# Preventing an Achilles Heel

*Corrosion of reinforced concrete is an ongoing battle, but corrosion inhibitors are offering an optional prevention strategy to cathodic protection. Graeme Jones, C-Probe Technologies Limited, Paul Lambert, Mott MacDonald, and Ian Wood, PLaN Area7, discuss the flexibility, value updating monitoring systems, and some of the pitfalls in the use of surface applied corrosion inhibitors for existing civil engineering structures.*

## Introduction

A corrosion inhibitor is essentially any substance that, when introduced to an environment at relatively low concentration, reduces existing metallic corrosion and limits the risk and extent of future corrosion.

Corrosion inhibitors are widely used in the protection of metals and have a long track record in the chemical, petrochemical and transportation industries in a variety of forms from injected to vapour phase compounds. There has long been interest in their potential use for the protection of concrete reinforcement, generally as inorganic admixtures based on nitrite or benzoate. One of the earliest such systems based on sodium benzoate was patented in the mid-1950s by the North Thames Gas Board.

Their use as a surface applied corrosion inhibitor (or S-ACI, for the purposes of this article) treatment to concrete is more recent with significant development, perhaps, only now becoming prominent as an option to the corrosion prevention designer or structure owner/manager.

This article attempts to explain through the use of data obtained in the field the flexibility and some of the pitfalls in the use of surface applied corrosion inhibitors for some bridges for a Highways Agency 'super agency'.

## Protection and monitoring

The environment provided by good quality concrete for embedded steel reinforcement is one of high alkalinity (generally >pH 13), produced by the hydroxides of sodium, potassium and calcium released during the various hydration reactions during curing. In addition, the bulk of surrounding concrete acts as a physical barrier to most of the substances that may lead to degradation of the reinforcement.

Provided this environment is maintained, the steel remains passive and any small breaks in the stable protective oxide film are soon repaired. However, if the alkalinity of the surroundings is reduced, for example by reaction with atmospheric carbon dioxide (carbonation), or if depassivating chloride ions are made available at the surface of the steel, then corrosion may be initiated, resulting in loss of steel section and spalling of concrete cover.

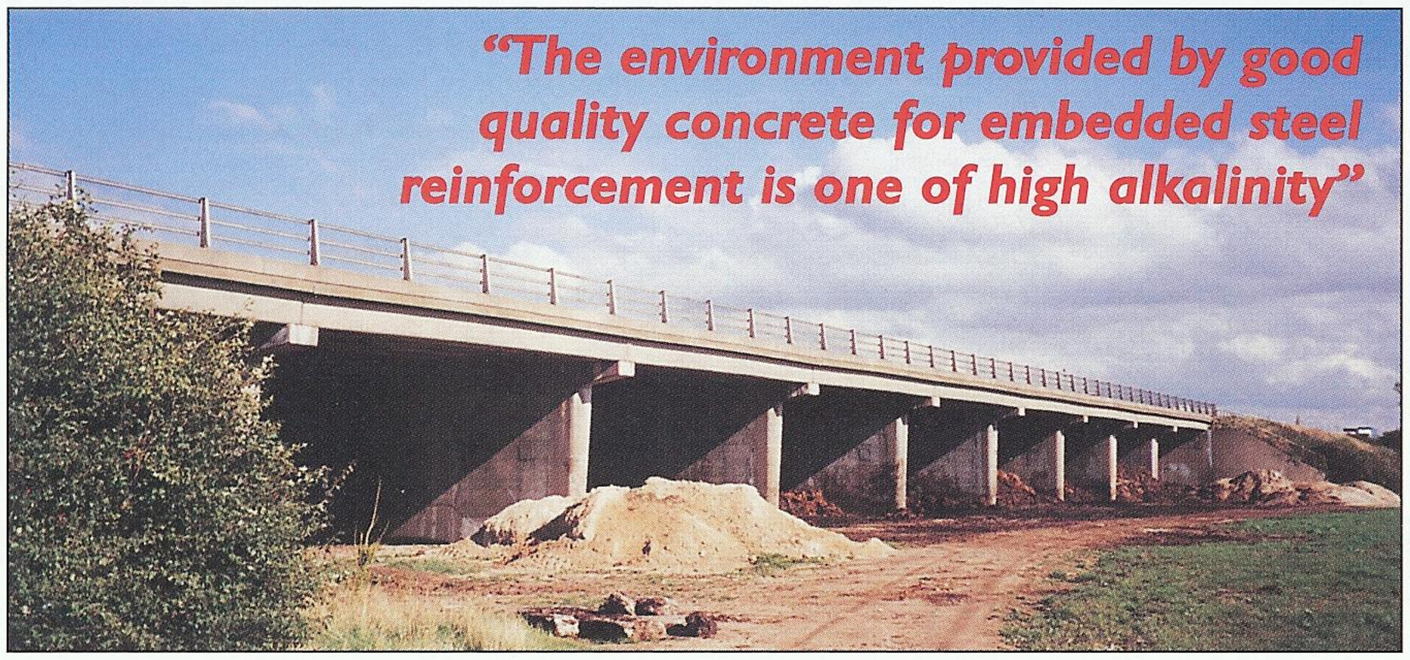
In the presence of moisture and oxygen, steel can suffer from corrosion. The rate and nature of the process depends on the specific alloy composition, environmental factors, design and the nature of any additional protection.

In its simplest form, the corrosion process can be represented by two dissimilar metals in an aqueous electrolyte, joined to allow electrons to pass from anode to cathode. In reality, when a metal corrodes, anodic and cathodic areas can be formed on a single surface in contact with the aggressive aqueous environment. As a result, corrosion can occur at many sites on the same section of metal. The metal dissolves (at the anodic sites) and reacts with hydroxyl ions (generated by the cathodic sites) to form corrosion products more commonly referred to as rust.

Corrosion therefore occurs by virtue of the presence of these anodes and cathodes existing in equilibrium on the surface of a metal, which in turn interact with its environment. Protection occurs when one of these parameters is modified to such an extent that the dissolution of metal is impeded, resulting in negligible corrosion. Consequently, corrosion inhibitors may be considered to operate in three basic forms: anodic, cathodic and mixed inhibitors.

Anodic and cathodic inhibitors essentially operate by acting on the respective anode and cathode sites occurring on the steel surface and impeding the reactions. They are quite different in chemical nature and have specific sensitivities of usage.

In aqueous environments, care must be taken with the dosage of anodic inhibitors, as too low a concentration can induce pitting corrosion in some instances, although no such effects have been observed in reinforced concrete. Cathodic inhibitors have no such sensitivity to concentration, but large amounts may




***View of Trent flood span bridge currently undergoing S-ACI installation as a result of the success of the bridges reported on in this article.***

be necessary to achieve full protection and are generally impractical for use in concrete.

Mixed inhibition is achieved by simultaneously impeding the reaction at both the anodic and cathodic sites, generally by forming a thin, adherent and highly protective film over the entire surface of the steel.

All three basic forms of inhibitor can cause a lowering of the corrosion rate. Their influence on corrosion potential can, however, be very different. Anodic inhibitors typically result in a positive shift in measured corrosion potential ($E_{corr}$) whilst cathodic inhibitors (akin to cathodic protection) will cause a negative shift in measured $E_{corr}$.

Mixed inhibitors can, in principle, result in no significant change in $E_{corr}$, although under certain conditions they will show a slightly preferential anodic response. It is therefore essential that with mixed inhibitor systems (and preferably with all forms of inhibitor) corrosion rate is monitored rather than corrosion potential (Figure 1). A more detailed explanation of anodic, cathodic and mixed control can be found in any good corrosion textbook.

Both of the surface-applied corrosion inhibitor systems evaluated in this study are reported by their manufacturers to operate as mixed inhibitors. With this in mind, corrosion rate monitoring (expressed as $I_{corr}$) should be the chosen monitoring method for demonstrating that corrosion protection by inhibition of both anode and cathode reactions has occurred.

In order to make this data accessible and given that the embedded probe geometry is designed deliberately to provide a known steel perterbation, it is possible to translate the less accessible corrosion rate unit of $\mu A/cm^2$ to an engineering term expressed in mm or $\mu m$ loss of steel per year. All the following data is expressed in this way.

## Field applications and sample data

The following examples have employed C-Probe's embedded corrosion rate sensor (CP100/101) to apply advanced electrochemical monitoring techniques to the site environment, all of which are managed efficiently by the AchillesIES. The structures are summarised in Table 1. These are categorised in terms of structure type and the specific structural element the sensors are assessing for S-ACI performance.

The results expressed for each structure are a representative sample from the total data. Similar responses were obtained from additional probe locations, but are excluded for reasons of brevity.

The case histories outlined below indicate probe populations designed with each structure's requirements in mind. All structures have been assessed using manual equipment to cross correlate with the AchillesIES remote software-controlled electronic equipment.

Two types of S-ACI product have been used, each applied as sprays. Both treatments are based on amino-alcohols with variations in their precise manufacture and application. Spray applications are performed in multiple layers using horticultural-grade aspiration equipment until the concrete surface is visibly soaked. The applications assume adequate protection of the steel by diffusion through the concrete cover to reinforcement or by direct application to the steel surface prior to concrete repair.

## Twyford Bridge, Nottinghamshire

C-Probe was commissioned to install an impressed current cathodic protection (ICCP) system to two half-joints for this overbridge on the A1 in Nottinghamshire for PLaN Area 7 HA super agency.

Early in the process of designing the ICCP system, some soffit damage was also identified on the suspended slabs between the joints and abutments. Although the damage was not severe, it was decided to use this site to test the comparative performance of two S-ACI products: Sika Ferrogard and Flexcrete MCI 2020.

It was necessary to apply the inhibitors directly to the soffit. Suspended slabs over opposite hard shoulders of the A1 were used for each S-ACI product for comparative purposes with both slabs being visually assessed to be of similar condition.

Attempts to apply both products to the soffit proved largely unsuccessful due to lack of absorption of the S-ACI into the concrete. The data shown

**Table 1. Summary of S-ACI applications for highways structures**

| Project application | Year of protected | Structural element application | Method of S-ACI |
|---|---|---|---|
| Twyford Overbridge | 1998/99 | Suspended slabs | Spray treatment to surface |
| Wansford Bridge | 1999 (pilot) | Deck soffit | Spray treatment to surface |
| Ranby Canal Bridge | 1999 | Portal frame and soffit | Treatment to surfaces and directly to steel |

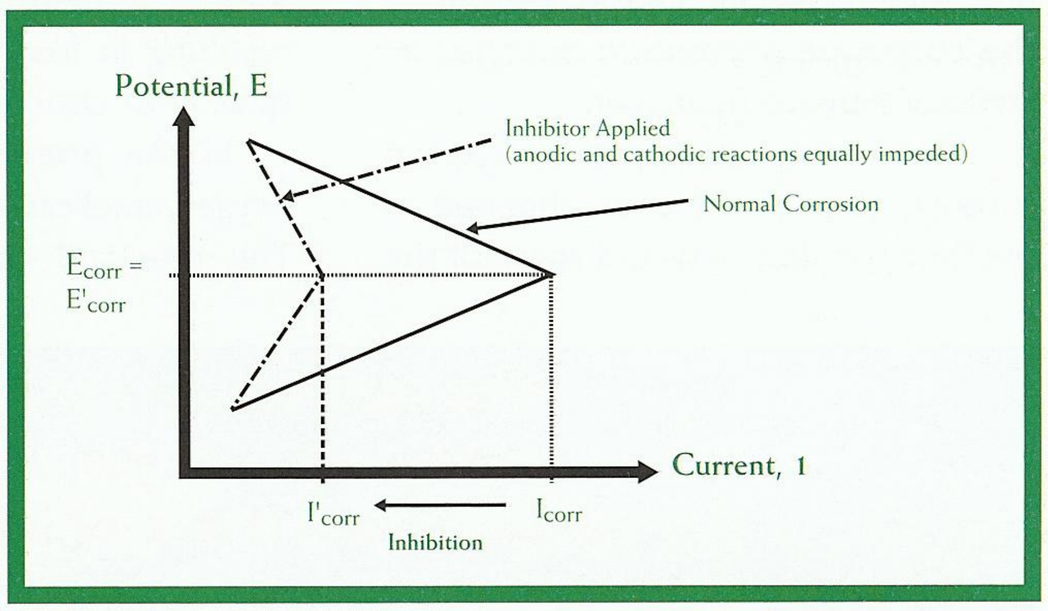



*Figure 1. 'Evans diagram' demonstrating mixed inhibitor performance.*

**Table 2. S-ACI performance at Twyford Bridge, Nottinghamshire**

| Probe location | Pre S-ACI | Post S-ACI 3mths |
|---|---|---|
| A (Ferrogard) | 12.79 | 1.42 |
| B (MCI2020) | 16.35 | 1.91 |
| *Measurements are quoted in μm/yr loss of steel* | | |

**Table 3. S-ACI performance at Wansford Bridge, Cambridgeshire**

| Probe location | Pre S-ACI | Post S-ACI (1st coat) | Post S-ACI (2nd coat) |
|---|---|---|---|
| A | 24.47 | 9.15 | 6.40 |
| *Measurements are quoted in μm/yr loss of steel* | | | |

**Table 4. S-ACI performance at Ranby Bridge, Notts/Derbyshire border**

| Probe location | Pre S-ACI | Post S-ACI 3mths |
|---|---|---|
| North Wall (direct S-ACI) | 51.12 | 0.71 |
| North Wall (surface S-ACI) | 11.36 | 3.44 |
| South Wall (surface S-ACI) | 19.96 | 1.62 |
| Soffit | 1.60 | 2.52 |
| *Measurements are quoted in μm/yr loss of steel* | | |

in Table 2 represents probe locations associated with newly grouted areas which may have afforded an easier path for the diffusion of the S-ACI.

## Wansford Bridge, Cambridgeshire

Wansford Bridge near Peterborough has been subject to a complex pilot of two types of ICCP systems and one type of S-ACI.

These are arranged with a discrete anode used for protection deep within the prestressed beams. Comparison of performance between the S-ACI and a mixed metal oxide (MMO) titanium ribbon either side of the beams to protect the 100 mm section to the reinforced concrete deck was also made.

Only S-ACI performance is shown here. In this case, although a soffit application was undertaken, it was found that the S-ACI did diffuse through the concrete and has been applied in two treatment coats.

## Ranby Canal Bridge, Nottinghamshire

Ranby Bridge carries the A1 over the Chesterfield Canal and is constructed as a portal frame. There is an old and new section as the bridge was widened with the requirements of traffic volume over the years.

North and South abutment walls (old and new sections) as well as the bridge soffit have been treated with the S-ACI, a total of approximately 500 $m^2$. In addition, the bridge was subject to some extensive concrete repair and as such an opportunity existed to apply the inhibitor directly to the reinforcing steel in these areas.

This direct application clearly removes the dependency on diffusion through the concrete prior to the S-ACI acting on the anode and cathode sites on the steel surface. The S-ACI was, however, also applied to the surface over and around the repair both as a future 'reservoir' of product for protection and to counteract any incipient anode formation at the periphery of the concrete repair.

Two probes were installed per structural element giving a total of ten monitoring points.

## Conclusion

It can be seen from the data presented that S-ACIs in their various forms are capable of inhibiting the progress of steel corrosion, irrespective of the form of application. There are, however, certain application sensitivities that demand further investigation.

For the corrosion inhibitors to work, it is first essential for them to arrive at the surface of the reinforcing steel. It is therefore not surprising that direct spray application onto the exposed steel produces the most spectacular reductions in observed corrosion rate. Some 100-fold decrease from base values has been observed.

However, by spraying onto the concrete surface, the relative porosity of the concrete and cover are both important factors. Despite this, it is still possible to observe a decrease in rate of some 10-fold from base with this situation being maintained for some time, provided that an adequate latent reservoir of product is available until such time that re-application may be required.

*Combined monitoring of ICCP and S-ACI protection systems: probes in position at Twyford.*

Since the usage of the S-ACI is linked to the equilibrium and relative activity of both the anode and cathode for the particular element in question, three scenarios seem possible:

- The corrosion is very advanced (i.e. there is a high anodic activity) at the onset of treatment and an excessive quantity of S-ACI will be required to be available immediately and in the future.
- A high moisture and oxygen content is present within the concrete cover resulting in the cathodic reaction being 'well-fed', with the consequence that the corrosion reaction at the anode is high. This too may result in a high consumption of S-ACI.
- More commonly, a condition between the first two points may exist where the onset of corrosion can be staved off by the use of S-ACI or where the existing corrosion rates and chloride levels are at moderate levels resulting in the S-ACI coping well for an acceptable period of time of perhaps five to ten years.

There is presently great interest in the possible benefits of S-ACI in providing additional protection directly to steel during repair and enhancing protection against macro-cell or incipient anode formation adjacent to patches.

Without an appropriate form of corrosion rate monitoring, adopted from pre-application and operated throughout the extended life of the structure, the client will not be in possession of the necessary knowledge to fully establish either immediate performance or future re-application and maintenance requirements

AchillesIES, in conjunction with the embedded sensor technology developed at C-Probe, has proven to be an invaluable monitoring tool for the above projects.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