

The use of embedded probes for monitoring reinforcement corrosion rates

MALCOLM McKENZIE
TRL Ltd., Wokingham, UK

ABSTRACT

The effect of environmental conditions on the response of embedded linear polarization resistance (LPR) corrosion monitoring probes was investigated using a concrete specimen containing steel bars. The bars were divided into segments that were electrically isolated inside the specimen but connected together outside the specimen; this allowed the location of corrosion to be identified from galvanic current flow between the segments. A second specimen without embedded probes was used to evaluate surface mounted probes. Corrosion rates increased with temperature and, to a much greater extent, when the surface concrete was saturated with water. There was significant variability in LPR measurements under constant conditions. Surface sensors, even those employing a 'guard ring', did not pinpoint particular corroding sections as identified from the galvanic current flows.

KEYWORDS Corrosion, probes, LPR, concrete

INTRODUCTION

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Reinforcement corrosion is one of the major causes of premature deterioration of reinforced concrete structures. It is advantageous to be able to detect the onset and rate of corrosion before there are visual signs of deterioration so that remedial measures can be taken at an early stage. There is a growing interest in using embedded probes to monitor corrosion. These generally rely on linear polarisation resistance (LPR) measurements – an electrochemical technique that estimates corrosion currents; these relate directly to the corrosion rate. Routine monitoring of such instrumentation could be incorporated into schemes to develop 'intelligent structures' that automatically report their condition – in this case the level of corrosion activity. Embedded probes could also be used to 'calibrate' surface mounted probes used to provide a less frequent but more comprehensive survey of a structure. It is vital that the results from such probes are reliable but at the moment there are a number of unresolved issues. These include the variability of probe response as environmental conditions change, interpretation of probe response in terms of corrosion activity, and how results from embedded probes relate to those from surface mounted probes.

To investigate these issues a number of monitoring probes were retro-fitted into a concrete specimen containing steel bars divided up into segments. The segments were electrically isolated inside the specimen but connected together outside the specimen; this allowed the exact location of corrosion to be identified from galvanic current flow between segments. A

second specimen had no embedded probes and was intended mainly to evaluate surface mounted probes. Corrosion was induced at particular locations in the specimens by ponding with sodium chloride solution. The level of corrosion activity, both from the galvanic current flow, and from embedded and surface mounted probes was measured under a range of environmental conditions. A limited investigation of a 'guard ring' LPR surface measurement meter was also carried out. Such instrumentation aims to control the area of steel affected during the test so should allow specific corroding regions to be identified more closely.

TEST SPECIMENS

The test specimen design is shown in Figure 1. It incorporates five bars each consisting of five electrically isolated segments. These are supported on but electrically isolated from, three non-segmented lower bars. To provide rigidity, the segmented bars were constructed using steel tube (outside diameter 12.7 mm, wall thickness 3.3 mm) with a central core of epoxy glass laminate rod. The individual segments were separated by nylon washers embedded in a resin. Electrical connections were made to each bar segment on the underside and protected with the same resin. The bar segments were connected together outside the specimen through switch boxes to facilitate monitoring. Once corrosion started, current would flow between active areas (anodes) and passive areas (cathodes). This design allowed this galvanic current flow around the bar network to be monitored using a zero resistance ammeter (ZRA) and hence the positions of active corrosion to be identified. Note that this only measures currents flowing between the segments. It is possible for corrosion to take place such that the anodes and cathodes are within a single segment. However the magnitude of such corrosion currents is likely to be less than currents between segments because of the smaller effective cathodic areas involved. Two specimens were cast using a Grade 30 concrete with a water/cement ratio of 0.65. Cover to the segmented bars was 30 mm. After casting and curing two corrosion monitoring probes were installed in one of the concrete specimens: positions are shown in Figure 1. The probes were 50 mm in diameter and comprised a ring of graphite and a central Ag/AgCl reference cell. The probes were positioned about 25 mm from the reinforcement.

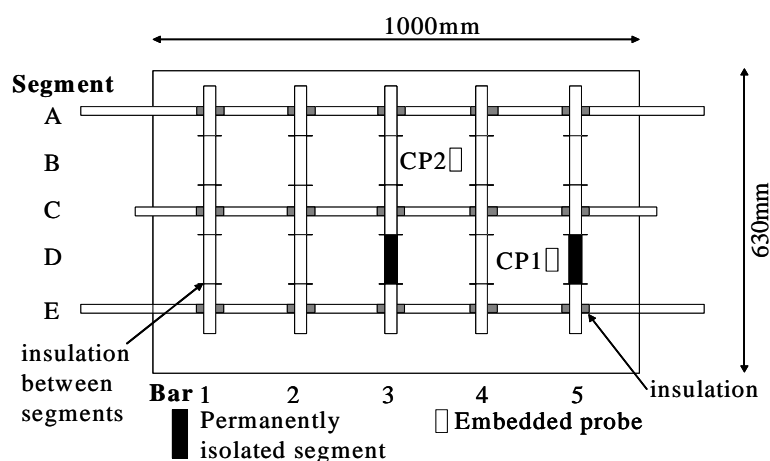


Figure 1 Test specimen design showing location of embedded probes



Figure 2 Embedded probe

CONDITIONING OF TEST SPECIMENS

There were two test specimens, one with embedded probes (Specimen B) and one without (Specimen A). The specimen without embedded probes allowed assessment of surface probes; the probe connection wires restricted the use of some surface probes on the other specimen. Each specimen was ponded with 5% sodium chloride solution. Specimen B was ponded

using 65mm diameter tubes at specific positions on the surface to encourage corrosion at these locations but not in adjacent segments. Some of the ponded locations were next to the embedded probes (Figure 3). For the specimen without embedded probes a larger ponding reservoir was attached covering the whole length of three of the segmented bars (Figure 4).



Figure 3 Ponding tubes on Specimen B



Figure 4 Ponding reservoir on Specimen A

Preliminary testing was carried out in an environmental chamber to establish the general level and location of corrosion activity, and assess the environmental factors leading to change in activity. This showed that whilst there was a rapid response to temperature, response to humidity was much slower. However, wetting the surface of the specimens did lead to large changes in corrosion activity. It was also apparent that the location of corrosion activity could vary as conditions changed. Following this preliminary investigation, the environment was set to 20°C and 50%RH for the first series of tests of LPR variability. Further testing was carried out at 30°C/50%RH and 10°C/50%RH. Change in corrosion activity was assessed by changes in the magnitude of the galvanic current measurements. LPR measurements were carried out when the galvanic current measurements had stabilised under the new temperature conditions. After this the surface of each specimen was covered with damp towelling to keep the surface of the specimens moist. Plastic sheeting and a controlled RH of 80% were used to limit evaporation. Testing at 20°C, 30°C and 10°C was carried out under these conditions where the surface of the concrete was saturated.

Half cell potentials were also measured using a surface mounted calomel electrode under the two moisture conditions but only at 20°C.

LPR MONITORING PROCEDURES

LPR measurements are carried out by changing the potential of the test area of steel (the working electrode) with respect to a reference electrode, then measuring the current which flows between this working electrode and an auxiliary electrode. The potential and associated current are used to calculate the linear polarisation resistance which gives the technique its name. This LPR value can be converted to an equivalent corrosion current. If the area over which this current is flowing is known then the corrosion current density can be calculated and equated directly to a loss in metal. However in many cases this area is not known and this imposes limitations on the accuracy of LPR estimates of corrosion rate. LPR probes either incorporate all three elements (ie the working and auxiliary electrodes, and the reference electrode) or just comprise the auxiliary and reference electrode. In the latter case the reinforcement forms the working electrode and this was the case for the probes used in these experiments – the ring of graphite acting as the auxiliary electrode. There are various

ways of carrying out LPR measurements [1]. For these experiments a potential sweep method was used in which the potential was moved from the rest potential to 20mV above the rest potential at a rate of 10mV/minute. Compensation for solution resistance was based on an impedance measurement at 1000Hz and an amplitude of 10mV. This LPR test method gives a graph of potential against current so that the linearity assumptions underlying the LPR procedure can be assessed. The LPR value is estimated from the slope of the line. This procedure was used both for the embedded probes and an external surface sensor. This consisted of a stainless steel disc with a diameter of 70mm and a central hole of diameter 13mm to allow for a calomel reference electrode. This surface sensor was placed on a wet sponge on the concrete above the segment of bar of interest.

The test method described above is an unconfined test in that there is no control over the area of reinforcement that is polarised during the test. This makes it difficult to estimate the area over which the corrosion current is flowing and hence the corrosion current density. One approach to this is to electrically isolate a section of the reinforcement so that the area that can be polarised is known. To investigate variability in response under such conditions two segments of Specimen B (segments 3D and 5D see Figure 1) were electrically isolated throughout the testing. This meant that there were no galvanic current measurements with which to estimate the corrosion activity of these locations. However they were chosen to be in what were thought to be passive and active regions respectively. Segment 5D was adjacent to embedded probe CP1 so all measurements with this embedded probe relate to this isolated segment.

More sophisticated instrumentation attempts to control the area tested on continuous steel by using a special configuration of sensor. This incorporates a 'guard ring'; this limits the change in potential to the area of steel beneath the sensor. Such instruments give a corrosion current density directly. Some tests were carried out using one such instrument — a GECOR. The size of the individual steel segments comprising the reinforcement in the specimens was chosen to match the length of steel polarised by the GECOR instrument so that it should indicate corrosion activity on individual segments. The size of the GECOR sensor meant that it could be only used on specimen A; it would not fit between the connection wires from the embedded probes in Specimen B.

The embedded probes allowed a series of measurements to be carried out at intervals of a few hours with the results being logged for later examination. This was done for each temperature/moisture combination to provide information on variability in response under constant conditions. In some cases more than one run was carried out to assess variation over longer time periods.

Measurements using the surface mounted probes were generally single sets because of the number of measurement positions and the difficulty in maintaining constant conditions between the surface mounted sensor and the concrete over an extended period. Some repeat measurements were carried out using the GECOR instrument. Two measurements at each test position were obtained with at least a five minute gap between consecutive measurements. This was to allow the potentials in the specimen to stabilise after the previous test as the confinement method used by the GECOR can polarise surrounding steel to greater extent than the standard unconfined test method. A further set of measurements was taken three days later but not in all positions.

RESULTS

Effect of environmental conditions on corrosion activity

Galvanic current distribution was only measured in areas which had been ponded with chloride solution - ie on bars 3, 4 and 5. On Specimen B only segment 4B appeared to be active at 50%RH. Galvanic current increased with temperature although effects were relatively small (Figure 5). Saturating the surface of Specimen B had little effect on the distribution of currents – segment 4B remained active and a small current was detected in segment 3B but only on one occasion. However there was a large increase in the magnitude of the currents. Again there was a clear effect of temperature under saturated surface conditions (Figure 6).

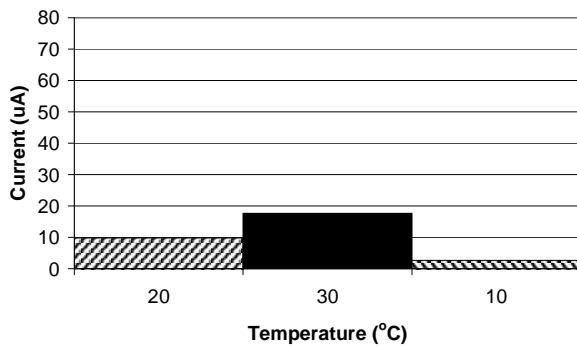


Figure 5 Effect of temperature on galvanic currents: Specimen B, segment 4B at 50%RH

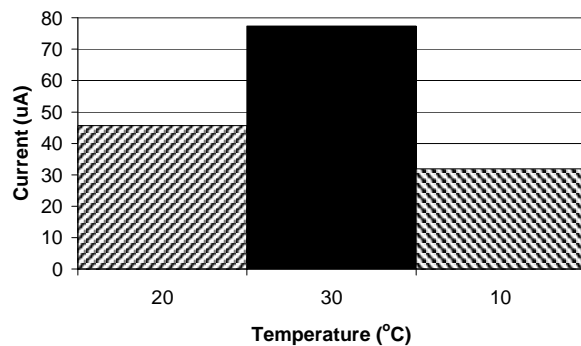


Figure 6 Effect of temperature on galvanic currents: Specimen B, segment 4B with saturated surface

Similar effects of temperature and moisture were observed on Specimen A. However the distribution of the currents changed under saturated conditions with more segments becoming active (Figures 7 and 8).

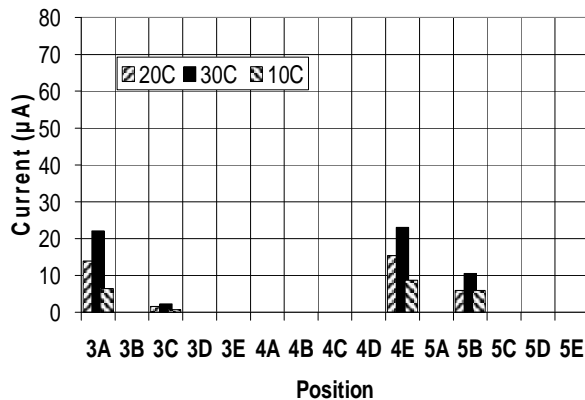


Figure 7 Effect of temperature on galvanic currents: Specimen A at 50%RH

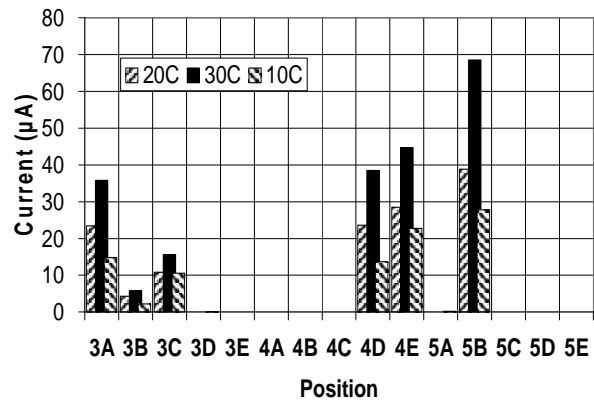


Figure 8 Effect of temperature on galvanic currents: Specimen A with saturated surface

LPR measurements on embedded probes

Embedded probe CP2 was adjacent to segment 4B in Specimen B. From the galvanic current measurements this was an active area of corrosion. The LPR potential/current graphs resulting from logging were sometimes clearly non-linear so these were discarded from the data set. At 50%RH increasing temperature led to lower LPR values – note that lower values of LPR indicate increasing corrosion rates – but there was considerable variability in sets of measurements under the same temperature conditions. When the concrete was saturated the LPR measurements were generally lower with the same temperature effects (Figure 9).

Embedded probe CP1 was adjacent to the isolated segment 5D, which appeared from potential measurements to be an actively corroding area. At 50%RH none of the results at 10°C gave useable traces. Otherwise measurements on this probe showed the same effects as recorded for CP2 although equivalent LPR values were higher for CP1 (Figure 10). For both embedded probes there was not the clear difference in measurements between saturated surface conditions and dry conditions apparent with the galvanic current measurements, although differences were more pronounced for probe CP1.

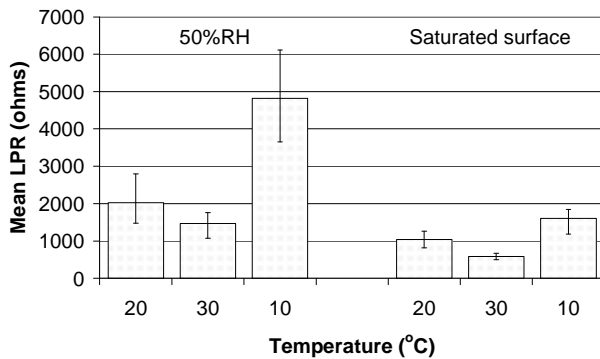


Figure 9 Average and range of LPR values under differing conditions of temperature and wetness: Specimen B, probe CP2

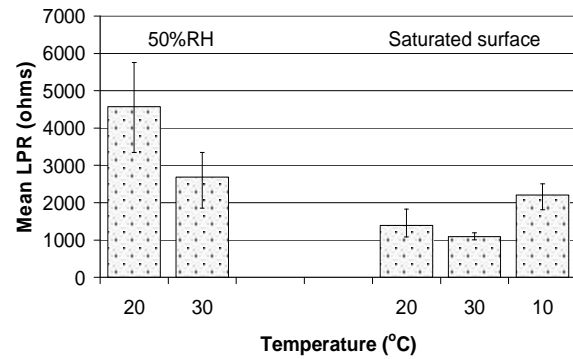


Figure 10 Average and range of LPR values under differing conditions of temperature and wetness: Specimen B, probe CP1

LPR measurements using unconfined test surface sensor

On specimen B at 50%RH and 20°C higher LPR values were measured over bars considered to be passive (bars 1 and 2). Segment 4B, active according to galvanic current measurements, gave the lowest LPR value, and this value was similar to that obtained with the adjacent embedded probe CP2 under the same conditions. Measurements on the isolated segment thought to be passive (segment 3D) did not give a useable trace although any estimate from the traces obtained would have indicated a very high LPR value. Measurements on isolated segment 5D were similar to those from the adjacent embedded probe CP1 (Figure 11).

After the surface of Specimen B had been saturated, further measurements were carried out at 20°C. These indicated similar relationships between positions as found at 50%RH although absolute LPR values were lower indicating increased corrosion rates (Figure 12).

On Specimen A, LPR values at 20°C and 50%RH were higher on bar 1, which was considered to be passive, and lower on bars 3,4, and 5 where corrosion was active according to galvanic current distribution. However the measurements did not clearly pick out the segments where corrosion was active based on the galvanic current measurements (Figure 13). For example on bar 4 there was little difference in the LPR results on different segments although only segment 4E was active based on the galvanic current measurements (see Figure 7).

Under surface saturated conditions on Specimen A, LPR measurements were carried out at 20°C, 30°C and 10°C. Results were generally lower than those measured at 50%RH and values fell as temperature increased (Figure 14). LPR measurements did not clearly pick out the positions of active corrosion indicated by the galvanic current measurements. For example LPR values on segment 4B were little different from the other values measured on that bar but the 4B segment was not corroding according to the galvanic current measurements (see Figure 8).

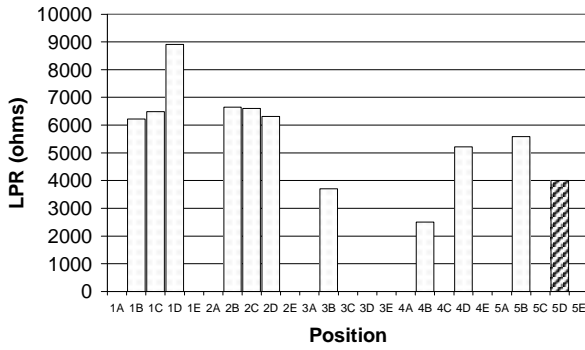


Figure 11 LPR measurements using unconfined test surface sensor: Specimen B, 20°C and 50%RH (segment 5D was isolated)

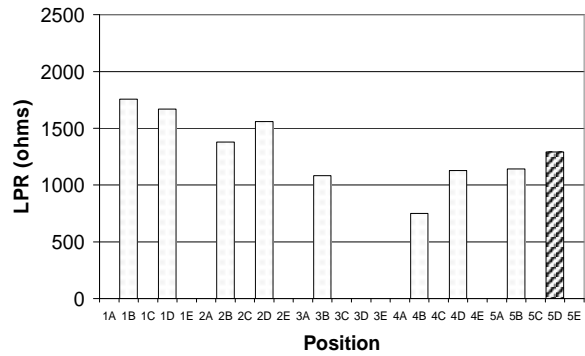


Figure 12 LPR measurements using unconfined test surface sensor: Specimen B, 20°C and saturated surface (segment 5D was isolated)

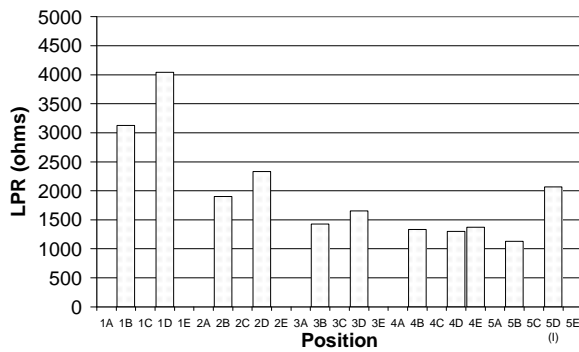


Figure 13 LPR measurements using unconfined test surface sensor: Specimen A, 20°C and 50%RH

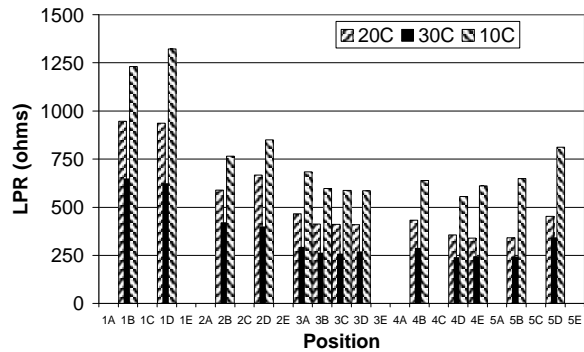


Figure 14 LPR measurements using unconfined test surface sensor: Specimen A, saturated surface

LPR measurements using the confined test surface sensor (GECOR)

Measurements using the GECOR were carried out on Specimen A at 20°C when the surface was saturated. Agreement between the initial duplicate measurements and measurements three days later was in most cases good. However in some instances more variability was evident (Figure 15). The corrosion current densities were higher on bars 3, 4 and 5 where corrosion was active. However the measurements did not show large differences between different segments of the bars. For example the corrosion rates on segment 5B and 5D were similar whereas there was a large difference in galvanic activity between the two positions.

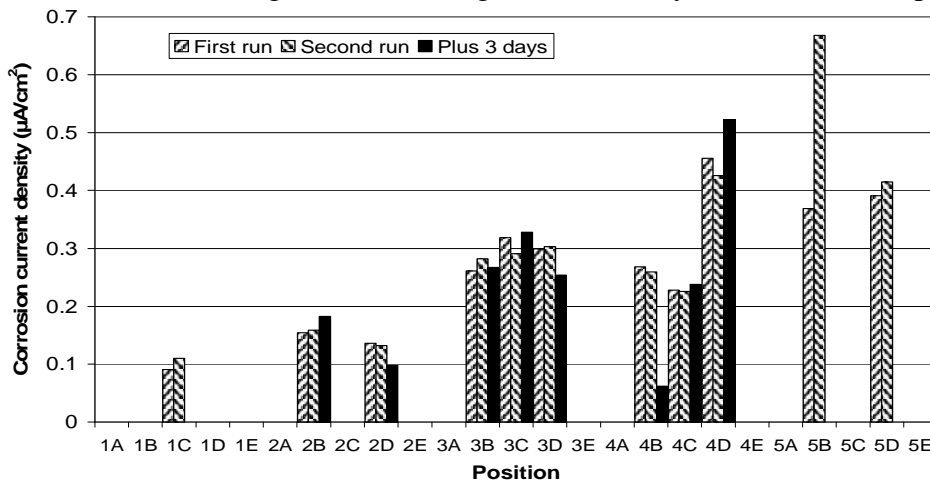


Figure 15 LPR measurements using GECOR: Specimen A 20°C and 50%RH

DISCUSSION AND CONCLUSIONS

LPR measurements using embedded probes were affected by temperature and moisture conditions but there was also significant variability in a series of LPR measurements under constant conditions. For an exposed structure the interaction of these two sources of variability – the effect of the environment and the inherent variability in the measurement – would result in even greater variability. This highlights the need for multiple measurements to provide an accurate assessment of corrosion activity. Embedded probes certainly assist in generating such data. There was reasonable agreement between the response of the embedded probes and a surface mounted probe. By regular monitoring of an embedded probe the variability associated with the measurements could be established and the embedded probes used to calibrate more extensive surveys carried out using a surface mounted probe.

The results obtained using probe CP1 referred to a single segment so in this case the corroding area was known and corrosion current densities could be estimated. Note that in reality even in this case corrosion might be taking place on only a part of the segment so the area should be considered as the maximum corroding area. The estimated corrosion current densities ranged from approximately $0.10 \mu\text{A}/\text{cm}^2$ to $0.75 \mu\text{A}/\text{cm}^2$. According to published guides on interpretation of LPR results [1] this range covers passive to moderate/high rates of corrosion. This reinforces the danger of relying on limited sets of data for estimating corrosion rates.

The results obtained using the surface sensors did give an indication of the general location of corrosion. However neither the unconfined test method, nor the use of a ‘guard ring’, could pinpoint particular corroding segments as identified from the galvanic current flow. It is possible that corrosion is active on segments not identified by galvanic current flow. In such cases anodes and cathodes would both be present on the same segment but it is likely that such corrosion rates would be less than those resulting from the macrocells measured by the galvanic currents. Variability in measurements with surface mounted sensors warrants further investigation.

REFERENCE

1. Trend 2000 Ltd, BRE, Broomfield J, Risk Review (2001) Handbook for corrosion rate measurements, Corrosion in concrete – report 2, Degradation of materials in aggressive environments programme – Area 5.1, Department of Trade and Industry