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# Risk-based investigation of steel reinforcement corrosion using the AeCORR technique

M.J.Ing, S.A.Austin & R.Lyons

*CICE, Loughborough University, Loughborough, Leicestershire, UK*

J.Waston

*Physical Acoustics Limited, Cambridge, UK*

**ABSTRACT:** The use of a non-destructive acoustic evaluation technique as a Risk Based Inspection tool to detect the corrosion of steel reinforcement in concrete is presented in this paper. It offers the potential to save time and money for facilities owners and users. Recent research has demonstrated that AE has the ability to identify corrosion activity in concrete before conventional NDT methods, enabling faster intervention and increasing the repair options available. Monitoring a structure using the AeCORR technique, currently being researched and under development in the field, can create a digital map of part of a structure enabling an unbiased reference point for that structure for future maintenance tests as well as being able to distinguish areas of active corrosion. This paper reviews the principles and development of the new AeCORR technique for detecting and estimating the scale of corrosion induced damage and its ability as a tool to index test parts of structures.

## 1 INTRODUCTION

The detrimental role that corrosion of embedded steel rebar plays in the service life of reinforced concrete is well documented (Boyard et al. 1990), costing the UK an estimated £615m per annum. Over the past 25 years, a number of methods for assessing the state of corrosion of reinforcing steel have been under development (Vassie 1978, Dawson 1983, McKenzie 1987), but to date difficulties in accuracy and reliability are still present (Dhir et al. 1993). Consequently a reliable and accurate corrosion tool that can be used to survey reinforced concrete structures is required.

The AeCORR system is a novel, non-destructive technique for detecting corrosion of embedded rebar in concrete and has been under development over the last four years. Current electrochemical techniques such as half-cell and linear polarisation are based upon the electrochemical dynamics of the corrosion reaction. In contrast the AeCORR system detects microscopic damage within the concrete created during the formation of expansive oxide at the steel / concrete interface as a consequence of the corrosion reaction.

## 2 PRINCIPLES OF AECORR

Steel reinforcing bars embedded in good quality concrete are usually protected against corrosion due to the existence of a protective  $\gamma$ -Fe<sub>2</sub>O<sub>3</sub> film on the surface of the steel formed under the highly alkaline conditions. In many cases the passive film remains intact for the life of the structure, but can be destroyed by the following mechanisms acting in isolation or together:

- ~ The presence of aggressive species such as chlorides, that have migrated to the bar depth or were added at the time of casting.
- ~ The reduction in alkalinity due to carbonation of the concrete cover.

Once depassivation of the steel has occurred, corrosion of the steel reinforcement can initiate if in the presence of oxygen and water. For clarity the corrosion process can be divided into two reactions, primary and secondary.

### 2.1 Primary Reactions

The primary reaction involves the coupled anodic and cathodic reactions that take place on the metal surface. At the anodic sites, the metal ions pass into solution as positively charged ferrous ions (Fe<sup>2+</sup>)

liberating electrons that travel through the steel to the cathodic sites. At the cathode, oxygen ( $O_2$ ) and water ( $H_2O$ ) are reduced and combine with the free electrons from the anode to form hydroxyl ions ( $OH^-$ ). To conserve balance of charge, the  $OH^-$  ions migrate through the pore water towards the anode and combine with the ferrous ions diffusing from the anode forming an electrically neutral ferrous hydroxide  $Fe(OH)_2$ .

## 2.2 Secondary Reactions

Although the initial products of corrosion are  $Fe(OH)_2$  and occasionally  $Fe_3O_4$ , these products can undergo secondary reactions by reacting with water and oxygen present in the concrete pores forming a hydrous ferric oxide  $Fe_2O_3 \cdot 3H_2O$  (or haematite) – usually seen as a red-brown rust. This secondary reaction is significant to the durability of the concrete due to the change in the volume ratio of corrosion product to steel. Ferrous hydroxide has a volume of expansion of approximately 2.1:1, which can increase up to ratio of 10:1 if secondary reactions proceed to the formation of hydrous ferric oxide (Carney et al. 1990). The increase in volume at the steel / concrete interface generates large tensile stresses in the concrete, inducing microcracking in the concrete cover. Over a prolonged period of corrosion, a sufficient volume of corrosion products may accumulate resulting in the spalling or debonding of the concrete cover.

The rapid release of energy yielded by the formation of a microcrack is emitted from the source as a stress wave, detected on the surface of the concrete by a piezoelectric sensor. The magnitude and frequency of the stress waves will be related to the concrete properties (Ing et al. in prep.a) and corrosion rate (Lyons et al. in prep.). Furthermore, they will be related to and so a direct indication of the damage occurring to the concrete, enabling an early warning system against debonding and steel section loss. The detection and interpretation of these stress waves provides the basis of the AeCORR technique.

## 3 PARAMETERS INFLUENCING AECORR PROTOCOLS

This paper describes the development of the AeCORR procedure by providing a review of the influential parameters and shows how they have been incorporated into the AeCORR testing procedure.

Cost-effective maintenance strategies for the repair of reinforced concrete need to be based upon reliable information about the rate of corrosion induced dete-

rioration. The success of AeCORR to detect and monitor reinforcement corrosion will rely upon an appreciation of the variables, which can then be incorporated into Risk Based Investigation (RBI) protocols. These factors can be broadly split into three categories: *environmental, electrochemical and material influences*. The RBI methodology incorporates the variables within these categories to enable a full assessment of the condition to be made rather than just recording instantaneous measurements.

### 3.1 Environmental Influence

The corrosion rate of steel in concrete is highly dependent on many factors such as temperature, internal moisture content, resistivity and the availability of oxygen (Liu & Weyers 1998). These factors simultaneously influence the rate of corrosion and whilst they may be studied in isolation, in practice they are inter-dependent and can have significant control upon the rate of the corrosion reaction. An understanding of their influence and an ability to incorporate their effects into a testing procedure is essential if an accurate assessment of the corrosion rate is to be determined.

#### 3.1.1 Temperature

The temperature of concrete imposes a significant effect on the corrosion rate of reinforcing steel. An increase in temperature aids solubility of the  $Fe^{2+}$  ions into the pore liquid of the concrete and consequently increases the development of the anodic reaction, increasing the corrosion rate. The change in internal temperature also induces changes in other parameters such as the concrete resistivity, oxygen diffusion in the cathode reaction and can reduce the critical  $Cl^-$  concentration required for depassivation. The overall influence of temperature is very complex but as a rule of thumb, every  $10^\circ C$  increase in temperature corresponds to a doubling of the corrosion rate (Bentur et al. 1997). Consequently, implications arise as to when corrosion measurements should be taken, and if normalised values are desired, adjustment factors must be used to normalise the data.

#### 3.1.2 Resistivity

Corrosion rate is found to be strongly dependent on the electrical resistivity of concrete, which is influenced largely by temperature and the internal relative humidity (RH) of the concrete. The ohmic resistance of concrete may change significantly from more than  $10^4$  ohms in dry concrete to about several hundred ohms when the concrete is fully saturated (Liu & Weyers 1998). In very dry concrete the very high internal concrete resistance arrests the corro-

sion rate to negligible values. (Parrot 1996), suggests that the minimum RH required to support corrosion in concrete is 75% RH. An upper limit of 95-98% RH has also been suggested for very wet concrete because the corrosion rate can be dramatically reduced due to oxygen starvation at the cathode in concrete near or at saturation. This principle has been illustrated in Figure 1.

In natural conditions, the RH and temperature are in constant flux due to diurnal and seasonal variations thus also causing the corrosion rate to be constantly changing. Small changes in either temperature or RH may significantly affect the dissolution rate, and in some instances, be significant enough to suppress the reaction. It is also clear from Figure 1 that if the internal RH is below 70%, the corrosion rate falls to negligible values in carbonated concrete, inducing a dramatic increase in the number of years required to cause cracking. As AeCORR monitors for corrosion by detecting microcracking activity, a low RH will affect the duration of the monitoring period required. Therefore protocols are required that enable an estimation of the rate of activity possible under the environmental conditions present.

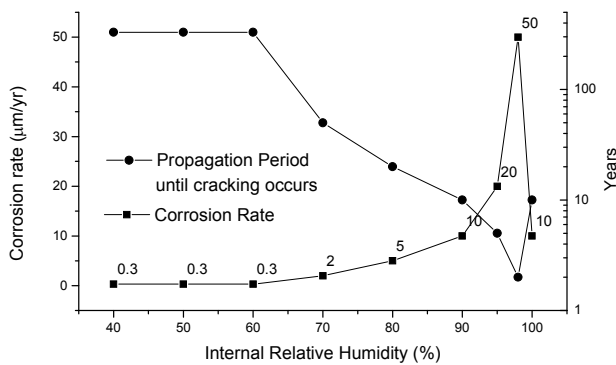


Figure 1. Influence of internal RH on corrosion rate in carbonated concrete (Bentur et al. 1997)

This is addressed within the procedure by taking resistivity measurements. The resistivity values are grouped into three categories, red, orange and green. If the measured values fall into either of the former two, testing is possible. If they fall into the latter, monitoring is not recommended, as the conditions are not favorable for corrosion activity.

### 3.2 Electrochemical Influence

The electrochemical influences are concerned with factors such as the corrosion rate, the corrosion type and oxide formation. Whilst there is overlap between each of these factors, singularly they are of importance.

#### 3.2.1 Corrosion Rate

Typical corrosion rate values of steel in concrete can vary from 0.1 – 100  $\mu\text{A}/\text{cm}^2$  on real structures, with the values between 0.1-1  $\mu\text{A}/\text{cm}^2$  being the most frequent (Andrade & Alonso 2001). The maximum corrosion rate a section of a particular structure is able to support will be strongly influenced by the water / cement ratio of the concrete, which will determine the resistivity and the oxygen permeability values of the concrete.

The rate of corrosion has a significant influence on the time to failure of the concrete. Figure 1 illustrates how different corrosion rates dramatically reduce the time taken until cracking of the concrete cover occurs. Due to this phenomena it has been shown that AeCORR is able to estimate the rate of corrosion through measurement of the rate of damage (Energy/sec) as shown in Figure 2 (Lyons et al. in prep). The Energy/sec values are related to the rate of oxide production and microcracking within the concrete. Not only does this give a reasonable estimate of corrosion rate, but it also gives an indication of the rate of damage occurring within the concrete cover.

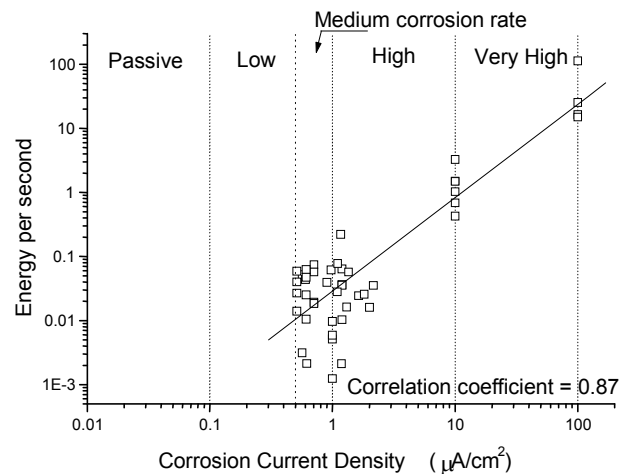


Figure 2. Variation in Energy/hour with corrosion rate.

#### 3.2.2 Corrosion Type

Corrosion of steel reinforcement can be induced via two main processes: the chloride ion or carbonation of the cover concrete. Whilst both methods result in a loss of steel section and the production of oxides, there are crucial differences between the two for which any protocols for a measurement technique must cater.

Carbonation induced corrosion causes a general loss of section of the rebar over a relatively large area producing solid oxides on the surface of the bar. Conversely, chloride induced corrosion is usually associated with localised pitting corrosion. The

acidic condition inside the pit prevents the formation of solid oxides on the bar. Due to its localised nature and the oxide type, pitting corrosion is sometimes not detected by existing methods until extensive damage has occurred.

The AeCORR method incorporates the different corrosion types within its protocols. Research has found that the technique is able to clearly detect chloride-induced corrosion (Austin et al. in prep). Furthermore, the RBI procedures help to identify which parts on the structure are at risk from which type.

### 3.3 Material Influences

The material properties of a structure will not only influence the resistance to corrosion and subsequent corrosion rate but will also affect the magnitude of the emissions caused by microcracking.

It is essential that differences in the emission caused by variations in for example, concrete strength, can be quantified to enable normalisation of readings between structures.

#### 3.3.1 Strength of Concrete

Reducing the water / cement ratio in concrete mix design usually results in an increase in the compressive strength, increasing the resistance to the ingress of aggressive species that may initiate corrosion.

However, good quality concrete alone is not sufficient to prevent corrosion occurring and if it occurs a greater force is required to exceed the local tensile strength of the matrix resulting in a larger stress wave being emitted during micro-fracture for a given volume of corrosion.

Previous work (Ing et al. in prep.a) has suggested that an exponential relationship exists between the compressive strength of concrete and absolute energy per gram of steel loss, as shown in Figure 3.

## 4 RISK BASED INVESTIGATION PROCEDURE

To ensure successful application of AeCORR, a RBI procedure is under development with the aim of determining whether active corrosion is occurring on a structure, its location and how badly it is corroding. Figure 3. Influence of Compressive Strength on absolute energy per gram of mass loss

To achieve this aim, the procedure has four objectives:

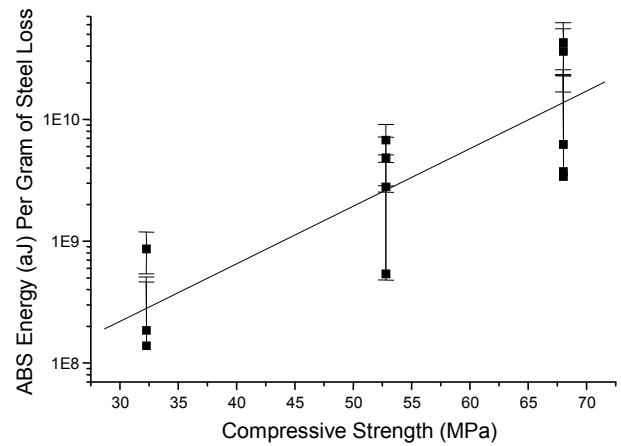


Figure 3. Influence of Compressive Strength on Absolute Energy per Gram of Mass Loss.

- 1 To enable an accurate and efficient application of the AeCORR technology to undertake reliable and repeatable corrosion measurements on reinforced concrete structures.
- 2 To assess the likelihood of corrosion occurring at a selected point on a structure.
- 3 Using AeCORR adjustment factors, grade the extent of corrosion induced damage of the structure into one of five grades, ranging from A-E.
- 4 Using the grading band, and information about the type of structure and history, be able to undertake a risk assessment of the structure for the purpose of prioritising for maintenance.

These four objectives can be achieved by incorporating the influential parameters (environmental, electrochemical and material) discussed in earlier sections and combining them with structure specific information. The basic outline of such a procedure is presented in Figure 4.

The procedure in Figure 4 combines the environmental, electrochemical and material parameters together to form a simple test procedure that if employed correctly, will provide a reliable and accurate test technique.

The start for any structural investigation must be a comprehensive desk study. This process assembles all the information about the structure (age, exposure, orientation, concrete details etc) which is combined with a preliminary visual survey to assess the risk posed to the structure. This study is very similar to routine maintenance or principal inspections undertaken on most reinforced structures. If the structure (or a specific element) fails a number of predetermined criteria, the investigation can proceed.

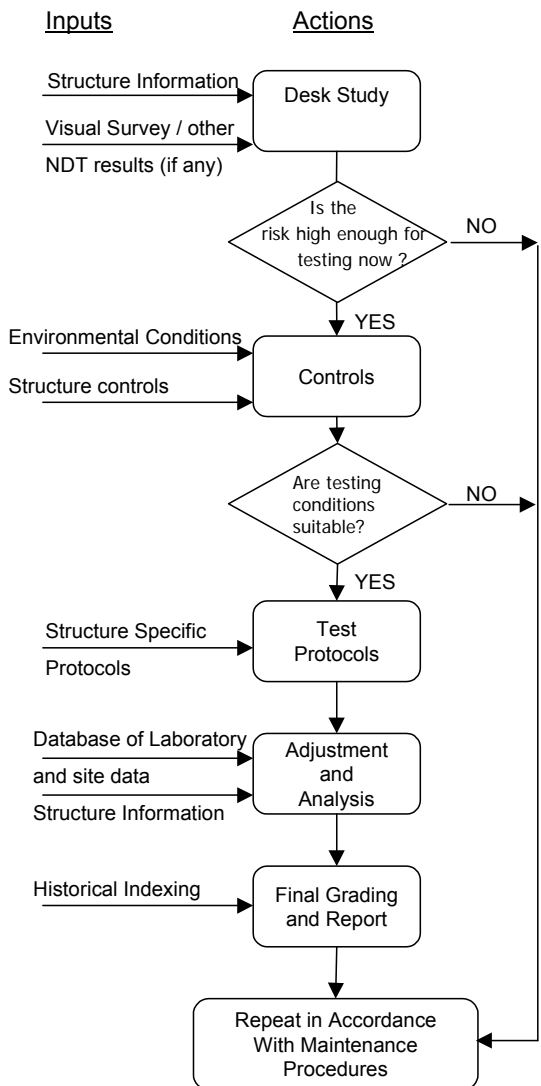


Figure 4. Risk Based Investigation Procedure

It is essential that on the day of the monitoring, conditions in the concrete are known to estimate the ability of the concrete to support corrosion. Therefore, conformance checks such, as resistivity measurements are required prior to testing. The control protocol awards each element one of three activity gradings based on the results of the conformance checks ranging from *very suitable* to *not suitable for testing*.

Obviously if the structure is *suitable* or above, testing can proceed. Each type of structure has specific test protocols developed from field experience to avoid collection of rogue or 'bad' data.

After successful data collection, post analysis of the results normalises the data for the factors discussed in Section 3. For instance, the strength of the concrete can strongly influence the rate of emission for a given mass of steel loss (Fig. 3). Consequently, the strength of the concrete needs to be normalised to enable comparisons and realistic assessments to be undertaken. The weightings and adjustment factors

have been developed from extensive laboratory testing and field experience.

Finally the structure or structural element can be graded which will enable prioritisation for repair and provide a benchmark for future testing.

## 5 GRADING OF STRUCTURES

The output of the AeCORR method grades the scale of activity on a range from A-E, where A is Minor – insignificant, and E is Major – immediate intervention recommended. This gives the engineers a clear and immediate indication of the condition of the structure. Furthermore, in the situation where engineers are responsible for hundreds of structures or structural elements, it can provide a means of index testing, aiding the formation of maintenance schedules (Ing et al. in prep.b). An example of the grading chart is shown in Figure 5, which shows the results from an area of a reinforced concrete swimming pool wall.

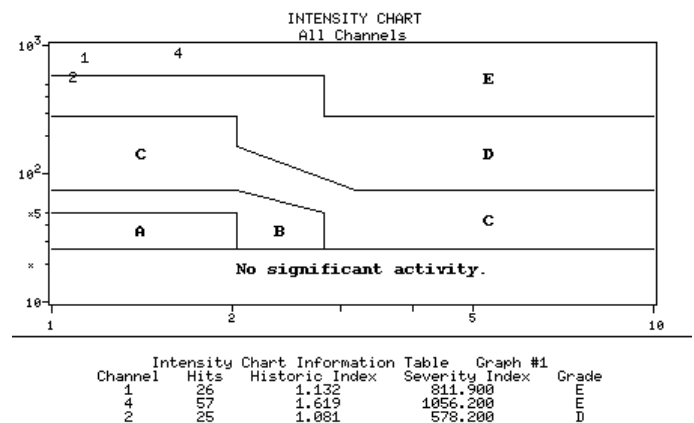


Figure 5. Activity grading chart

The numbers 1,2 and 4 represent three AeCORR transducers mounted on the concrete surface. Transducer 3 was the designated control and received insufficient emission to be graded due to the area being of sound nature. Large areas of the pool wall were being broken out due to significant deterioration from reinforcement corrosion. The warm, moist conditions, coupled with the chlorides in the pool water had enabled corrosion of the reinforcement to proceed unhindered leading to large areas of delamination and spalling.

The area monitored had been highlighted by the visual survey as an area of increased corrosion risk. Environmental conditions at the time of testing enabled monitoring to proceed. The results show that the area monitored indicated significant corrosion.

Whilst this area had not yet delaminated the results indicate that delamination would be imminent.

## 6 CONCLUSIONS

This paper has discussed a number of important parameters that were considered during the development of a new corrosion detection method for reinforced concrete. The focus of this paper has been the RBI procedure that supports the new technique. The procedure is a result of a significant amount of research that has recently been undertaken (Ing et al 2002a, Austin et al 2002, Lyons et al 2002).

1. The AeCORR method offers the potential to accurately detect active corrosion in reinforced concrete structures completely non destructively.
2. The approach of the RBI method aims to incorporate the important parameters in a well researched, structured and logical format to provide a reliable detection procedure.
3. Using this RBI procedure, the grading of structures can be made more easily and objectively, especially for planned maintenance of a number of structures.

## 7 ACKNOWLEDGEMENTS

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