



Potential pitfalls in assessing chloride-induced corrosion of steel in concrete

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ABSTRACT

Electrochemical assessment of the condition of embedded reinforcing bar (rebar) in concrete is being carried out increasingly routinely, both in the laboratory and in the field. However, because of the perceived need to produce results very rapidly, the results may not, in fact, be representative of the actual behaviour of the rebar. This paper describes some of the pitfalls the authors have encountered in their own work and have, therefore, analysed and quantified, together with others which have appeared in the literature.

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1. Introduction

The most common cause of deterioration of reinforced concrete structures is corrosion of the reinforcement caused by localised breakdown of the passive film on the steel by chloride ions. Because of the impact of this deterioration on both safety and the economy, the ability to accurately and reliably measure the corrosion condition of the reinforcing bars (rebars) in the concrete is essential. In this paper, the authors describe some of the difficulties and problems in such measurements that they have encountered in their work and in the literature.

In practice, chloride ingress into reinforced concrete takes many years. This means that the concrete has time to mature and the steel has time to equilibrate in the alkaline environment, before the steel encounters chlorides and corrosion is initiated. However, for laboratory experiments, it is impractical to wait many years to obtain results and most of the problems described below arise because of the desire to accelerate the onset of corrosion. Furthermore, for those assessing the condition of structures in the field, it appears that one main objective is to make as many measurements as possible in as short a time as possible, in order to reduce costs. This push for speed is, again, the cause of some of the problems described below. Other problem areas are the use choice of appropriate electrochemical techniques and specimen details. One problem, which cannot readily be overcome, is that almost all laboratory tests are conducted on young, immature concrete and at relatively constant ambient conditions. This is not the same environment as that encountered by steel in real

structures at the time that chlorides penetrate the concrete cover. This problem is beyond the scope of this paper but should be borne in mind when extrapolating research results to the field.

2. Accelerated laboratory testing

2.1. Admixed chlorides

The most common method for accelerating the corrosion of steel in concrete is to contaminate the concrete with chloride at the time of mixing. This is a completely acceptable method, for example, to determine maximum allowable limits of chlorides in concrete components, beyond which rebar corrosion might be a problem. However, for other applications, it may not be appropriate. Firstly, it takes time for steel to become passive in uncontaminated concrete, as illustrated in Fig. 1 [1]. If chlorides are mixed into the concrete, the steel does not have time to passivate before encountering chlorides and so the concept of localised passive film breakdown as the first step in corrosion initiation must be modified. It is probable that the mill scale present on most carbon steel reinforcing bars also results in localised corrosion but the mill scale is not as protective as a passive film. Secondly, there are extraneous effects of chlorides on the concrete itself. These can include: (i) acceleration of cement hydration which increases the porosity of the concrete [2]; (ii) an increase in the conductivity of the pore solution; (iii) changes in the pH of the pore solution and (iv) changes in the amount of chemically bound chlorides [3]. Moreover, the chloride cation influences the direction and magnitude of some of these effects: the pH is increased by NaCl and KCl but decreased by CaCl₂ and, probably, by MgCl₂ [3]; the amount of chloride binding when the chloride is CaCl₂ is significantly higher than when it is present as NaCl and KCl [4]. Despite the greater degree of binding, the rebar corrosion rate induced by CaCl₂ is greater than that

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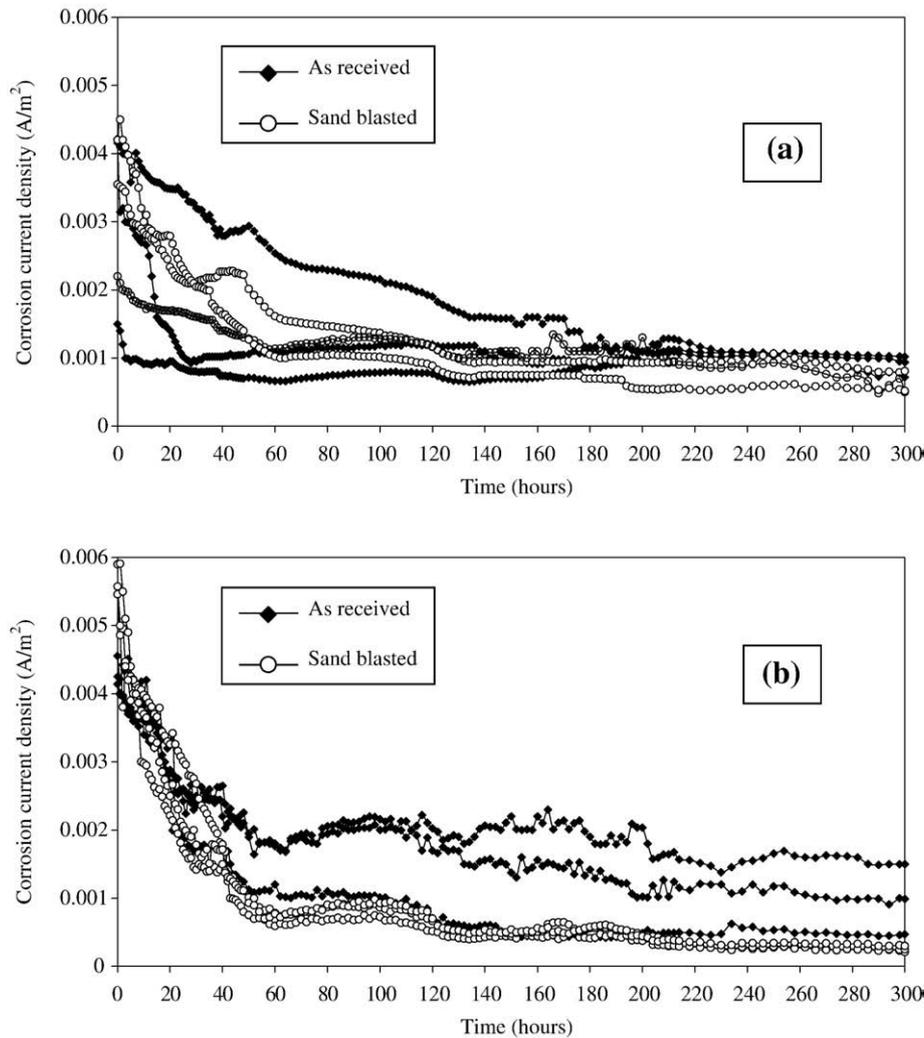


Fig. 1. The current density over the first 300 h of black steel (as received) rebar and sandblasted rebar (a) embedded in mortar, (b) exposed to synthetic pore solution [1].

by NaCl or KCl [3]. Consequently, in evaluating the amount of chloride contaminated constituents of concrete, it might be prudent to determine the exact nature of the contamination and the associated cation.

2.2. Applied anodic current to accelerate corrosion

The second accelerating method, which appears to be gaining in popularity, is the application of an anodic current to the embedded steel from an external power source in order to induce corrosion. The degree of corrosion can be controlled by varying the current density and/or the time interval of the impressed current. The advantages of using this technique are achieving a high degree of corrosion within a short period of time and the easy control of the desired corrosion degree [5]. Many studies have been carried out using this method in the past two decades, including the mechanical behaviour of corroded steel bar [6,7]; the effect of corrosion on the bond between rebar and concrete [8–13]; the structural behaviour of corroded elements [14–17] and the prediction of the remaining service life of rebar-corroded reinforced concrete structures [18].

From the electrochemical perspective, this accelerated corrosion process is very different from that occurring naturally by chloride-induced breakdown of the passive film. Based on the authors' experience and the research conducted by Yuan et al. [5] the following conclusions can be drawn:

1. The chemical compositions of corrosion products formed in a natural, chloride contaminated environment and those produced using the impressed current method appear to be different. The corrosion products show different colours caused by different



Fig. 2. Distribution of the corrosion products on the surface of the steel rebar: (a) due to impressed current which occur over the whole surface [61] and (b) due to natural corrosion which is localised [62].

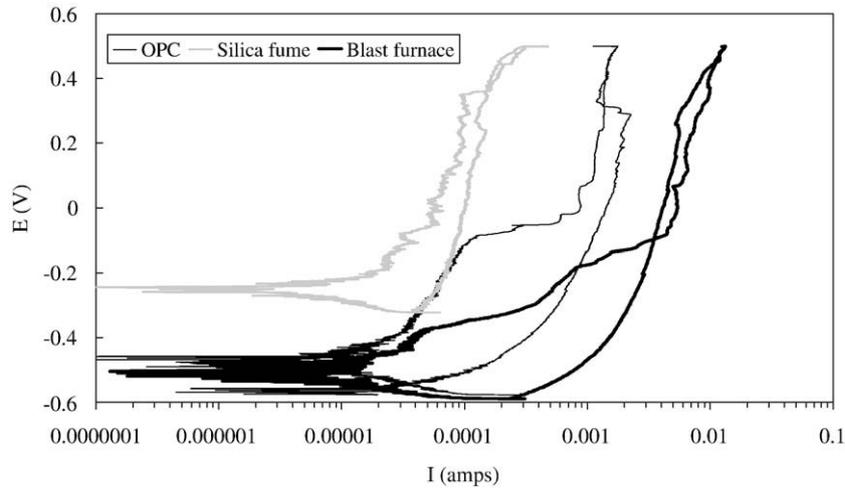
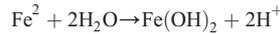


Fig. 3. Anodic cyclic polarization curves for black steel rebar in ordinary Portland cement concrete (OPC), silica fume concrete (SF) and blast furnace slag concrete (SG) each containing 0.1% Cl⁻ by weight of concrete as NaCl [33].

chemical compositions. The differences can be attributed to the time intervals of the corrosion process as well as the lack of chlorides [5]. The chemical composition of the corrosion products achieved by an impressed current and natural corrosion is currently under investigation by the present authors.

2. Corrosion occurs over the whole surface of the steel bar when using the impressed current method, as illustrated in Fig. 2a. The corrosion products are confined to the interface between the rebar and the concrete, thereby acting as a wedge between the steel and concrete. In contrast, while, in naturally corroded rebars, the corrosion is confined to discrete localised areas, determined by the inhomogeneous ingress of chlorides and the inhomogeneity of the passive film. Such localised corrosion is shown in Fig. 2b. Moreover, under natural conditions, the corrosion is generally initiated only on the side of the bar closest to the concrete surface and corrosion products can diffuse into the pores and cracks of the surrounding concrete before building up a pressure inside the structure. Since corrosion of rebars can reduce their load bearing capacity and ductile characteristics, a certain degree of uniform corrosion would have lower structural consequences than the same amount of corrosion occurring over a fraction of the total surface.
3. An impressed current can result in acidic conditions at the rebar. This is because the iron ions become hydrolysed in solution as indicated in the following reaction [19] because (i) the reaction products are being produced very fast and (ii), in many cases, the cathodic reaction is taking place outside the concrete, it is not

possible for the hydrogen ions to diffuse away and be neutralized by the hydroxyl ions produced at the cathode.



4. The potential of the rebar is not normally monitored during the impressed current, but the potential difference between the anode (the rebar) and the cathode is usually several volts. The potential difference between hydrogen evolution and oxygen evolution equilibria in aqueous solutions is only 1.23 V [20], and any potential difference greater than this would result in oxygen evolution at the anode and/or hydrogen evolution at the cathode. Such gaseous evolution would influence the composition and spatial distribution of the corrosion products as well as affecting the steel/concrete bond.

The last three problems would also occur if the impressed current were applied to an anode embedded adjacent to the reinforcement, rather than to the rebar itself, as has been proposed as a possible alternative [21].

2.3. Tests in “synthetic pore solutions”

Testing steel in solution has the advantage of avoiding the long time necessary for chlorides to penetrate the concrete cover. However, the same caution applies to solution as to the use of chlorides admixed into the concrete: the steel should be given time to passivate in the alkaline

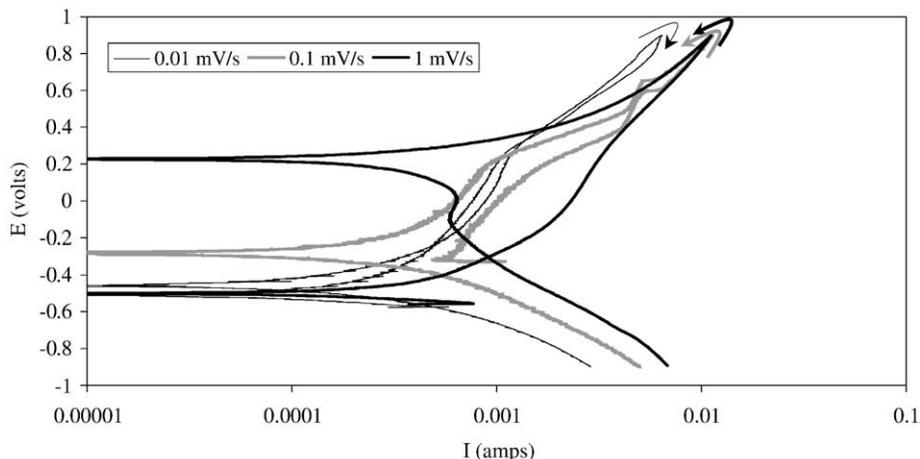


Fig. 4. Cyclic polarisation curves with different scan rates for a steel reinforced concrete sample with transverse crack. Arrows show the direction of the return potential.

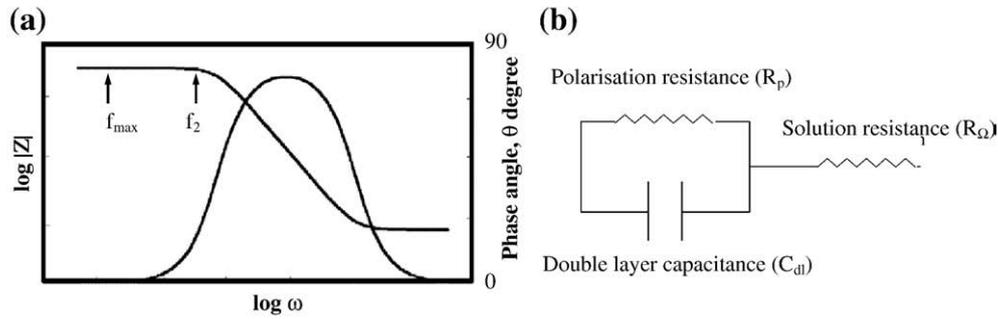


Fig. 5. (a) Bode plot of (b) a Randle circuit and the lower break-point.

solution before being exposed to chlorides. In a number of studies reported in the literature, it appears that insufficient time was provided for passivation before the steel was exposed to chlorides and, in some case the chloride was added to the pore solution at the beginning of the experiment [22–25]. Because of these unrealistic conditions, the application of such results, for example, to the prediction of the corrosion behaviour of steel in structures may be misleading. The half cell potentials and corrosion current densities shown in Fig. 1(b) [1] suggest a minimum of 3 days before adding chlorides, but the authors recommend at least one week.

It is well known that steel in high alkaline environments is passive. However, it should be noted the protective capability of the passive film increases with pH [26] and that the pH of most concretes is greater than 13 and typically ~ 13.5 [27,28]. The pH of saturated calcium hydroxide solution is about 12.6 [29] which does induce passivation but not to the degree encountered by steel in good quality concrete. Nevertheless, saturated $\text{Ca}(\text{OH})_2$ has been used in numerous studies of rebar corrosion [5–11] as a substitute for pore solution, although has been demonstrated that steel behaves differently at pH 12.6 than it does at $\text{pH} > 13$ [30]: the chloride threshold value for active rebar corrosion is lower and the corrosion rates are higher for steel tested in saturated $\text{Ca}(\text{OH})_2$ than in a pore solution of the same composition as expressed from mature concrete [23,31]. Moreover, the other ions present in pore solution, particularly, sodium and potassium, may also play a role in the corrosion process.

3. Appropriate electrochemical techniques

3.1. Linear polarisation resistance and cyclic polarisation

Gonzales et al. [32] have given an excellent review of the limitations of the linear polarisation resistance (LPR) technique and the fact that these limitations are particularly applicable to steel in concrete. Yet LPR is, by far, the most commonly used technique for measuring rebar corrosion rates both in the laboratory and in the field, again, to a large extent, because it is fast. One major limitation of LPR is that, while it gives a reasonable estimate of the corrosion rate at the time of measurement, it gives no indication of the behaviour of the steel should the conditions be changed. As an example, consider the LPR data in Table 1 and the corresponding cyclic polarisation curves in Fig. 3 for carbon steel rebar in three concretes with the same mix proportions except that the binder in the first was 100% ordinary Portland cement (OPC), in the second 9% of OPC had been replaced by silica fume and in the third, 25% of OPC had been replaced with slag [33]. The LPR data give corrosion rates on the border line between active and passive and, although the silica fume concrete has slightly lower values, the differences could be considered insignificant. Similarly, an approximate Tafel extrapolation of the cyclic polarization curves would show the corrosion rates for the steel in the three concretes to be very similar. The anodic cyclic polarisation curves, however, tell a very different story, with the steel in the OPC and slag

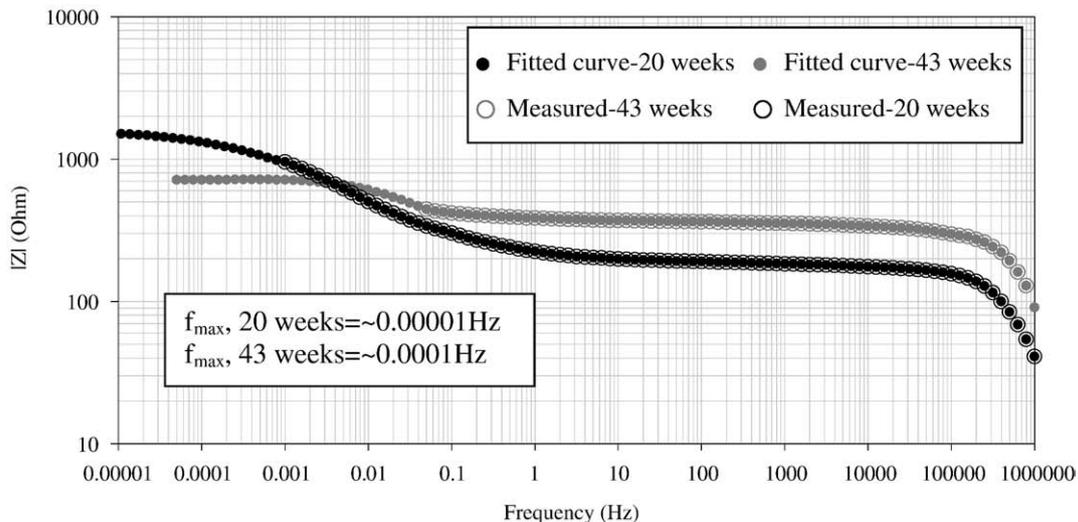


Fig. 6. The Bode plot obtained from a reinforced OPC concrete beam after 20 and after 43 weeks exposure to chloride.

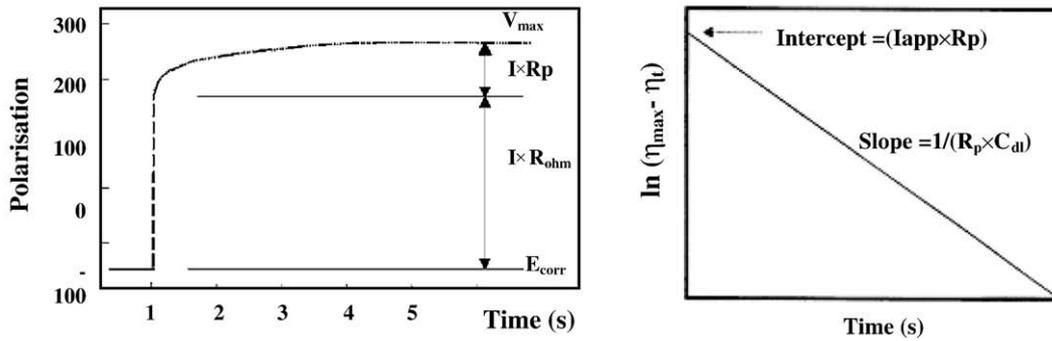


Fig. 7. Schematic illustration of galvanostatic pulse results.

concretes exhibiting clear chloride pitting potentials, while the silica fume cement exhibits passive behaviour at all potentials.

Consequently, these authors find potentiodynamic cyclic polarization to be a much more informative tool for laboratory measurement than LPR. It is a relatively non-destructive measurement that can provide information on (i) the corrosion rate, (ii) the corrosion potential, (iii) the leakage current of the passive film (i.e. its protective capability), (iv) the susceptibility of the metal to pitting and (v) any concentration limitations of the electrolyte in the system.

However, it is imperative that an appropriate cyclic polarisation scan rate for the specific system under study be used; otherwise the results do not accurately reflect the corrosion behaviour. As an electrical analogue, the metal/electrolyte can be considered as a resistor, R_{Ω} , (the electrolyte) in series with a parallel combination of a capacitor, C_{dl} (the Helmholtz double layer), and a resistor, R_p , (the polarisation resistance which is inversely proportional to the corrosion rate). To ensure that the current/voltage relationship reflects only the interfacial corrosion process at every potential of the polarisation scan, the effect of the capacitance should be minimised [34]. For this

purpose, the capacitor should remain fully charged; otherwise, some of the current generated would reflect charging of the surface capacitance, and the measured current would then be greater than that actually produced by the corrosion reactions. To achieve this, the scan rate should be slow enough to ensure that the capacitance remains fully charged during the experiment.

Fig. 4 shows the cyclic polarisation curves, obtained at different scan rates, for a steel reinforced OPC concrete sample, with transverse crack, exposed to a chloride solution. Clearly, the steel exhibits different behaviour at different scan rates. Because, the capacitance and resistance are functions of the material, environment and the applied potential, choosing the appropriate scan rate is not easy but a method for doing so has been described by Mansfeld and Kendig [35]. The principle of the method is based on the Bode plot, Fig. 5(a) [36], obtained from electrochemical impedance spectroscopy and represented by the Randles circuit, Fig. 5(b). At low frequencies, $|Z| = R_{\Omega} + R_p$; i.e. there is no capacitance component. Therefore, in order to determine the polarisation resistance accurately, the frequency characterisation of the scan rate should correspond to a frequency less than f_2 in Fig. 5(a). To ensure fully charged capacitor, the maximum scan rate can be based on a frequency, f_{max} , one decade lower than f_2 , as follows:

$$S_{max} = \Delta E \cdot \pi \cdot f_2$$

Where ΔE is the peak to peak amplitude. ΔE is usually ~ 20 mV to ensure the linear response of the system to the applied potential [37].

Fig. 6 shows Bode plots obtained from a reinforced OPC concrete beam with a $w/c = 0.45$, after 20 weeks exposure and after 43 weeks exposure to chlorides. The frequency range scanned was from 1 MHz to 0.01 mHz. It should be noted that this test took about a week to complete and, to obtain the full Bode plot, the results were extrapolated, using the Kramers–Kronig method with ZSimWin software [38,39].

From Fig. 6, the maximum scan rate, S_{max} (corresponding to $f_{max} = 0.00001$ Hz), for performing cyclic polarisation tests is calculated as ~ 0.0006 mV/s for the specimen after 20 weeks' exposure and 0.006 mV/s after 43 weeks' exposure. The different scan rates are because of the different concrete environments (chloride content, resistance etc.) and amount of corrosion of the steel bar after different exposure periods. Using a very slow scan

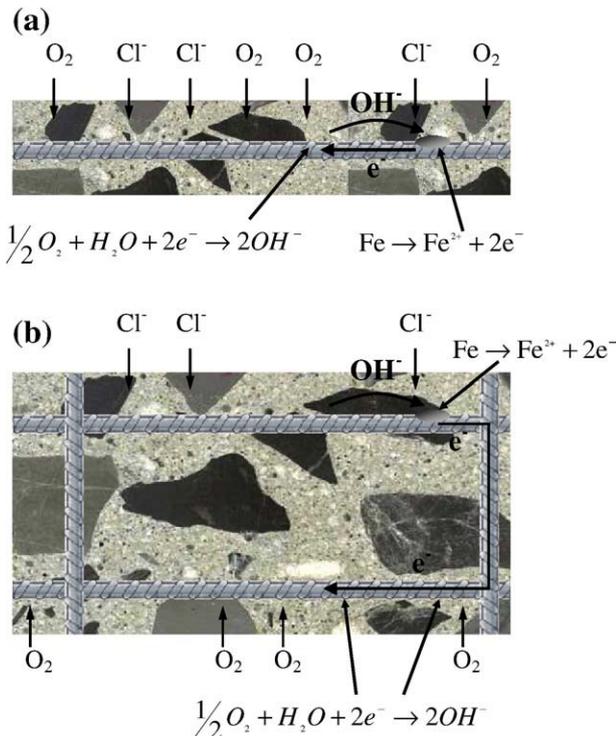


Fig. 8. (a) Schematic representation of (a) microcell corrosion, (b) macrocell corrosion.

Table 1
LPR data for carbon steel rebar in OPC, OPC-9% silica fume OPC-25% slag [33].

Corrosion current density mA/m ²	OPC concrete	OPC-9% silica fume concrete	OPC-25% slag concrete
At 7–9 days	7.53 ± 5.12	1.44 ± 0.41	7.76 ± 0.76
At 16–19 days	8.17 ± 4.82	1.42 ± 0.68	7.00 ± 3.97
At 26–28 days	3.37 ± 2.67	1.21 ± 0.47	6.12 ± 1.95

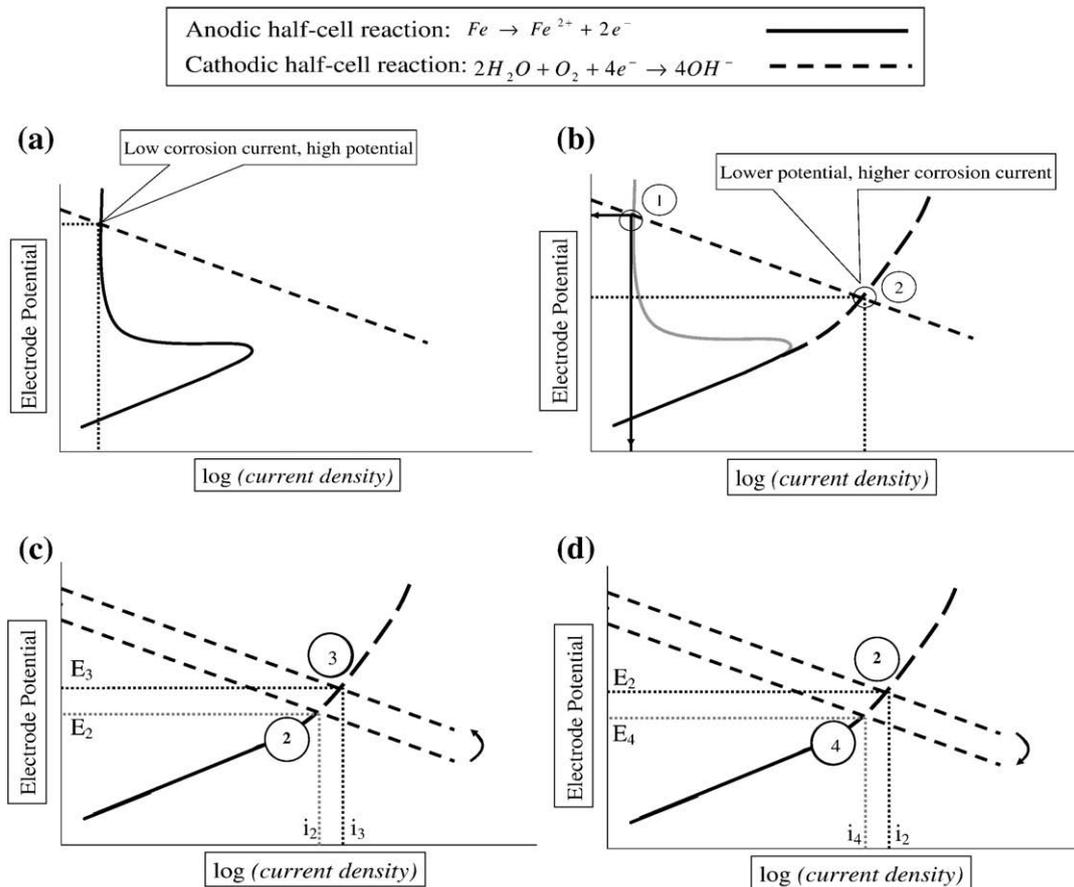


Fig. 9. The anodic and cathodic half cell currents and corresponding values of E_{corr} and i_{corr} for (a) passive steel in concrete; (b) actively corroding steel in concrete; (c) actively corroding steel in cracked concrete and (d) actively corroding steel in concrete with limited access to air.

rate, such as 0.0006 mV/s is not practical, however. For the potential ranges shown in Fig. 4, the test would need more than 50 days to complete. During this period, the corrosion behaviour could change considerably. For this reason and from a practical perspective, a scan rate corresponding to f_2 , rather than f_{max} , is recommended, although this could still take several days to complete. It should be noted that the lower scan rate corresponds to the steel in a passive state or when it is corroding at a low corrosion rate.

Alternatively, it is possible to determine the appropriate scan rate, in a shorter time, using the galvanostatic pulse technique. In this technique, a short-time anodic current pulse, I_{app} , is applied between a counter electrode placed on the concrete surface and the rebar. The resulting change of the electrochemical potential of the reinforcement is measured with a reference electrode. A typical potential response, η_t , for a corroding reinforcement is shown in the Fig. 7 [40] and is expressed as [41]:

$$\eta_t = I_{\text{app}} \times \left[R_p \times \left[1 - e^{\left(\frac{-I_{\text{app}} t}{R_p C_{\text{dl}}}\right)} \right] + R_\Omega \right]$$

The double layer capacitance can be obtained from this plot and correlated to the frequency using the following expression [42]:

$$C_{\text{dl}} = \frac{1}{(2\pi f)R_p}$$

While a test taking several days might be considered to be impractical, these authors believe that, in view of the expected service life of a reinforced concrete structure of 75–100 years, spending a few

days to ensure, or understand, the corrosion behaviour is definitely reasonable. However, this viewpoint must also be balanced with the fact that the test must be fast enough that the system does not change during the test period.

3.2. Macro- vs. micro-cell corrosion

Macrocell corrosion experiments are aimed at simulating the electrochemical situation of, for example, a bridge deck with chloride penetrating to the top rebar mat while the bottom mat remains in chloride-free concrete. The measurement of macrocell corrosion currents has become popular because they can be measured directly without expensive electrochemical equipment. The standard ASTM G109 specimen [43], which was designed to evaluate chemical admixtures, is being increasingly used for macrocell corrosion studies as is the modified Kansas State University method [44].

Microcell corrosion is the term given to the situation where active dissolution and the corresponding cathodic half-cell reaction (usually the reduction of dissolved oxygen) take place at adjacent parts of the same metal part. For steel reinforcing bar in chloride-contaminated concrete, this process always occurs in practice, for example, in specimens in the laboratory containing a single bar and in structures reinforced with a single rebar mat.

While a macrocell corrosion current can be measured directly, the same is not true of microcell corrosion and, therefore, many investigators choose to neglect the microcell component. This has led to the general assumption that macrocell corrosion is normally the dominant component. The theory is that the top mat will become the anode and the bottom mat the cathode, as illustrated in Fig. 8b. This is a rather simplified view because, in fact, the anodic and cathodic

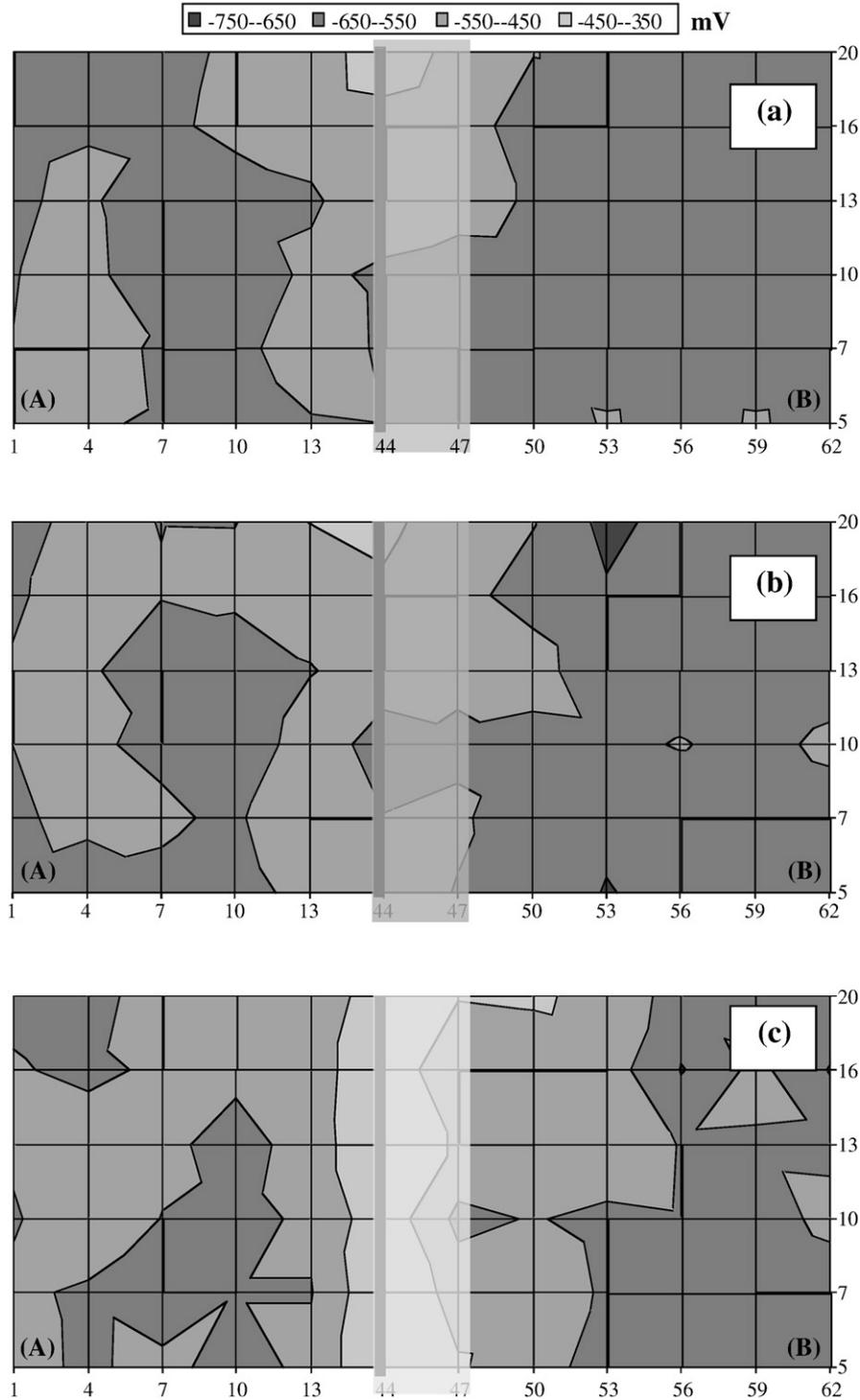


Fig. 10. Potential maps of the two bridge approaches (A and B): (a) May 2005 $T = 19^\circ\text{C}$, RH 58%, sunny; (b) May 2006, $T = 14^\circ\text{C}$, RH = 92%, sunny; (c) August 2005, $T = 16^\circ\text{C}$, RH = 91%, sunny.

reactions occur on both metal surfaces and, for the ionic part of the corrosion current, it is much easier to migrate to an adjacent area of the same bar, as in Fig. 8a, than via a longer path through the concrete between the two bars, Fig. 8b. In fact, it has been shown [45–47] that microcell corrosion is the dominant process.

Research has demonstrated that the microcell corrosion of steel in high performance concrete, HPC, was an order of magnitude lower than that of steel in ordinary Portland cement concrete, OPCC [46].

However, the macrocell currents in the HPC specimens were more than three orders of magnitude lower than those in the OPCC, because of the much higher electrical resistance of the HPC. Consequently, care must be taken in using the results of macrocell measurements: the absence of macrocell corrosion cannot be taken as an indicator that microcell corrosion is not occurring. This is particularly true for HPC where measured macrocell corrosion rates may be negligible while active corrosion of the top bar is taking place.

3.3. Half-cell potential

The half-cell potential, or corrosion potential, E_{corr} , is the most widely monitored parameter to assess the condition of steel in concrete, particularly in the field. The potential is a thermodynamic measure of the ease of removing electrons from the metal in steady state condition, and does not address the kinetics, i.e. the rate of corrosion, which is determined from the corrosion current density, i_{corr} . The measured half-cell potentials can be affected by several factors, which should be considered in the interpretation of their values.

Steel in concrete exhibits active–passive corrosion behaviour, in which the anodic half cell reaction is the dissolution or oxidation of iron and the cathodic half cell reaction is usually reduction of dissolved oxygen. The corrosion potential, E_{corr} , and the corrosion current density, i_{corr} , correspond to the intersection of the cathodic line for the reduction of oxygen and the anodic line for the oxidation of iron, as illustrated in Fig. 9. Fig. 9a shows typical passive corrosion behaviour of steel in sound, uncontaminated concrete in which the intersection occurs at a relatively high potential and low (= passive) current density. If the passive film is destroyed, e.g. by chlorides, the anodic curve changes to that shown in Fig. 9b for which the intersection with the cathodic curve gives a much more negative potential and a higher current density. This is the principal on which ASTM C876 [48] recommendations are based.

However, if access to oxygen increases (for example by cracking of the concrete cover), the cathodic reaction line moves to higher current densities (i.e. to the right of the diagram) and the new line intercepts the anodic curve at point 3, instead of point 2 as shown in Fig. 9(c). This results in a higher current and a more positive potential, a situation not addressed by the ASTM recommended guidelines.

Also, if the position of the cathodic line changes to lower current densities, as shown in Fig. 9d, because of a decrease in the concentration of oxygen, it intercepts the anodic curve at point 4, instead of point 2. Comparing points 2 and 4 shows that $i_2 > i_4$ while E_4 is more negative than E_2 , which again appears to contradict ASTM recommended interpretations. Examples of this behaviour have been given by Gu and Beaudoin [49] and by Soleymani and Ismail [50].

Therefore, a rigid adherence to the ASTM C876 [48] guidelines on steel reinforcement corrosion probability, without recognizing that these are simply guidelines, not fundamental facts, could cause mistakes in the evaluation of the structure. In addition to the examples above, a surface layer with high resistance gives less negative surface potentials which may cover underlying corrosion activity [51]. Feliu et al. [52], found that generally there is a poor correlation between half-cell potential values and corrosion current density measured by polarisation resistance method, while other researchers have found good agreement [53–56].

The most common method of presenting the half-cell potential field data is plotting the potential distribution or potential mapping contour. The advantage of this is that potential gradients can be detected and these generally correspond to current flow, i.e. corrosion. Nevertheless, other factors should be taken into account. Half-cell potential maps were obtained at different times of the year over a three year period for the approaches to a small traffic bridge and the results are shown in Fig. 10. As shown, the potential values were all more negative than -350 mV vs. CSE (Cu/CuSO₄ reference electrode) at all times and rust stains, cracks and delamination confirmed the reinforcement was actively corroding. However, these maps also show that measurements performed at the same time in each year, result in similar contour patterns, whereas those taken at different times of the year, have radically different contour patterns. The weather history, particularly the precipitation, over a fairly long period (more than a few days) prior to the measurement has an effect on the potential map.

A second observation of interest in these measurements and in parallel laboratory measurements, is that it is essential to thoroughly

wet the concrete surface and allow sufficient time for the moisture to penetrate the surface layers to stabilise the potential. ASTM C876 emphasizes that, if the measured value of the half-cell potential changes or fluctuates with time, the surface of the concrete should wet for at least 5 min. Unfortunately, in order to make as many measurements as possible in as short a time as possible, this recommendation is often ignored. Yet even 5 min were found to be insufficient to achieve a stable potential. Experiments in which the potential of a reinforcing bar embedded in a concrete beam was measured every 0.2 s for 90 min from the time of initial wetting, indicated that it took ~15 min for the potential to reach a stable value. This time would, again, be dependent on a number of factors, particularly the degree of saturation of the concrete.

It is also essential to emphasise the ASTM C876 recommended guidelines are for carbon steel (black steel) rebars in concrete and they should not be applied to other types of steel such as epoxy-coated bars or galvanised steel bars. Half-cell potential measurements of epoxy-coated rebar are not practical because the epoxy acts as a dielectric, preventing electrochemical measurements except at flaws in the coating. Thermodynamically, the half-cell potential values for galvanised steel could be -1000 mV vs. CSE in the passive state [24]. This potential may mislead the investigators during inspection. Therefore, knowledge of the type of reinforcing bar is essential for appropriate interpretation of the potential. Also it is important to mention that the chloride threshold for corrosion of galvanised steel is generally considered 4–5 times higher than that for black steel [57].

4. Specimen details

4.1. Influence of surface finish of the reinforcing steel on its corrosion initiation

Another practice of conscientious materials researchers is to conduct electrochemical tests on metallurgically polished specimens of reinforcing steel in the laboratory. Little effort has been addressed to the effect of surface finish of the steel on corrosion initiation [58] but those few results have shown that this polished condition does not reproduce the results obtained on black carbon steel. Even in the passive state, the corrosion rate of the sandblasted steel is less than that of black steel with the mill scale intact, as shown in Fig. 1b. Moreover, sandblasted steel was found to have a slightly longer initiation time than black steel and a significantly lower active corrosion rate [59]. The corrosion initiation in synthetic pore solution with increasing amounts of chloride was determined for (i) black ribbed reinforcing steel, (ii) smooth carbon steel bar with no mill scale and (iii) a section of the ribbed steel, which was metallographically polished to an 0.05 μm alumina finish. Active corrosion could not be initiated in the highly polished steel, even with a chloride concentration of 10% during the period of the experiment [31].

4.2. Comparison of different grades of steel

There has been a surge in the number of publications on corrosion resistant steels, in which these steels are compared with 316LN stainless steel and/or epoxy coated steel. In many cases, the steels are exposed to concrete or to synthetic pore solution into which chloride has been admixed. This puts some of the corrosion resistant steels at a severe disadvantage because they do not possess the atmospheric passivity of 316LN nor the early protection of the epoxy. To provide a reasonable comparison, they should be allowed to equilibrate in the high pH for some time before being exposed to chlorides.

There have also been some experiments described in the literature in which the corrosion resistant steels were partially embedded in concrete and exposed to alternate wet and “dry” cycles but the “dry” cycles were actually at 100% relative humidity (e.g. [60]). The exposed part of the specimens obviously continued to corrode in the “dry” part

of the cycle. Again a comparison of these steels with stainless steels, which are passive under damp atmospheric conditions, is unrealistic and not relevant to their behaviour in concrete.

5. Conclusions and recommendations

It is clear from the above that corrosion testing of reinforcing steels is a “minefield”, requiring a good basic understanding of the electrochemical processes involved and a large measure of common sense. In summary, any technique designed to accelerate the corrosion process should be considered with scepticism. If the goal is to assess a 100 year service life, spending a minimum of a few weeks or months on evaluation should be considered reasonable and necessary.

Accelerating the corrosion by applying an anodic current to rebar should be avoided unless the goal is to assess circumstances in which this happens in practice, such as stray current corrosion.

If solutions, rather than concrete, are to be used as the test environment, these should, to the greatest degree, mimic the pore solution of the specific concrete in question. Saturated $\text{Ca}(\text{OH})_2$ is not sufficient.

Exposure to concrete or pore solution containing chlorides should be avoided unless the goal is to determine the influence of contaminated mixture components. Instead, the sufficient time should be allowed for the steel to become passivated before exposure to chlorides. For black steel, this has been found to be a minimum of seven days for steel in OPC concrete and three days for steel in pore solution with a pH of ~ 13.3 [1]. These periods may be different for other types of reinforcing bars and for other concretes and pore solutions.

Cyclic potentiodynamic polarisation is one of the more informative electrochemical tests. However, using an appropriate scan rate in this technique is essential and, if the scan rate is too rapid, the result may not be representative of the system under the test. On the other hand, if it is too slow, the system may change during the measurement.

It is important to consider both microcell and macrocell corrosion, and ignoring the microcell component will underestimate the degree of corrosion.

Half-cell potential measurement is the most widely used technique in evaluation of the corrosion of steel in concrete. However, in interpreting the data, environmental factors should be taken into account and, wherever possible, repeated condition analyses should be conducted at the same time of the year. Moreover, it is recommended that a large area of the structure be thoroughly wet and measurements begin no sooner than ~ 15 min after the area of the first measurement is wet.

Except for fundamental research on the corrosion processes, the type of reinforcing bar and its surface condition should be representative of those used in practice, in order to evaluate field performance.

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