Determining the corrosion state of steel reinforcement in concrete

Dr. M.J.Ing, D.G.Kells
Balvac Limited, Birchwood Way, Somercotes, Derbyshire, UK

Prof. S.A.Austin, Dr. R.Lyons
CICE, Loughborough University, Loughborough, Leicester, UK

Abstract
The corrosion of reinforced concrete structures is a major issue in the UK and worldwide from both a structural view and maintenance management aspect. Early detection of this degradation process will provide the owner with the optimum number of repair options whilst minimising repair costs. This paper reports on the new non-destructive corrosion detection technique for reinforced concrete – AeCORR, specifically targeted towards detecting active corrosion damage occurring within the concrete during the very early stages of the degradation process. An overview of the technique is provided together with a recent case study.

Introduction
Steel reinforced concrete is one of the most widely used materials in construction due to its versatility and acceptability. However the detrimental role that corrosion of rebar plays in the service life of reinforced concrete is well reported, and is estimated to cost the UK £615m per annum [1]. Whilst a number of different methods can be employed to indicate the likelihood of corrosion, a reliable and accurate technique with the ability to detect corrosion, and the damage it induces, is required.

This paper provides a technical overview of the new non-destructive corrosion detection technique "AeCORR" developed by Balvac Ltd in conjunction with Loughborough University, Physical Acoustics Ltd and Atkins, which uses innovative acoustic technology to detect the damage that occurs within the concrete due to reinforcement corrosion. 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 the microscopic damage created during the formation of expansive oxides at the steel / concrete interface as a consequence of corrosion.

Principles of AeCORR
The highly alkaline environment of the concrete pore water chemically reacts with the steel to form a protective passive layer providing natural protection for the steel. In many cases the passive film remains intact for the life of the structure, but can be destroyed by the ingress of aggressive elements such as Cl^- and CO_2, acting individually or in combination.

During the corrosion process ferrous and ferric oxides are formed which have a greater volume than that of the steel from which they were reduced. This increase in volume exerts stresses within the cover that cannot be supported by the limited plastic deformation of the concrete, therefore microcracking occurs [2,3], which results in a sudden release of elastic energy. The formation of microcracks weakens the bond between the steel and concrete, reducing the bearing capacity, serviceability and ultimate strength of the concrete elements within a structure.

The AeCORR system comprises of a number of specialist transducers connected in series to an analogue to digital converter, housed inside a PC. The transducers are mounted directly onto the surface of the concrete as shown in **Figure 1** where they are left for a minimum of ten hours.

Figure 1 Transducer Mounting

The rapid release of energy yielded by the formation of a microcrack is emitted from the source as a stress wave and can be detected on the surface of the concrete by the piezoelectric transducers. The magnitude and frequency of the stress wave is related to the concrete properties [4] and corrosion rate [5]. Therefore detecting and analysing these signals can provide an early warning system against debonding and steel section loss, thus forming the basis of the AeCORR technique.

Potential Cost Savings

One major and unique benefit of AeCORR is the ability of the technique to detect and indicate the rate of very early age corrosion damage, thus enabling immediate intervention before loss of bond and delamination. Corrosion in concrete is a progressive problem and if caught just after initiation, treatment is simpler and significantly cheaper than if degradation continues.

Signal Parameters

The stress wave generated due to the formation or propagation of a microcrack is partially emitted as a sound wave and usually comprises of a wide range of frequencies each of various magnitudes. To enable detection of these waves and to minimise the influence of background / extraneous noise, special transducers with a resonant frequency corresponding to one of the main characteristic frequency components in the original emission source are used. These transducers are usually only excited by emissions that contain the resonant frequency component, thereby causing the transducers to ‘ring’ at their own natural frequency of oscillation, and generate an electrical signal in response to the initial excitation frequency. The transducers do not respond to frequencies outside the resonant range thus excluding unwanted source mechanisms.

Through monitoring these signals using a single or an array of transducers mounted directly onto the concrete surface, it is possible to detect the very early stages of reinforcement corrosion, long before surface deterioration occurs [4,6] and in some instances, while the half-cell technique still indicates nobility [5,7,8]. On the basis of both site and laboratory testing, a rigorous site testing procedure has been developed with an overview reported by Ing *et al.* [9].

On site there may be many potential sources of background or extraneous emission such as the impact noise of wind blown objects striking the structure, movement of bearings and from other sources that generate microcracks. Thus before each test a comprehensive assessment is undertaken to determine the probability of these sources arising during the monitoring period and assessing the severity they may have on the quality of the data collected. Suitable procedures are then implemented to either to eliminate the extraneous source or to minimise its effects. For example, freeze thaw may induce microcracking, thus to eliminate its effects on the test data, monitoring is undertaken at temperatures greater than $0^{o}C$, thus removing any potential effect completely.

A further guard against collection of unwanted data is the ability to post process the data. After the test all recorded data is reviewed during the interpretation stage, enabling the identification and removal of noise signals before evaluation of the data is undertaken.

Parameters Influencing Corrosion Measurements

Cost effective maintenance strategies for the repair of reinforced concrete need to be based upon reliable information about the rate of corrosion induced deterioration. However, the rate of deterioration is influenced in part by the rate of corrosion and the material properties of the structure.

The corrosion rate of steel in concrete is highly dependent upon many factors such as temperature, internal moisture content, resistivity and the availability of oxygen [10]. The rate of corrosion has a significant influence on the time to failure of the concrete as shown in **Figure 2** (adapted from ref [11]), which illustrates how different corrosion rates dramatically reduce the time taken until cracking of the concrete cover occurs.

The time taken for cracking to occur is clearly influenced by the rate of corrosion. Thus as AeCORR detects microcracking due to corrosion, the amount of microcracking sustained during a monitoring period will vary according to the rate of oxide production and rate of microcracking – both influenced directly by the corrosion rate. The ability for AeCORR to estimate the rate of corrosion through measurement of the rate of damage (microcracking) is shown in **Figure 3** [5]. Thus the Energy / Second values can be used to give a reasonable estimate of the corrosion rate at that instant in time, in addition to an indication of the rate of damage occurring within the concrete cover.

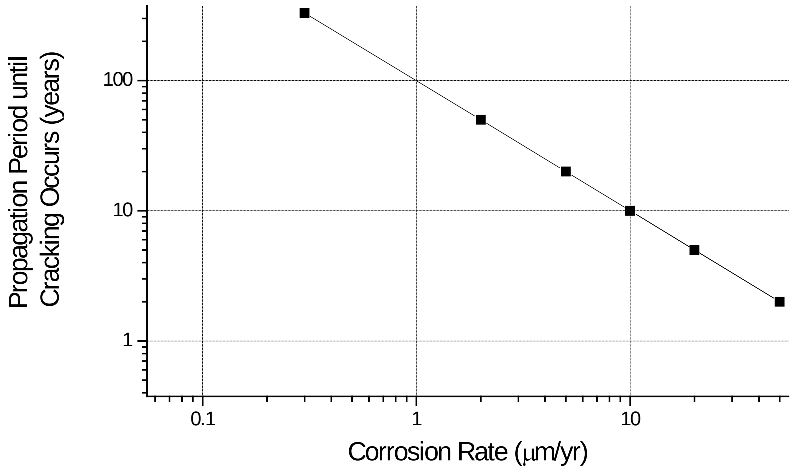

Figure 2 Influence of corrosion rate on time to cracking (adapted after Bentur et al. 1998).

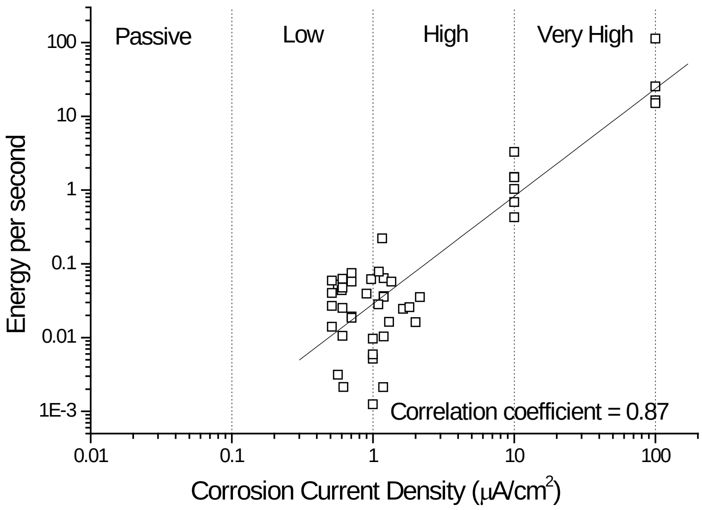

Figure 3 Variation in Energy/hour with corrosion rate

The instantaneous rate of corrosion is largely influenced by seasonal and diurnal temperature variations. In real concrete structures, the internal relative humidity (RH) and temperature are continuously changing within the concrete [10,12], evolving with the seasonal and diurnal cycles of the environment. Thus the rate of corrosion is a non-stationary phenomenon, in continual non-equilibrium with the environmental dynamic processes. As AeCORR is used to obtain readings over a 10 hour period, studies were undertaken to establish the influence of a continuously changing corrosion rate on the ability of AeCORR to detect corrosion [5]. As shown in **Figure 4**, short-term changes in corrosion rate are emulated by the rate of emissions

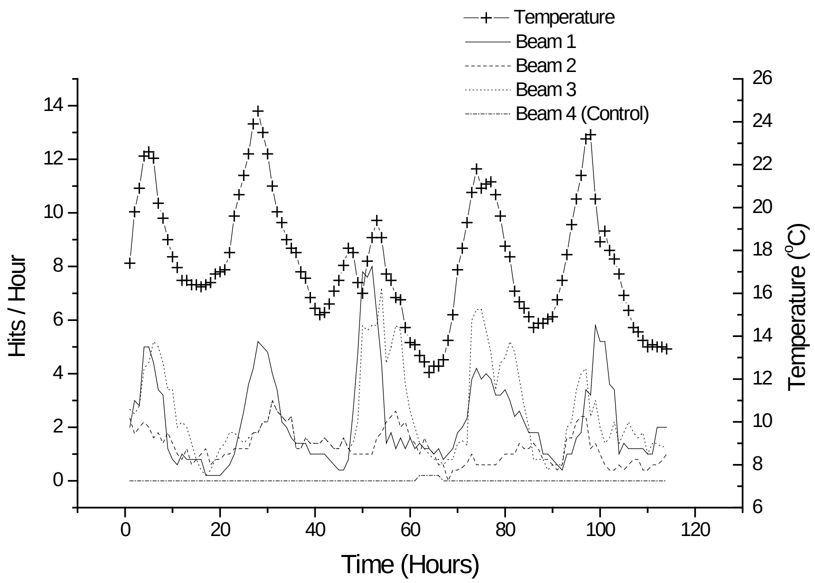

Figure 4 Influence of short term changes in Temperature on Hits / Hour

It can be seen in **Figure 4** that the Hits (activity) per hour obtained from the three corroding concrete prisms emulates the temperature evolution cycle. The control, a non-corroding specimen, produced zero emissions over the five day period proving that the emissions obtained in Beams 1 –3 were not thermally induced and proved that AeCORR can distinguish between active and passive systems. The actual corrosion density in Beams 1-3 was low, ranging from 0.02 to 0.12 $\mu A/cm^2$ (2.32 to 13.92µm/yr of steel loss respectively), indicating the high sensitivity of the technique.

Maintenance Planning Tool

Existing maintenance strategies usually involve identifying problems, establishing priorities and undertaking repairs using the limited funding available. Therefore to prioritise and allocate funds in a manner that is most efficient and effective, structure owners require detailed information on the state of each structure and knowledge of how best to resolve the problems being faced.

Extensive studies have been undertaken which demonstrate the ability of the AeCORR technique to detect the onset of corrosion [4,6]. If corrosion is identified in this period, the extent, ease and cost of repair is minimal providing real savings to the structure owner.

The AeCORR onsite test is forerun by an extensive preliminary investigation, which uses structure specific knowledge such as exposure conditions, visual survey results, structural information, and other techniques which are combined with our expertise to prioritise elements on a structure based on the risk of corrosion occurring. The study considers each element of the structure rather than the structure as a whole, as it is recognised that each element will be at a differing stage of deterioration due to its own unique exposure and design. The elements ranked as a first priority will be monitored using the AeCORR testing apparatus. This approach ensures that the technique is used in a suitable and efficient manner, whilst also providing the client with information about the risk of corrosion in other parts of the structure.

The AeCORR test gives information about the amount and approximate location of any corrosion damage occurring underneath the surface of the concrete. Rather than provide estimated corrosion rates or the likelihood of corrosion, which can be of little practical use, AeCORR will give the output to the engineer in a form of an activity grading on a scale of A-D, which results from comparing recorded data to an experience database. In this instance A implies no corrosion activity, no further action required and D signifies major corrosion activity – immediate intervention required.

The intermediate ratings, B or C grade, indicate that the rate of corrosion-induced damage is within a progressive stage. In this instance there may be two choices available to the management team:

a) Accept that the structure is in a bad state, but still in a serviceable condition.
b) Intervene as soon as possible to prevent further degradation and to maximise limited maintenance funding.

If early intervention is considered appropriate, then repeating the AeCORR test a year or so later would assess the success of any remedial work undertaken and should correspond to a lowering of the grade.

If the intended life of the structure is only for a few more years, then option (a) may be a more effective strategy combined with yearly inspections using AeCORR and minimal maintenance to ensure that the deterioration does not increase significantly.

Case Study

AeCORR has been applied to a number of different structure types, such as buildings, water / liquid containing structures [13] and bridges / highway structures. In a recent test, AeCORR monitoring was undertaken on in a reinforced concrete column located in a fully operational school building. Significant delamination of the carbonated concrete had occurred throughout the building, imposing a serious risk to the safety of the occupants from spalling concrete.

The area selected for monitoring showed no immediately obvious signs of corrosion and existing testing techniques, such as the half-cell potential indicated that the member was sound. Thus it was the intention of the test to determine if the column was corrosion free or whether it was at an earlier stage on the degradation curve, i.e. before visible signs of corrosion or spalling.

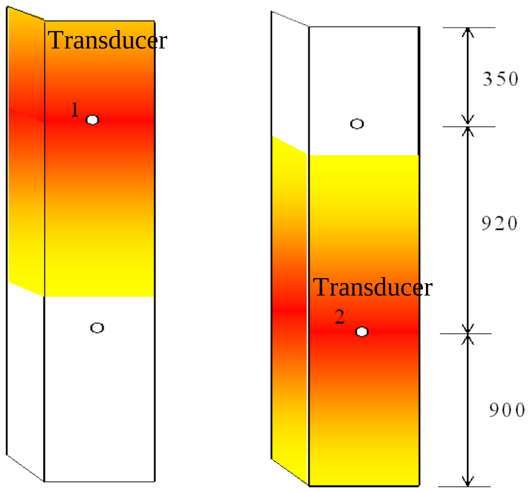

Figure 5 Acoustic coverage of the column

Testing was undertaken by attaching two transducers directly to the surface of the column, and then monitored overnight. Once the transducers were mounted, an acoustic calibration test was undertaken to determine the detection range of each transducer. The column had a low acoustic attenuation, thus with two transducers a 100% coverage of the column was possible (**Figure 5**), with sufficient overlap between the two transducers to enable zonal location of any corrosion activity.

The results of the test are displayed in **Figure 6** where the top graph corresponds to Transducer 1 and the bottom graph to Transducer 2. The maximum amplitude of each emission has been plotted against the time of arrival. It can be seen that there was significantly more emission received from Transducer 2 compared to Transducer 1. The absence of any significant emission received by Transducer 1 indicated that there was no corrosion activity occurring within the locality of this Transducer, thus the zone was awarded an A Grade. Consequently, the emission obtained by Transducer 2 had to be occurring beneath the transducer, outside the range of Transducer 1. The results indicated that despite the outward appearance of the column, active corrosion was present in the bottom metre, and based on the test results, this area was awarded a grade C: medium corrosion activity.

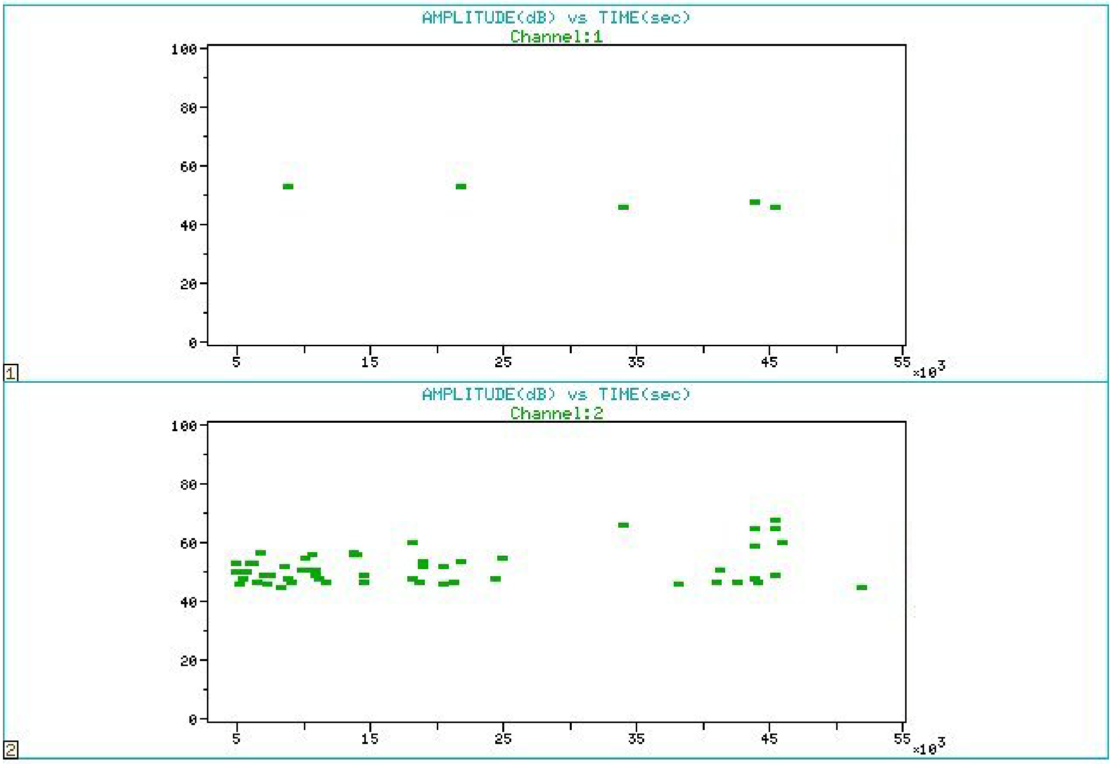

Figure 6 Results of the column test

On the basis of the AeCORR results, it was recommended that remedial works were undertaken at the bottom of the column, before significant damage to the integrity of the column occurred. Localised removal of the cover in this area revealed that corrosion of the reinforcement had occurred.

No immediate corrosion repairs were required on the remaining part of the column although it would be advisable to apply an anti-carbonation paint to limit any further deterioration and prevent the ingress of moisture and oxygen.

Consequently, whilst other areas of the school had obvious and significant corrosion damage, corrosion was also active in other elements but at an earlier stage in the destructive process, hence detection by conventional methods proved difficult and unreliable.

The benefit of being able to detect corrosion at this stage could be maximised in the instances where risk assessments are undertaken to assess the maintenance liability likely to be encountered over the term life of a maintenance contract. By monitoring a number of key structural elements for corrosion activity before deterioration is visible, a more accurate analysis of the structure’s condition and future expenditure may be obtained.

Whilst AeCORR is a fully non-destructive corrosion detection technique, corrosion detection only forms a part of any condition survey. When undertaking an AeCORR test it may be prudent to undertake complementary testing which can help establish the cause of corrosion, (such as carbonation or chloride contamination) and identify other deterioration mechanisms such as alkali-aggregate-reaction, thus enabling a complete and appropriate repair and maintenance strategy to be developed.

Conclusions

The AeCORR technique offers the ability to detect and grade active corrosion in reinforced concrete structures, completely non-destructively.

The case study identifies the ability of AeCORR to detect corrosion in concrete before significant corrosion damage occurs and its ability to locate the zone of activity. It is recommended that a number of key structural elements at risk from corrosion activity are monitored before deterioration is visible to enable a more accurate analysis of the structure's condition and future expenditure to be obtained, thus enabling a better deployment of limited maintenance funding.

References

1 Broomfield, J.P. (2000), MonoSys Guide to Monitoring, Quarter 1, pp. 10
2 Cabrera, J.G. (1996) Cement and Concrete Research, Vol. 18, pp.47.
3 Francios, R., Arliguie, G., (1999), Magazine of Concrete Research, Vol. 51, No. 2, pp. 143.
4 Ing, M.J., Austin, S.A., Lyons, R. (2002), Submitted to Cement and Concrete Research 2002.
5 Lyons, R., Ing, M.J., Austin, S.A., (2003), Submitted to Corrosion Science, 2003.
6 Austin, S.A., Lyons, R., Ing, M.J. (2004), Corrosion, Vol. 60, No 2, pp. 203.
7 Dunn, S.E., Young, J.D., Hartt, W.H., Brown, R.P., (1984) Corrosion Vol. 40, No. 7, pp. 339.
8 Li, Z.,Li, F., Zdunek, A., Landis, E., Shah, S.P., (1998) ACI Materials Journal Vol. 95, pp.68.
9 Ing, M., Watson, J., Lyons, R., Austin S., (2003a), 3rd International Conference on Emerging Technologies in NDT.
10 Lui, T., Weyers, R.W., (1998) Cement and Concrete Research, Vol. 28, No. 3, pp. 365.
11 Bentur, A., Diamond, S., Berke, N.S., (1997), E&FN Spon, London, ISBN 0 419 22530 7.
12 Andrade, C., Alonso, C., Sarría, J, (2002), Cement and Concrete Composites, Vol. 24, pp. 55.
13 Ing, M., Austin, S., Lyons, R., (2003b), Innovative Developments in Architecture, Engineering and Construction, Ed. C.J. Anumba, pp. 215-226, ISBN 90-5966-008-0.