Monitoring The Corrosion Of Concrete Reinforcement Using Control Curves

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Summary: Corrosion testing (half-cell and LPR) was carried out on a number reinforced concrete panels which had been taken from the fascia of a twenty five year old high rise building in Melbourne, Australia. Corrosion, predominantly as a result of carbonation of the concrete, was associated with a limited amount of cracking. A monitoring technique was established in which probe electrodes (reference and counter) were retro-fitted into the concrete. The probe electrode setup was identical for all panels tested. It was found that the corrosion behaviour of all panels tested closely fitted a family of results when the corrosion potential is plotted against the polarisation resistance (R_p). This enabled the development of a so-called 'control curve' relating the corrosion potential to the R_p for all of the panels under investigation. This relationship was also confirmed on laboratory samples, indicating that for a fixed geometry and experimental conditions a relationship between the potential and polarisation resistance of steel can be established for the steel-concrete system. Experimental results will be presented which indicate that for a given monitoring cell geometry, it may be possible to propose criteria for the point at which remediation measures should be considered. The establishment of such a control curve has enabled the development of a powerful monitoring tool for the assessment of a number of proposed corrosion remediation techniques. The actual effect of any corrosion remediation technique becomes clearly apparent via the type and magnitude of deviation of post remediation data from the original (pre-remediation) control curve.

Keywords: Corrosion in concrete, Monitoring, Reinforcing Steel, Polarisation Resistance, Control Curve

1   INTRODUCTION

Reinforced concrete is undoubtedly the major material of construction in the world today, thus the corrosion of concrete reinforcement is considered a major issue facing the civil engineering sector in modern society. Corrosion of reinforcing bars can not only lead to costly remediation, but may end the life of a structure well prior to its design life, causing massive financial disruptions in cases where structures are both costly and provide a source of revenue (e.g. high rise buildings, jetties, etc.). Most developed cities presently have a large number of buildings whose facades consist of reinforced concrete fascia panels suspended over the face of the building. Although the manufacture of such panels can be carried out under controllable off-site conditions resulting in a good quality product, when buildings have a design life from 25 to 100 years, deterioration of the panels can eventually take place. Carbonation of the concrete by atmospheric CO_2, sulphate attack from urban pollution or chloride ingress through cracks can lead to cases where corrosion of the reinforcement can occur, ultimately leading to spalling of the concrete. The consequences of such an event are such that responsible maintenance of a building requires routine monitoring of the possibility of reinforcement corrosion.

In the event that corrosion of the concrete reinforcement occurs, several methods are presently available for the remediation of the condition and the extension of life of the structure. These methods include, cathodic protection (CP), re-alkalisation, desalination (electrochemical chloride removal), crack sealing, anti-carbonation or anti-moisture coatings and inhibitors. Most often the selection of an appropriate remediation technique will depend on factors that are unique to each individual situation.

The ability to monitor the corrosion of steel that can be buried several centimeters beneath concrete presents certain challenges, especially in terms of physical inspections. Clearly, suitable reinforcement corrosion monitoring techniques must be non-destructive, whilst also providing accurate information regarding the corrosion activity of embedded steel. Techniques that

have been developed to monitor corrosion processes that may be occuring at the reinforcement surface, but of which there is as yet no evidence on the concrete surface, include: half cell potential measurements, concrete resistivity measurements (Gerritsen and Dacre, 2001) and linear polarisation resistance measurements. Each of these techniques provides some information as to what is going on within the concrete, but none give the complete story. Indeed recently much scrutiny has been focused on the accuracy and suitability of these common monitoring techniques, namely LPR, for use on the steel-concrete system (Birbilis et al, 2001). However, this paper introduces an alternative approach to analysing data such that conventional monitoring techniques may become more meaningful, especially in the context of ranking corrosion remediation techniques.

2   HALF CELL POTENTIALS

Measuring the corrosion potential (half-cell potential, HCP) of reinforcing bars is the commonest of the corrosion monitoring methods available, and is widely used in practice as an indication of the possible corrosion risk. HCP monitoring is outlined in ASTM C876. "Standard Method for Half Cell Potentials of Uncoated Reinforcing Steels in Concrete" (1993). In this technique the electrical potential of the reinforcement is measured against a reference electrode (half-cell) placed on the surface of the concrete immediately above the reinforcement. The non-mandatory information appended to the Standard reports an empirical interpretation of the results obtained. This interpretation is summarised in Table 1 below:

Table 1. ASTM C876 Criteria (1991)

Half Cell Potential (vs. Cu/CuSO$_4$ electrode)	Corrosion Condition
> -200mV	Less than 10% probability of corrosion
-200mV > -350mV	Between 10% and 90% probability of corrosion
< -350mV	Greater than 90% probability of corrosion

The corrosion potential however only indicates the relative risk of corrosion, providing no quantitative information regarding corrosion rates. This indication of corrosion risk by the corrosion potential reading may be based upon a simple model of the quality of passive film that protects the steel in good quality concrete. The quality of the passive oxide film upon the steel may be represented by α, where α may represent the ratio of filmed to unfilmed area in the corrosion microcell upon the steel surface. In the case where diffusion effects upon the corrosion potential can be neglected, it is shown by Cherry (2001) that the corrosion potential can be represented as:

$$E_{corr} = \ln a - K - \frac{I_{corr} r}{B} \qquad (1)$$

$$\text{where} \quad B = \frac{b_a b_c}{2.3(b_c + b_a)} \quad \text{and} \quad K = \frac{E^a_o}{E^c_o}$$

E_{corr} is the corrosion potential, I_{corr} is the corrosion current, $ß_a$ and $ß_c$ represent the Tafel slopes for the anodic and cathodic processes, r represents the electrical resistance associated with the anodic portion of the corrosion circuit and E^a_o and E^c_o represent the equilibrium electrode potentials of the anodic and cathodic processes respectively.

Equation 1 gives a qualitative rationalisation of the ASTM C876 criteria, in that it indicates an increase in the corrosion current as the corrosion potential becomes more negative. Although this relationship is generally observed, it has been shown by Cherry *et al* (1986) that corrosion potentials measured at the surface of the concrete will vary markedly with the thickness and resistivity of the concrete. This serves as somewhat of a limitation to the HCP technique.

It is also possible that corrosion potentials can provide misleading information when used with some more recently developed remediation measures. For example, effective inhibitors may have a significant impact on the exchange current densities of either cathodic or anodic corrosion reactions. In such cases the relative movement of E_{corr} may give no indication of the effectiveness of the inhibitor when using ASTM C876. Anti-carbonation coatings and silane type concrete coatings may affect the resistance polarisation of the cathodic or anodic corrosion processes by varying amounts and so again, a reduction in corrosion current may be accompanied by either positive or negative movements of the rest potential. As a result a more independent estimate of the corrosion current is required when assessng corrosion remediation measures.

3   LINEAR POLARISATION RESISTANCE

To date, the most common method of monitoring the corrosion rate of concrete reinforcement is based on the Linear Polarisation Resistance (LPR) technique as developed for metals in solution in the late 1950's. In the LPR technique, the potential of the rebar is scanned slowly over a small range in the vicinity of the open-circuit (corrosion) potential. As the current densities and potential shifts associated with the technique are small, it was considered in the original derivation of the

theory that mass transport (diffusion) effects could be neglected. The slope of the polarisation curve (i.e. the potential change divided by the applied current change) at the point at which the applied current equals zero is defined as R_p, or the Polarisation Resistance, and is considered a measure of the opposition to metallic dissolution.

If we assume that the total area of the corroding electrode (reinforcement) probed by an LPR measurement is s , then R_p can be converted to a corrosion current rate via:

Where B has been previously defined, and is reported to have values between 14 and 52mV for the steel in concrete system.

$$I_{corr} = \frac{B}{sR_p} \qquad (2)$$

Both the values of B and s are somewhat uncertain, thus equation 2 cannot give accurate figures for the rate of corrosion. It has been highlighted by Roberge (1999) that the theoretical considerations used to derive LPR theory, strictly speaking, rarely apply under actual operating conditions. None the less it is shown in this paper that there is considerable value in monitoring with LPR, especially for determining relative corrosion rates brought upon by environmental changes in samples with fixed geometry.

It has been reported by Cherry (2001) that the critical corrosion current density of $1mA/m^2$ is considered by various authors to be the borderline corrosion rate for passive steel in concrete.

4   EXPERIMENTAL
A number of precast reinforced concrete fascia panels were obtained. These panels were 75mm thick and reinforced along their centre line by a mesh of 8mm$\varnothing$ reinforcement. Corrosion probes of the form indicated in Fig. 1 were installed (retro-fit) into the panels just above an intersection point of the reinforcing mesh. The probes installed consisted of a silver/silver chloride (saturated) reference electrode mounted such that its tip was about 20mm from the reinforcing bar, and two mixed metal oxide (MMO) coated titanium rods that served as counter electrodes that could provide a polarising current to the reinforcing bar to the concrete.

The corrosion potential was measured using the reference electrode, whilst sufficient current was then provided by the counter electrodes to the reinforcing bar to shift the corrosion potential in the cathodic (more negative) direction by no more than 20mV. A plot of the impressed current against the potential shift was used to yield values for R_p. In all cases a portable 3LP device was used for the measurements.
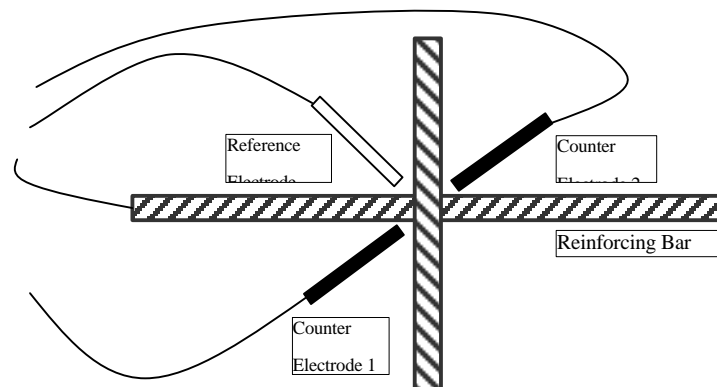

Figure 1. Diagrammatic representation of polarisation cell

Following installation of the probes, all panels were subjected to various wet-dry cycles in order to stimulate and suppress corrosion such that a spectrum of results could be obtained for panels of varying corrosion activities. The panels were made from very high quality concrete and were initially in a non-corroding state. Consequently the panels were all brought into a state of corrosion by means of electrochemical polarisation. Following on from this, various remediation techniques were applied in order to assess the relative effectiveness of the chosen techniques.

Data was also collected on reinforced mortar prisms specifically designed for laboratory testing. The prisms were $220 \times 100 \times 70$mm with a 12mm$\varnothing$ carbon steel reinforcing rod placed centrally in the longitudinal direction. The mortar mix was 4:2:1 (sand:OPcement:water). An Ag/AgCl reference electrode and a mixed metal oxide (MMO) coated titanium counter electrode were embedded in each prism. The prisms were exposed to various environments within the laboratory and electrochemical testing was carried out using a PAR/BES potentiostat.

5   RESULTS AND DISCUSSION
In view of the two sets of criteria for the detection of corrosion (ASTM C876 and current density of $1mA/m^2$) it was decided to determine the variation in E_{corr} with the polarisation resistance for the fascia panels. A set of results is shown below in Fig. 2.
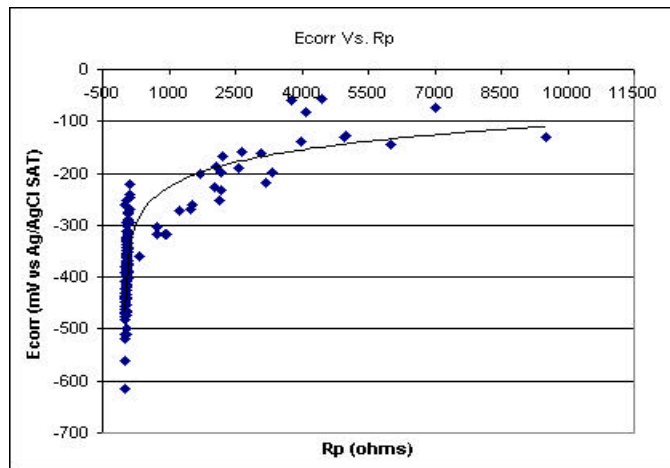
Figure 2. Variation of polarisation resistance with half cell potential

It should be noted that the results presented in Fig. 2 are reported with respect to a silver/silver chloride (saturated electrode) for which potentials of -150mV and -300mV correspond to -200mV and 350mV on the copper/copper sulphate scale. The results shown indicate a very apparent trend in the data, in that all results obtained (from twelve distinct monitoring locations that went into the construction of Fig. 2) seem to fit a 'family' of results. This trend becomes even more apparent when a log scale is used for the polarisation resistance values as shown below in Fig. 3.
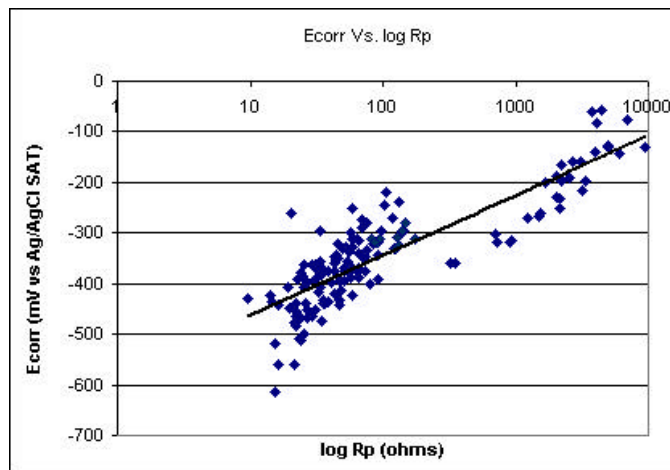

Figure 3. Variation of log polarisation resistance with half cell potential

The above results indicate that it is possible to define a distinct relationship between E_{corr} and R_p, provided that the cell geometry of the samples under investigation remains constant. The development of a plot such as that seen in Fig. 3 can then indicate the value of E_{corr} that corresponds to a corrosion current density of $1mA/m^2$. In this case the geometry of the polarisation cell was constructed such that $100cm^2$ of reinforcing bar is polarised, therefore putting B equal to 30mV in equation 2 indicates that a corrosion current density $1mA/m^2$ corresponds to a corrosion potential of approximately -150mV. In this case there seems to be a good consistency between the results obtained using LPR and ASTM C876. However the construction of a control curve such as that seen in Fig. 3 can alleviate the use of ASTM C876 since customised criteria can be established for each unique situation under investigation. The criteria as set out in the ASTM standard are relevant for bridge decks in North America that are subjected to de-icing salts, however the majority of local reinforcement corrosion cases are destined to be subjected to conditions which bear little resemblance to such a situation. This notion can be confirmed when we inspect the control curve seen in Fig. 4. The data in Fig. 4 are from laboratory prism specimens that also have a polarised area of reinforcement equal to $100cm^2$. In this case it is thus seen that a corrosion current density $1mA/m^2$ corresponds to a corrosion potential of approximately -220mV, which is rather different to that of the fascia panels. This highlights the dependence of the control curve upon geometry of the polarisation cell.
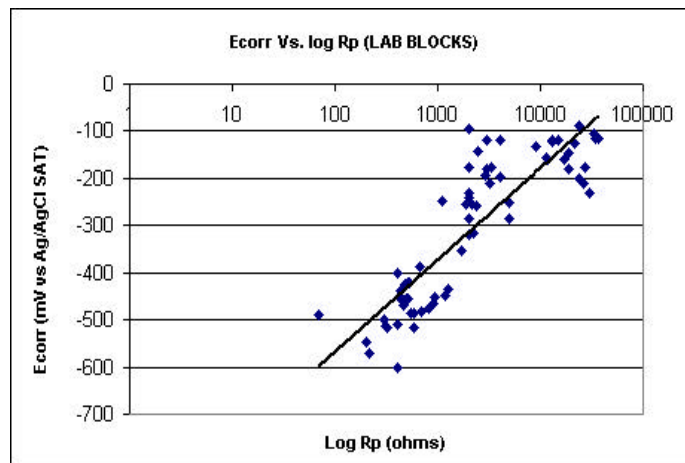
Figure 4. Variation of log polarisation resistance with half cell potential for laboratory samples

The notion of using control curves, such as those presented above, to monitor the corrosion of concrete reinforcement presents several advantages. The major reason for this is that measurements of the corrosion potential and polarisation resistance versus time, which is common practice within the industry, can be misleading due to environmental factors that can give results a cyclic nature. This phenomenon can be seen in Fig. 5 for data that was collected for a large marine structure over a period of seven months.
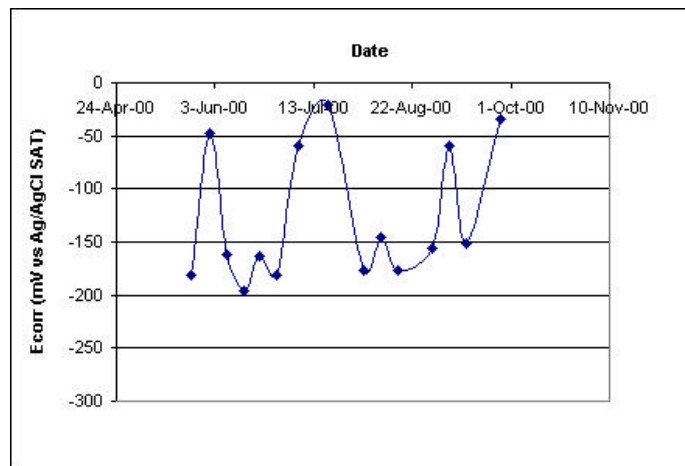

Figure 5. Variation of corrosion potential with time for a marine structure

When monitoring with control curves (E_{corr} vs. R_p), the data obtained is combined into a 'family' of results that characterise the system under investigation. If monitoring occurs over a long period of time, then data can be added to the control curve in a time-dependant manner such that it becomes obvious whether or not the form (eg. gradient) of the control curve remains constant throughout the lifetime of a structure, or whether or not the control curve changes as a result of environmental factors that may be altering (i.e. properties of the concrete).

Once a control curve for a certain system has been established, such as that seen in Fig. 3, then this curve can act as tool for monitoring the effectiveness of any subsequent corrosion remediation techniques. The reason for this is that the type and magnitude of any deviation from the control curve of post-remediation data can be compared with that of pre-remediation data.

In order to assess the effectiveness of certain corrosion remediation techniques on the fascia panels, the panels under investigation were all brought into a similar state of corrosion (as determined by potential and LPR measurements) by means of electrochemical polarisation. The results following remediation for the two corrosion remediation techniques presented in this paper are shown below in Fig. 6 via means of a control chart. The remediation techniques presented in this paper are surface applied Organic Migrating Corrosion Inhibitor (MCI – 2020) and surface applied Silane cream. The results presented in Fig. 6 indicate that each remediation technique alters the corrosion behaviour of the reinforcement in a different manner.
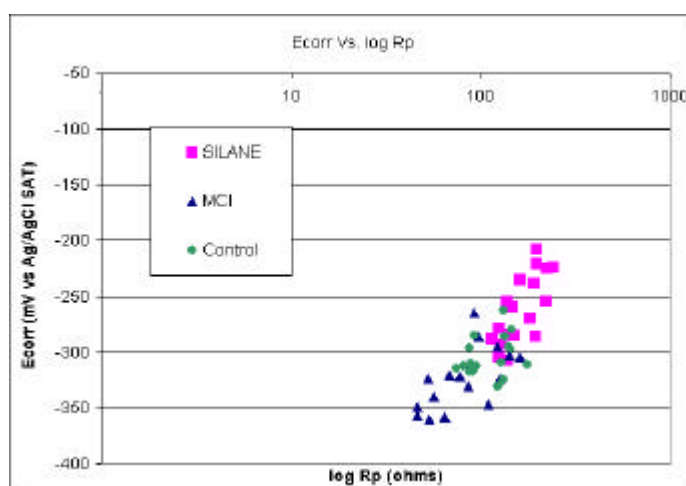
Figure 6. Variation of log polarisation resistance with half cell potential for remediated fascia panels

It can be seen that with respect to the control (un-treated) panel, that the MCI actually lowers the half cell potential. Although the MCI tested is a commercial product of which the active ingredients are unknown, this behaviour is common of many inhibitors that are known to be 'cathodic' in nature and may not necessarily indicate that corrosion attack is being intensified. However the decrease in polarisation resistance observed for the MCI treated samples does indicate that at this stage of the treatment (the results reported are up to 6 months following MCI application) when compared to the control panel, corrosion rates are apparently higher for samples treated with MCI. This could indicate that the MCI may be in fact anodic in its action. It should however be noted that such MCI's are dependent for their action on diffusion processes (Phanasgaonkar, 2000) and it may be some time before benefits from such a remediation strategy become apparent.

The panels treated with silane indicate an increase in half cell potential and polarisation resistance when compared to the control panel. The increase in half cell potential with respect to the control may not have been expected if in fact a silane coat can limit the availability of oxygen to the reinforcement, which should ultimately lead to a decrease in half cell potential. However, the polarisation resistance results indicate that corrosion protection is afforded by the silane, although this may not be via limiting oxygen supply to the reinforcement, it may well be due to an increase in the concrete resistivity.

It is apparent that the presentation of results as is done in Fig. 6 presents an attractive and simple procedure for evaluating remediation suitability and effectiveness. Further to this it may also be possible to reveal aspects related to the mechanisms that afford protection in various corrosion remediation measures.

6   CONCLUSION

The use of control curves to monitor the corrosion of concrete reinforcement provides a useful way of interpreting data, in that unique criteria can be established for the monitoring of each unique structure. This alleviates a reliance on criteria such as ASTM C876, which have been shown to not be applicable in all cases. Control curves remove the uncertainty that is seen when separately monitoring corrosion potential versus time and polarisation resistance versus time. Furthermore, control curves present a powerful and attractive way of ranking remediation techniques against one another

7   ACKNOWLEDGMENTS

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