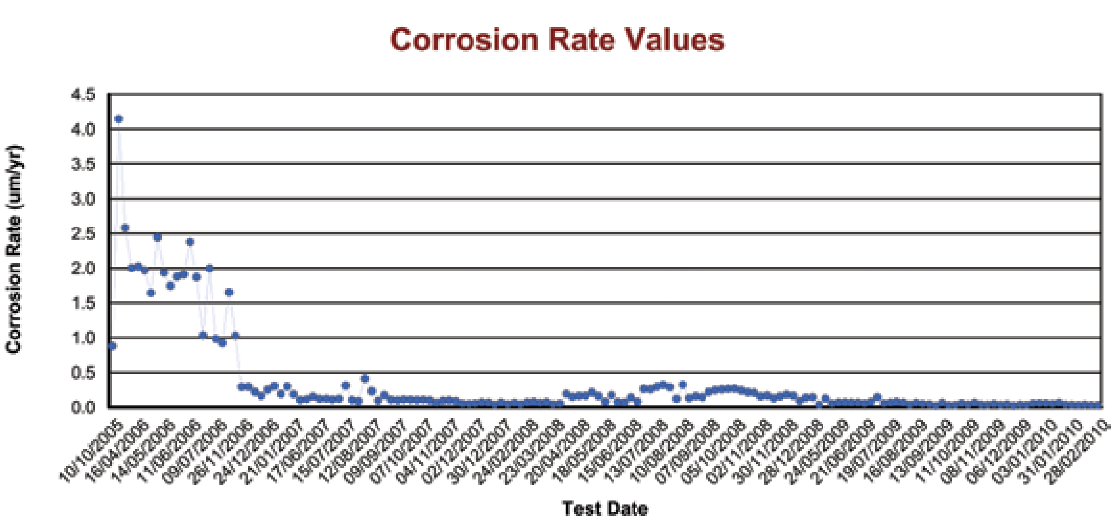

Fig. 2: Period of gradual change followed by dramatic and sustained reduction in corrosion rate around 9 months after application of SACIs

during the durability assessment period. One also has to bear in mind that other aspects of the repair strategy may also influence the corrosion rate at the steel surface.

APPLICATION AND REAPPLICATION

It is also important to consider accessibility, both in terms of getting the inhibitor into the cover concrete and when considering the life and reapplication of the product. Needless to say, the concrete surface needs to be "open"—that is, free from laitance and oil. This is achieved by a light grit-, sand-, or water-blast. There is no need to blast the surface to expose aggregate, as bond is not critical unless a coating or membrane is being applied after the inhibitor application is complete.

SACIs are usually packaged with surfactants that ensure penetration into the cover rather than evaporation into the atmosphere. These additives are waxy or soapy in texture and need to be washed off the surface before any coating or membrane is applied. Assuming that there has been correct application and penetration, the consideration of life expectancy should be made in conjunction with the ability to revisit the concrete surfaces to reapply the SACIs.

MONITORING AND PERFORMANCE CRITERIA

Across the world, the repair and protection industry has so far only offered performance acceptance criteria for the use of ICCP systems for corrosion prevention.[2,3] Little guidance is therefore available in the literature to use as a platform for acceptance of the performance of SACIs.

ASTM C876-99[4] offers guidance for the measurement of corrosion potentials and provides an indication as to the severity of corrosion in terms of a probability of corrosion taking place. It is important to note that corrosion potentials is a thermodynamic measurement and will not tell how fast corrosion is developing.

Some of the pitfalls with interpreting half-cell potential are covered in The Concrete Society's Technical Report No. 60 (TR60).[5]

ASTM G59-97(2009)[6] offers guidance on the measurement of corrosion rates using the linear polarization resistance method (LPRM) that is advanced again for reinforced concrete within The Concrete Society's TR60.[5]

Only the SAMARIS D21[7] document takes the next step of providing guidance after characterization by survey methods regarding the performance acceptance criteria that corrosion prevention is being achieved by the specific treatment.

One can use these publications in combination as the basis of how to view the performance of protection methods, as they directly indicate the electrochemical behavior at the steel surface. If this changes in any way, then the corrosion rate can be noted to change in the following ways: 1) for the better; and 2) sufficiently enough to be comfortable in the design choice working over time.

For inhibitors, the priority given to which method best demonstrates performance is related to the perceived mechanism of protection, as covered previously.

For reinforced concrete structures, doing one or all of the following is suggested:

1. Delay the onset of corrosion at areas of currently limited corrosion activity;
2. Reduce existing corrosion that has formed but not yet caused damage to the cover; and
3. Manage the effects of incipient (or ring) anode that can form as a direct result of a repair being undertaken.

For the sake of brevity, concentrating on ambiodic inhibitors throughout, then for Scenario 1, the corrosion potentials may begin to move in the negative direction if the environment is conducive to the initiation of corrosion (that is, risk is increasing). If the inhibitor is being effective, however, then the corrosion rate should remain low. Corrosion is not permitted to propagate by the presence of inhibitor on the steel surface if inhibition is effective.

The question of percentage reductions (efficiencies) would therefore have limited relevance to this scenario, as low measurements merely stay low, rather than reduce from a high to low value.

For Scenario 2, potentials more negative than –350mVCSE with initial pretreatment corrosion rates of >10 μm per year may be measured as a demonstration of the propagation of corrosion.

If performance is achieved after treatment, then no dramatic change in potential may be seen, but corrosion rates should be reduced to below the level anticipated to cause real damage to the cover.

For the purpose of building in a performance "cushion," corrosion rates <5 or <2 μm per year may be desired, depending on how conservative one wishes to specify a performance. A percentage reduction from untreated base values of >65% as a measure of the extent of service-life extension for the structure may also be desired. Corrosion potential would remain worth measuring as a view of prevailing and local environmental conditions.

For Scenario 3, potentials anywhere in the spectrum but trending negatively to below –350mVCSE may be measured as an indication that passivation is being lost and an anode is forming. Measuring any dramatic increase in the corrosion rate if the SACIs are performing is not desired, as this would confirm the establishment of the incipient or ring anode around the new repair area.

Therefore, a criterion akin to the one previously described in Scenario 1 would seem appropriate.

These criteria are intended to open debate on the subject and are currently under discussion at ICRI with the development of a guideline on the use of penetrating treatments. It would be contended, however, that they have some substance in corrosion science and relate to known and respected publications on the subject of assessment of corrosion in the field.

PERFORMANCE AND LIFE EXPECTANCY

There are arguably two service-life expectations: 1) the expectation of the service life of the mitigation product; and 2) the impact of using the product to extend the service life of the structure itself. To test whether service life has benefited from the investment in SACIs, monitoring can be used to achieve verification and test retreatment moments.

The following examples were extracted from over 40 monitored projects. The responses are typical or, in some instances, used to highlight individual features during the prolonged testing of these systems.

The following list includes frequently asked questions when considering the performance evaluation of SACIs:

- Is the probe working?
- How does normal performance manifest itself: dramatic change and gradual reduction?
- What is the extent of penetration/migration of the inhibitor?
- Are there value-added effects of combining the use of inhibitors with waterproofing membranes?

Each query is addressed in order, using real site examples in an attempt to provide answers.

PROBE INTEGRITY

The response from the probe is clearly dependent on the integrity of the installation, where the concrete cover being tested should not be disturbed around the steel so the corrosion cell being tested is not altered. The type of mortar used and the period of the curing of the mortar—where abnormally high values may be measured when wet or not fully cured, giving a false indication of corrosion rate reduction—will also have a bearing on the integrity.

Figure 3 is from a probe installed within a parking deck, where the initially high measurement of the corrosion rate of around 45 µm per year was probably measured when the mortar around the probe was still curing and acted as a low resistance path for the perturbation current used during the LPRM test. Therefore, it is prudent to wait at least 48 hours before performing the LPRM test.

The dramatic reduction to zero that is maintained over time probably arises as a result of the formation of a void around the probe head, which results in a high resistance to the passing of the perturbation current during the LPRM test.

A similar response has been observed with mortar infill that has been too highly modified and provides too high a resistance for the test to be successful.

This is not to be confused with a dramatic reduction in the corrosion rate that occurs when the inhibitor treatment readily penetrates the concrete cover due to low permeability (refer to Fig. 4).

NORMAL BEHAVIOR

The term “normal” can be misleading, as good performance can manifest itself in a number of ways. For example, it is typical to observe some environmental effects during the continuous monitoring of these structures. This is shown in Fig. 5 for a parking

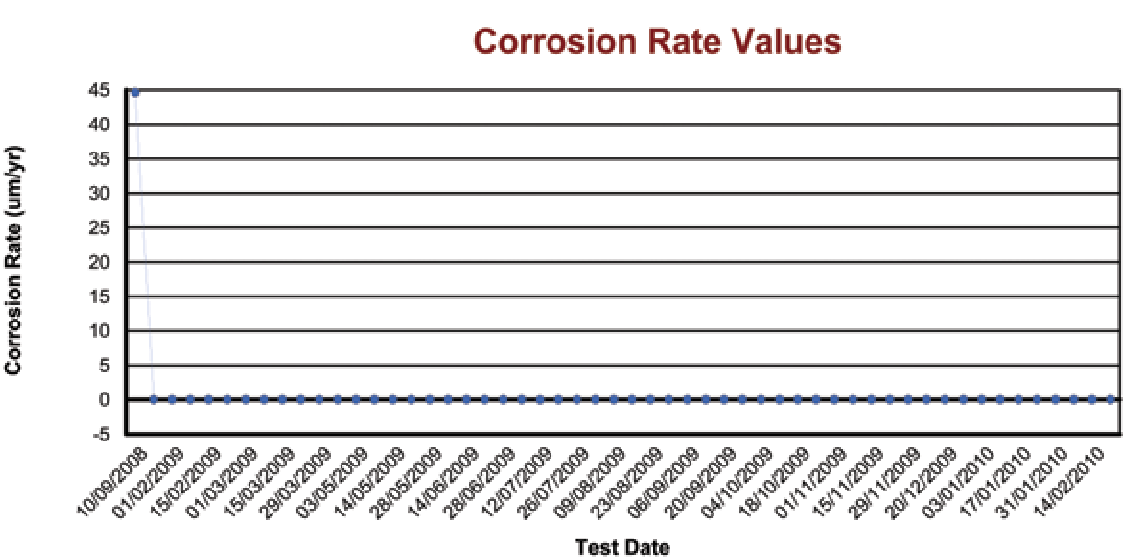

Fig. 3: Corrosion rate with time for an embedded LPR probe within a parking deck

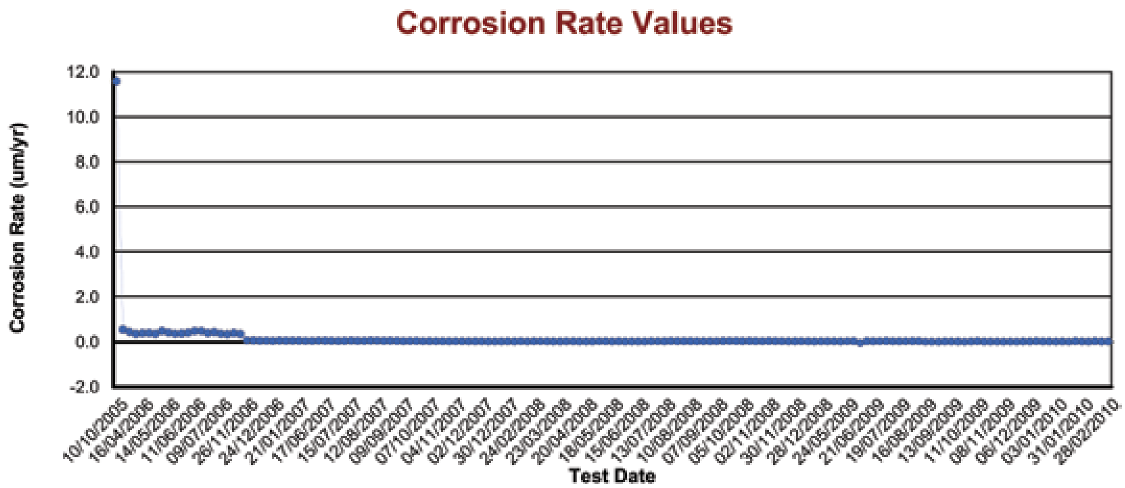

Fig. 4: Immediate dramatic and sustained corrosion rate reduction in high-permeability concrete cover following application of SACIs

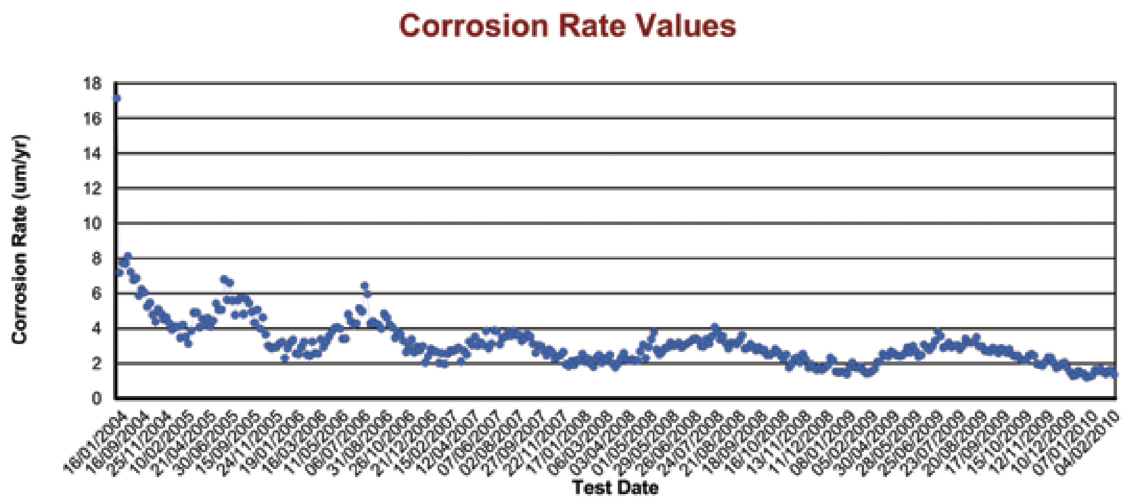

Fig. 5: Gradual corrosion rate reduction over a 6-year period from SACI application

deck of approximately 1 to 1.5 in. (25 to 37 mm) of cover with no waterproofing treatment applied.

Figure 5 shows a parking deck with gradual improvement with peaks coinciding with the environmental impact on the corrosion cell but the inhibitor coping with that change. The other response often observed, however, is a sudden and dramatic change, where the penetration of the inhibitor through the cover may be quicker due to higher permeability. On arrival at the steel reinforcement (where corrosion may only be at the initiation/propagation point), however, then the change in the corrosion rate response can be dramatic (refer to Fig. 4).

EXPECTATION OF PENETRATION THROUGH THE COVER

Qualitative penetration tests through the cover can be performed by extracting a small core and using chromatography tests on the cement paste to assess the depth through the core of the inhibitor treatment after a known passage of time; these can be very useful tests to link to contractual obligations. Typically, up to 3.1 to 4 in. (80 to 100 mm) cover penetration has been quoted from independent testing,[8] which would account for the concrete cover of most reinforced concrete structures. Manufacturers may recommend a penetration of 2.0 to 2.9 in. (50 to 75 mm) as being achievable.

Embedded monitoring can also be used. The graphs in Fig. 6-10 are from another case study at a parking structure, where the test regime assessed the ability of the inhibitor to penetrate through a structural slab used as the running surface and supported by prestressed concrete planks beneath. The test was designed to assess whether the inhibitor would offer protection to both levels by application to the top surface only.

The answer was found by monitoring two positions. This confirmed that corrosion rate reduction was experienced in both locations and maintained for the nearly 3-year period of the test. It should be noted on the example performance graph (refer to Fig. 6) that there have been two incidents during the period where the corrosion rate started to increase toward the base values, only to

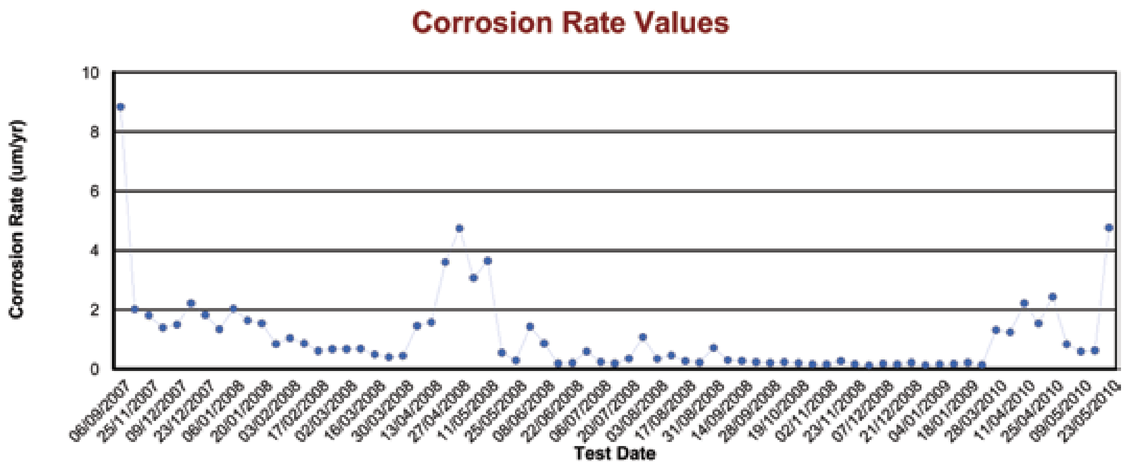

Fig. 6: Corrosion rate reduced after 2 months following penetration through slab to planks and sustained apart from two incidents after 6 and 30 months

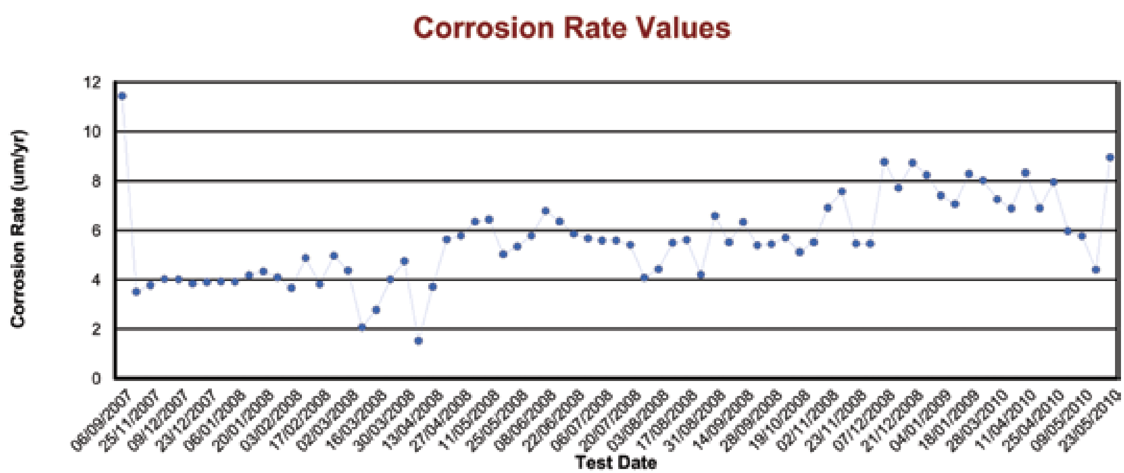

Fig. 7: No treatment to parking deck

recover to a low value after 2 months. The second incident is still being assessed for the ability to recover from the surge in the corrosion rate. This probe was placed within the prestressed plank.

ADD-ON BENEFIT OF WATERPROOFING TREATMENTS

During the assessment of value in most projects, it is inevitably discussed whether there is benefit to adding corrosion mitigation before the use of waterproofing to decks. Risk arises with the continued presence of chloride contamination within the concrete cover and whether this will mobilize with residual moisture to accelerate (incubate) corrosion following membrane application. If this occurs, then it would most likely lead to more concrete problems beneath the membrane, ultimately leading to failure of the waterproofing and the need for further remediation.

The assumption is also made in this assessment that the level of chloride contamination is not already past the threshold where the inhibitor can be used and that the option remains to apply it before the membrane is applied. The purpose of using the inhibitor in this instance is with all three performance expectations of their use because they can delay the onset of corrosion that has yet to manifest itself, reduce existing corrosion rates, and control the ring (incipient) anode locations around new repairs.

The following data show an example from a parking structure, where an extensive test regime was undertaken before proceeding with the full project. The first comparison was made with no treatment on the deck with monitoring of the progress of corrosion over a 33-month period. Another test area with the sole use of a waterproof membrane to an area of 100 ft^2 (10 m^2) was set up. A similar-sized area was used for the use of SACIs alone and with the combined use of both SACIs and waterproofing.

Figure 7 shows the corrosion rate with time measuring the response of steel reinforcement within a parking deck running surface with no treatment (control conditions).

The control graph is compared to the corrosion rate, with time measuring response of steel rein-

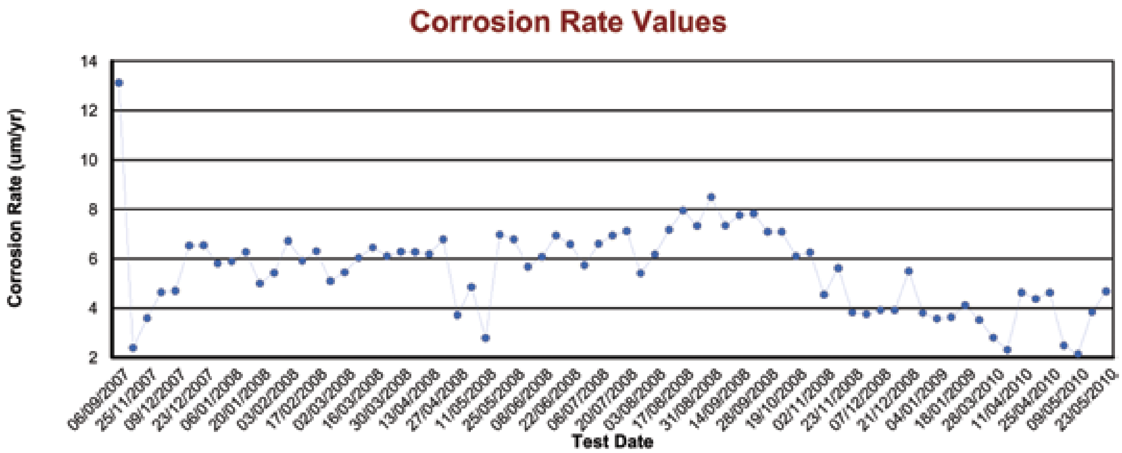

Fig. 8: Corrosion rate measured with time for parking deck with only a waterproofing membrane applied

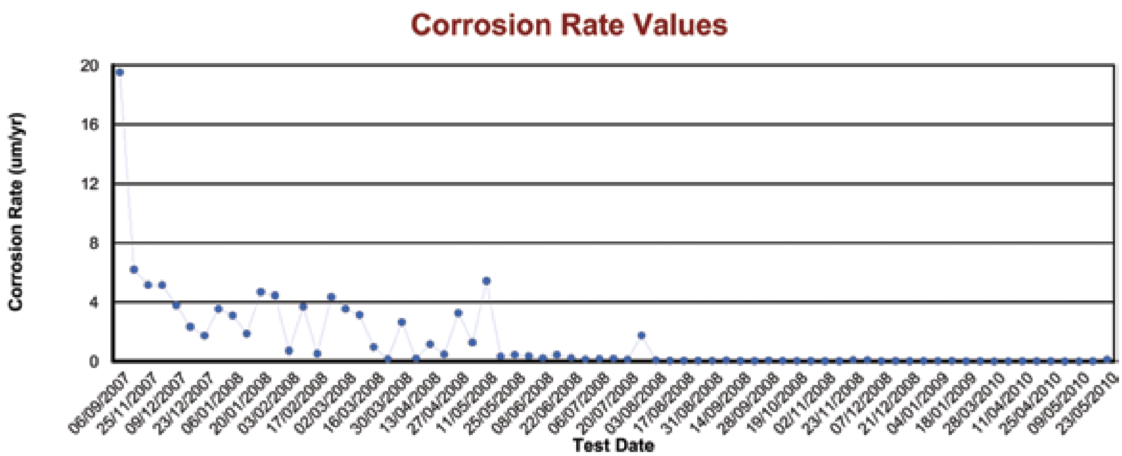

Fig. 9: Corrosion rate measured with time for parking deck with waterproofing membrane applied after the use of SACIs

forcement within the running surface following application of waterproof treatment only (Fig. 8).

Corrosion rates that do not reduce within the control area and only reduce slightly after approximately 1 year following the application of the membrane can be observed.

This is in contrast to the effect of adding the inhibitor as a pretreatment ahead of the waterproofing, where it is shown in this comparison that the sole use of waterproofing, while not at intrinsically high corrosion rates, does not reduce the corrosion rate to very low levels, as experienced by the supplemental use of SACIs (refer to Fig. 9). A lowering of the corrosion rate over time can be seen that is impressively low in value and sustained over time, which is primarily attributed to the use of SACIs. This is confirmed in Fig. 10, where only SACIs are used without the membrane in position.

Similarly, the sole use of an inhibitor to a similar parking deck also performed as substantively as with the combined use of waterproofing and SACIs (refer to Fig. 10). However, this is likely to have less durability over the service life without the additional barrier protection offered by the use of the membrane. It can be seen that the very low (near zero) corrosion rate is already being tested after 1 year at those levels but may recover before increasing again. This will be reviewed over the next few years.

TARGETED USE

There are many corrosion mitigation techniques available to protect steel in concrete and consequently increase the service life of a structure—the use of SACIs is only one. With targeted use and managed expectations, however, the repeated repair of structures can be avoided.

The educated use of monitoring lends itself to planned preventative maintenance of infrastructures. This provides added value and ultimately cost savings through early intervention and subsequent avoidance of such repetitive repairs.

As a budget exercise, the following case can be made: a budget of 10 to 30% of the repair cost of a structure is identified for sustainable corrosion protection with 1 to 5% of that figure built in for monitoring and management, depending on the complexity of the site.

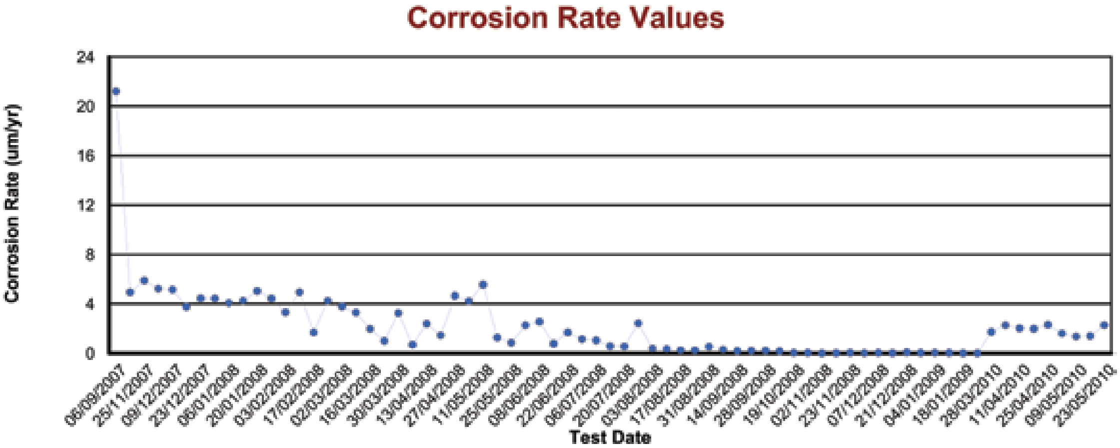

Fig. 10: Corrosion rate measured with time for parking deck with only the use of SACIs

Fortunately, corrosion is a relatively slow process. The key to reasonable decision making is knowledge and understanding of available options.

This article is intended as a preface to the publication of the ICRI Technical Guideline concerning the use of penetrating treatments for reinforced concrete structures (due to be published in 2011) by elaborating on field experiences with the use of SACIs and their management through monitoring.

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