CONDITION MONITORING OF REINFORCED CONCRETE STRUCTURES AT RISK FROM REINFORCEMENT CORROSION

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ABSTRACT

The corrosion of reinforced concrete structures is a major issue in the UK and worldwide, both structurally and from a maintenance management aspect. Damage induced by the corrosion of the steel can dramatically reduce the designed service life of the structure through loss of bond between the steel and concrete, or from localised loss of section of the corroding rebars. Failure to manage the maintenance of reinforced concrete may result in the premature replacement of the structure or in extreme cases, structural failure. Avoiding such scenarios can be aided through improved detection and monitoring of corrosion in concrete. In addition, combining this with a condition management tool, capable of benchmarking, index testing and prioritising areas of the concrete structure(s) for remedial action, would provide robust facilities management techniques for structural assets. This paper suggests how the results of a novel non-destructive corrosion detection technique, currently being developed, could be incorporated into a condition-monitoring tool for the facilities management of structures. The development of protocols based on laboratory and field data enable the formation of a condition-monitoring tool forming part of a long-term maintenance strategy for estate owners and managers.

Keywords: Concrete, condition-monitoring, corrosion

INTRODUCTION

Steel reinforced concrete is one of the most widely used materials in construction due to its versatility and acceptability (Arora *et al* 1997). Once constructed, good quality concrete can last for many years without the need for any significant maintenance work, making it an ideal candidate for high trafficked structures such as car parks and bridges. Closure of such structures for maintenance can be a costly issue for the structure managers or owners and be a source of major inconvenience for the users. The situation can also be difficult in large residential buildings where the interests of the residents, housing authorities and home-loan organisations have to be considered (Parrott 1990).

Protection of the steel against corrosion is provided naturally by the highly alkaline environment of the concrete pore water that chemically reacts with the steel to form a protective passive layer. The stability of this layer over the life of the structure is largely influenced by the ability of the concrete to resist the ingress of aggressive species such as Cl^- and CO_2. Chloride ions may enter the concrete prior to hydration as admixtures and contaminates or, after hydration, from external sources such as seawater and de-icing salts. Once at the depth of the reinforcement they are able to destroy the passive film (Batis & Routoulas 1999) and initiate corrosion when in the presence of oxygen and water.

During the corrosion process, the increase in volume of rust products exerts stresses within the concrete that cannot be supported by the limited plastic deformation of the concrete therefore inducing cracks (Cabrera (1996) and Francios & Arliguie 1999). This weakens the bond between the steel and concrete, reducing the bearing capacity, serviceability and ultimate strength of concrete elements within the structure. In the case of pitting corrosion, extreme section loss of the rebar can occur before any visible cracking is evident on the surface, presenting an invisible danger to the users and owners as well as being an urgent maintenance issue.

Repair and rehabilitation of existing structures is becoming a major part of construction activities. The estimate for repair and rehabilitation of transportation infrastructure in the U.S. exceeds several billion dollars (Auyeung *et al* 2000) and is estimated to cost £600m annually in the UK. Corrosion of reinforcement is a major contributing factor to deterioration of reinforced and prestressed concrete structures, and with the ageing bridge and car park stock in the UK, the structural integrity of reinforced concrete is increasingly under threat. This was demonstrated by such events as the sudden collapse of a post-tensioned bridge deck at Ynsygwas and the collapse of a multi storey car park in the US.

This paper reports on the potential use and benefit to owners and estate managers being offered by the new and innovative corrosion detection / monitoring tool, AeCORR, under development at Loughborough University in partnership with Balvac Whitley Moran, Physical Acoustics Ltd and Atkins. Furthermore, it discusses how AeCORR could be incorporated into a condition-monitoring tool for the facilities management of structures.

CORROSION DETECTION AND MONITORING

Methods for assessing the state of corrosion of reinforcing steel have been under development for over thirty years (Dhir *et al* 1991). However a number of difficulties remain and there remains a need for the introduction of a simple, quick and practical tool which can be used to survey complete structures.

Corrosion Model

Assessment of the loss of serviceability of reinforced concrete is made on the basis of models or the measurement of corrosion rates using some form of measurement device. The most well known conceptual corrosion model is by Tuutti (1982), shown in Figure 1, in which the service life of a structure is divided into two stages; the initiation stage (ingress of aggressive species to bar depth) and the propagation stage involving active corrosion.

The gradient of the propagation line corresponds to the corrosion rate, primarily influenced by temperature, relative humidity and oxygen content. Thus the rate of corrosion will be constantly changing in response to the local environmental conditions making predictions of time to failure, based on an instantaneous measurement, difficult. Moreover, determining the time of depassivation is also difficult, hence when assessing a corroding structure, it is not usually known how far along the curve the structure lies.

In any one structure, the time of initiation will differ for each area or between elements due to local differences such as exposure, orientation, temperature and cement content. These factors will also affect the ensuing corrosion rate. Consequently, the situation arises where there are multiple areas of corrosion on one particular structure, all at various levels of activity and rate. For this reason it can occasionally be more economic to remove just the active areas of corrosion rather than to remove the chlorides from the whole concrete and to manage the risk of further corrosion in the non-repaired areas by future monitoring (Guliker 1995).

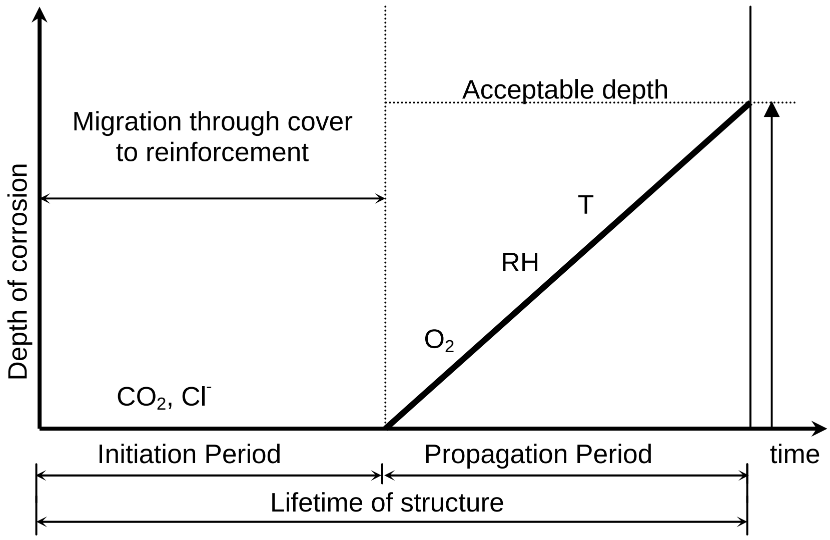

Figure 1 Conceptual Corrosion Model

Existing Techniques

Current techniques, such as the half-cell potential report the probability of corrosion occurring based upon the potential difference between the half-cell and the embedded steel. Its major limitation is that it can only indicate the direction of the reaction (i.e. reduction or oxidation) and not the rate.

Measuring the rate of corrosion is not directly possible due to conservation of the balance of charge law which states that the net current in any corrosion reaction must be zero. The linear polarisation technique, first introduced for metals in solutions, attempts to quantify the rate of corrosion by measuring the response to a small electrochemical perturbation. However, questions still remain about the accuracy and reliability of this technique on concrete structures.

Hammer testing is often used to find areas of advanced corrosion where significant oxide build up has resulted in the cover being forced away from the steel rebars. In such circumstance air and water have easier access to the steel, increasing the corrosion rate thereby worsening the degree of damage.

AeCORR CORROSION MONITORING

AeCORR is a novel acoustic evaluation technique, able to detect corrosion of the rebar by a non-destructive method. Extensive laboratory trials have provided strong evidence of the ability of the technique to detect very early age corrosion of steel in concrete, and in some instances, before detection by the commonly used half-cell technique (Ing *et al* 2002).

Principle of AeCORR

The AeCORR technique is a novel approach to detecting corrosion in reinforced structures. Unlike the two existing methods mentioned above, the AeCORR technique is not electrochemically based, but rather is a passive technique that detects the sudden release of strain energy during the formation of a microcrack. The metallic deformation that is undergone during corrosion is not as harmful to the steel as the damage imposed by the formation of expansive oxides to the structure, resulting in loss of structural bond. Consequently, by detecting the fairly regular microscopic damage induced by corrosion, AeCORR is able to detect, indirectly, reinforcement corrosion.

AeCORR comprises of a number of surface mountable sensors that are placed directly onto the concrete surface. Depending upon the number of sensors used, they may be placed singularly or in a triangular array to enable global testing of an area offering the possibility of source location. The sensors are connected to a digital signal-processing unit that converts the analogue input into digital data, stored on the hard-disk for post-test analysis.

Reliability

The essence of the AeCORR technique is the ability of the method to detect corrosion only when it is occurring. For example, in saturated concrete, the restriction of oxygen may result in very negative half-cell potential readings, which cannot be associated with corrosion of the steel. In this situation, AeCORR would correctly determine that corrosion was not active due to the absence of expansive oxide formation.

Environmental Effects

Laboratory work undertaken at Loughborough University (Lyons *et al* 2003), has investigated the response of AeCORR to seasonally induced changes to the corrosion rate. Current electrochemical methods are largely affected by fluctuations in the moisture content induced by seasonal climatic variations (CBDG 2002), however the modest changes in seasonal corrosion rate were shown not to strongly influence the result.

Early Age Detection

One major benefit of AeCORR is the ability of the method to detect very early age corrosion, thus enabling immediate intervention before loss of bond and major delamination and providing the client with the maximum opportunities for early remedial works.

Figure 2a illustrates a localised area of corrosion, on a 16 mm deformed rebar placed in a concrete prism of characteristic strength 50 MPa, having a nominal cover of 16 mm. Corrosion was induced on the specimen as described in earlier work (Austin *et al* 2002). On breakout, it was discovered that the area of corrosion was localised, with minimal penetration into the steel surface (confirmed by removal of the corrosion products). As shown in Figure 2b, there was no external evidence of corrosion.

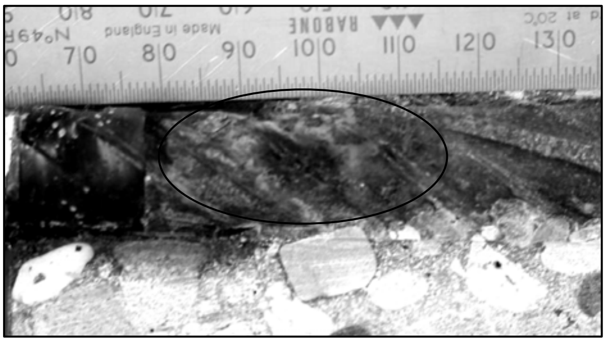

Figure 2a Corrosion of the rebar

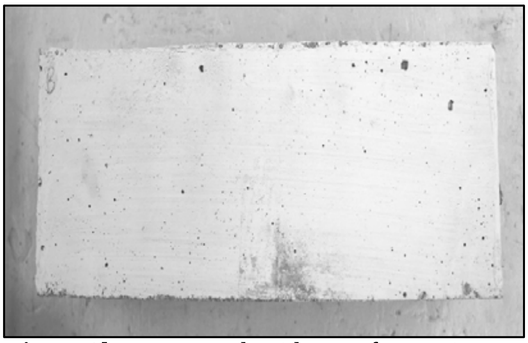

Figure 2b No external evidence of corrosion

CONDITION MONITORING

It has been highlighted in previous sections that corrosion of reinforcement is potentially a major maintenance problem for all concrete structure owners. If left unmonitored, the scale of the corrosion is likely to increase until such a point that immediate action is required. A structure management procedure is therefore required that enables objective decisions to be made, incorporating a detailed structure maintenance strategy.

Current maintenance is largely a matter of identifying maintenance problems, establishing priorities and undertaking repairs within the available budget (Jones 1989). Therefore, one of the main objectives of any structure management procedure is to prioritise and allocate funds in a manner that is most efficient and effective. In order to facilitate this, structure owners require detailed information of the state of each structure and knowledge of how to best resolve the problems being faced, which may vary from structure to structure.

AeCORR, together with the Risk Based Inspection process protocols, which form part of the inspection tool, could be used as part of a prospective structure management procedure, providing objective, decision enabling ~~?~~information to the engineers.

Maintenance Management

Present practice is such that only small funds are available for inspection, maintenance and repair therefore only the structures with the most serious damage are dealt with and the remaining structures are left to degrade to a low level of condition before any intervention is made (Rostam (1989). This approach does not optimise the best deployment of funding as chloride induced corrosion is a progressive problem and if caught before or just after initiation, treatment is far simpler and cheaper than if permitted to degrade further.

The AeCORR technique may be applied to structures to determine the corrosion state of the reinforcing bars. Rather than provide estimated corrosion rates or the likelihood of corrosion, which can be of little value, AeCORR will give the output to the engineer in a form of an activity grading on a scale of A-E. In this instance A implies no corrosion activity – no further action and E signifies major corrosion activity – immediate intervention required.

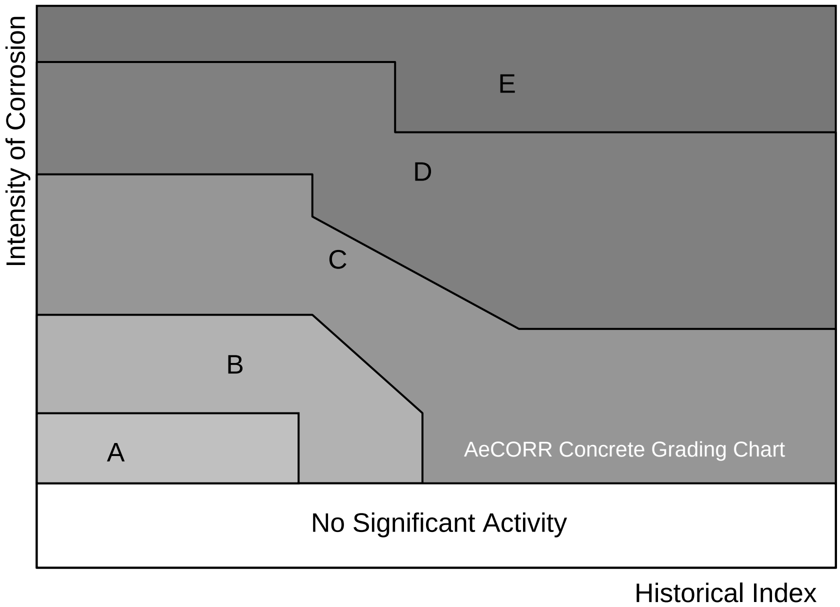

Figure 3 AeCORR concrete grading chart

The boundaries of the grading bands will be determined from a historical database, ensuring an ever increasingly accurate analysis of the results. The initial grading can be adjusted depending upon specific structural properties such as strength of the concrete, or for environmental conditions such as temperature, to improve accuracy of the grading. An example of the grading structure is shown in Figure 3.

Obtaining a grading figure provides the structure management team with a simple benchmark from which all future maintenance decisions can be made. In the case of a relatively new structure, where corrosion is not present, AeCORR may be combined with other inspection tests such as chloride ion depth analysis. It may be found that whilst the AeCORR has awarded the structure an 'A' grade because of the lack of corrosion, the chloride ion concentration is close to the initiation threshold. Rather than delay treatment (despite being awarded an 'A' grade) it may be prudent to take relatively cheap remedial action before corrosion begins.

Conversely, the structure may be awarded a B, C or D grade, which would indicate that the rate of corrosion-induced damage is within a progressive stage. In this instance there may be three choices available to the management team:

a) If awarded a B grade, it may be prudent to undertake further NDT;
b) to intercept as soon as possible to prevent further degradation or

c) to accept that the structure is in a bad state, but still in a serviceable condition.

If early interception is considered appropriate, then repeating the AeCORR test a year or so later would assess the success of any remedial work, represented by a lowering of the grade.

If the intended life of the structure is only for a few more years, then option (c) would be a more effective strategy combined with yearly inspections using AeCORR and minimal maintenance to ensure that the deterioration does not increase significantly. Such a strategy would enable comparable monitoring of the structure's deterioration and enable an objective assessment of the future life of the structure.

Index Testing

It is often the case that a large number of structures fall under one overall maintenance plan, and the primary problem is the lack of detailed information regarding the state of each structure. Furthermore, the type, rate and effect of deterioration of concrete structures are often unique for each individual structure, hence to compare condition between structures can be an arduous task.

The AeCORR method may aid this process through provision of the simple grading system, which enables listing the structures in order of the activity weighting. On a high-level this approach would give the engineers an objective list from the worst cases through to the low risk structures. However, each structure could be decomposed into a number of structural elements, which can also be graded. This enables prioritisation of both structural elements within a structure (low level) and prioritisation between similar structures (high level).

CASE STUDY

An ageing reinforced concrete swimming pool, situated in central England or the midlands, ~~(?)~~ was the subject of a successful trial of the AeCORR technique. Chlorides added to the pool water had over time permeated through the walls of the pool resulting in corrosion of large areas of reinforcement, with the corrosion reaction accentuated by the warm and consistent temperature within the pool cavity.

Repair works to walls of the pool were confined to the spalled and delaminated areas of the structure that showed severe section losses. However, the possibility still remained that corrosion was occurring in other locations, at an earlier stage in the propagation phase, before spalling or delamination.

A damp area of concrete, near a construction joint was selected as a trial location for AeCORR. This area exhibited a number of features, which using AeCORR area selection protocol placed the area at high risk from corrosion. A hammer survey prior to testing confirmed that the concrete had not yet delaminated.

The half-cell survey results shown in Figure 3 indicated a 90% probability of corrosion occurring in the centre of the damp area and the immediate surrounding area suggests an intermediate probability. Using AeCORR the actual presence of corrosion was to be determined, together with a grading (A-E) of the rate of activity. The sensors were mounted as shown in Figure 3, where Channels 1 and 2 were located on the outskirts of the damp patch and Channel 4 located near the centre. Channel 3 was sited in an area classed through the AeCORR site selection protocol as being of low corrosion risk, out of range of the area covered in Figure 3.

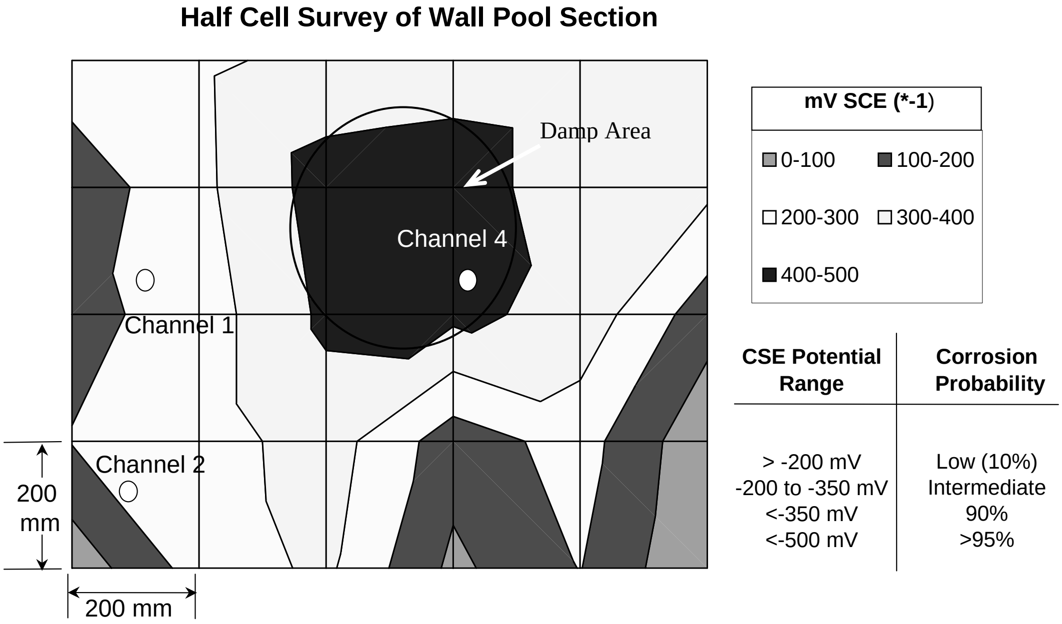

Figure 3 Half Cell Potential results for section of pool wall

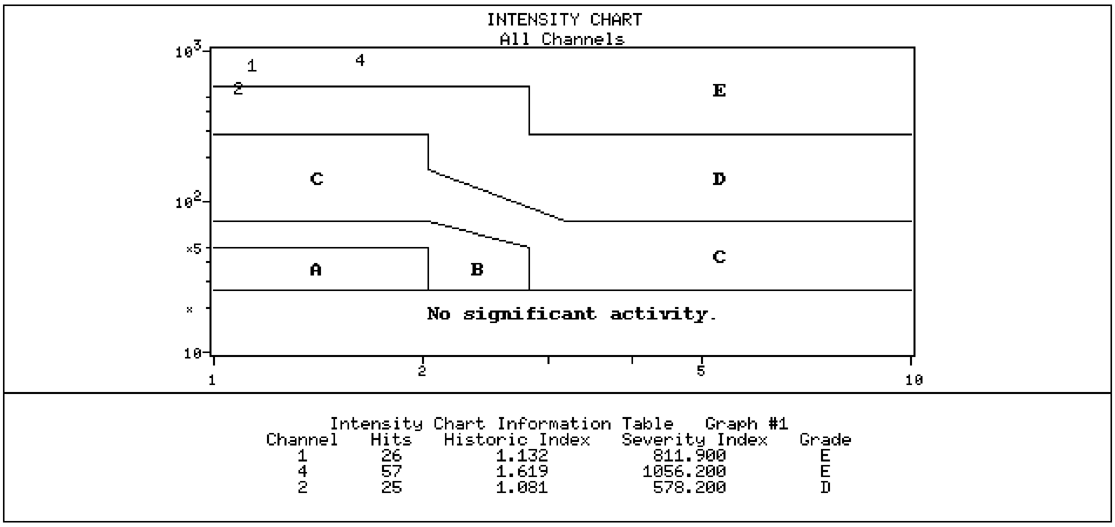

Figure 4 Grading results from AeCORR test (screen shot)

The results from the AeCORR test are presented in Figure 4. Sufficient corrosion activity was detected over a 2-hour test period enabling grading of the data. Channels 1 and 4 are clearly within the E grading, with Channel 2 on the border of D and E. The control (Channel 3) had insufficient activity to register on the scale. The E grading may suggest that delamination is imminent if no action is taken.

The difference in grading between Channels 1,2 and 4 exists due to the sensors being located at different distances from the corroding rebar. As the stress wave emanates away from the source, the energy contained in the stress wave is attenuated therefore those sensors furthermost away will receive less energy. Using the difference in arrival times, rather than the energy of a single stress wave hitting three sensors, this principle can be used to locate the source of the activity.

To qualify the E grading, the energy per second values were compared with a database of known corrosion rates versus energy per second, which has been developed from extensive laboratory tests undertaken as part of this research. To avoid errors in quoting specific corrosion rates, the range of rates likely to be encountered on a reinforced concrete structure have been dissected into corrosion bands (Andrade & Alonso 2001) as shown in Table 1. The energy per second values for channel 4 (closest to the area of corrosion) fall within the top end of the High corrosion band which is consistent with the extent of corrosion found on the exposed rebar undergoing repair.

Current density ($\mu A/cm^2$)	Corrosion Band
< 0.1	Passive
0.1 – 0.5	Low
0.5 – 1	Medium
1 – 10	High
10 – 100	Very High

Table 1: Corrosion Bands

In summary, AeCORR has been shown to identify, locate and grade areas of corrosion. In this case study, the pool was only required to be serviceable for a further five years and as such no further areas were broken out.

CONCLUSIONS

The new AeCORR technique is a promising method that can be used to assess the state of corrosion occurring in a structure, and additionally be used as part of a higher level structured maintenance plan.

AeCORR can enable ranking of a number of structures from the worst to the best cases and highlight areas within a single structure that are in need of repair, indicating rates of corrosion which other methods are unable to do reliably.

Using AeCORR as part of a condition monitoring procedure, degradation of the structure can be monitored over time, paramount in those cases where it might be decided that immediate intervention is not suitable or affordable.

AeCORR, combined with other testing, such as chloride sampling, can be used as part of a preventative maintenance plan.

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