THE INFLUENCE OF COATING DISBONDMENT ON THE CORROSION OF COATED REINFORCEMENT - A NUMERICAL MODEL

R.A. Cottis,
Corrosion and Protection Centre, UMIST
P.O. Box 88, Sackville Street,
Manchester M60 1QD, UK

ABSTRACT

This paper describes a simplified, *ab initio* numerical model of the oxygen transport and electrochemical reaction kinetics associated with a hole in a coated reinforcement bar. The model examines the influence of area of disbondment of the coating around the hole on the corrosion rate of the exposed steel. The significance of coating disbondment is found to depend on the concrete permeability. An important conclusion is that experiments in which the coated bar is coupled to uncoated bar can be expected to give markedly different results, as the uncoated bar (assuming that it is passive) will provide a large area cathode that negates many of the assumptions made in this model. It is also clear that coupling between coated and uncoated bar provides a very severe test of the coating integrity. The thin solution layers in the crevice are able to transfer the current produced by oxygen reduction efficiently to the anodic site at the holiday in the coating. It appears that for nominally dry concrete the oxygen permeability of the epoxy coating and the radius of disbondment of the coating will have an important influence on the total metal loss occurring, and it should have a low oxygen permeability and disbond as slowly as possible. The area of hole in the coating will be important when processes in and around the hole are rate-controlling, including situations when there is very widespread disbonding and/or the coating has a very high oxygen permeability. Corrosion occurring as a result of oxygen transport through the hole will be important when the coating is not disbonded and/or has a very low oxygen permeability.

INTRODUCTION

This paper is concerned with the problem of the corrosion of reinforcement bar in concrete, and in particular with the influence of polymeric coatings on the corrosion rate. It is now well-known that steel reinforcement is protected from corrosion in fresh, chloride-free concrete by virtue of its passivity in the alkaline pore solution. Corrosion problems may commence when the passivity breaks down as a result of the combined action of falling pore solution pH, due to carbonation, and increasing chloride concentration, due to chloride ingress from the surface or to the chloride in the original mix. The corrosion of the reinforcement bar leads to local precipitation of voluminous corrosion products, and this causes cracking of the cover as a result of the tensile stresses developed in the concrete. Various methods have been used to

Copyright

©1998 by NACE International. Requests for permission to publish this manuscript in any form, in part or in whole must be made in writing to NACE International, Conferences Division, P.O. Box 218340, Houston, Texas 77218-8340. The material presented and the views expressed in this paper are solely those of the author(s) and are not necessarily endorsed by the Association. Printed in the U.S.A.
\[ O_2 \text{ flux} = \left( \frac{1}{d_{\text{conc}} + \frac{d_{\text{epoxy}}}{P_{\text{conc}}} + \frac{d_{\text{soln}}}{P_{\text{epoxy}}}} \right) \times \left( C_{\text{O}_2, \text{bulk}} - C_{\text{O}_2, \text{crev}} \right) \times A_{\text{element}} \]

where \( d_{\text{epoxy}} \) = thickness of epoxy (etc)
\( P_{\text{epoxy}} \) = permeability of epoxy (etc)
\( C_{\text{O}_2, \text{bulk}} \) = bulk concentration of oxygen
\( C_{\text{O}_2, \text{crev}} \) = concentration of oxygen beneath film
\( A_{\text{element}} \) = area of finite difference element
\( = 2 \pi r \delta r \)
\( r \) = radial distance from centre of defect

For the purposes of this analysis, oxygen concentrations are expressed as the relevant fraction of the concentration that is in equilibrium with 1 atm. partial pressure of oxygen gas.

2. Lateral oxygen diffusion along the crevice

The crevice beneath the epoxy coating will generally have a relatively high oxygen permeability compared to that of the epoxy coating above it, therefore the lateral oxygen transport between neighbouring elements used for the finite difference analysis must be considered. This is given by the difference equation

\[ \text{lateral } O_2 \text{ flux} = \left( C_{\text{O}_2, n-1} - C_{\text{O}_2, n} \right) \times 2\pi \left( \frac{r - \delta r}{2} \right) \times \left( C_{\text{O}_2, n-1} - C_{\text{O}_2, n} \right) \times 2\pi \left( \frac{r + \delta r}{2} \right) \times \frac{d_{\text{soln}} \times P_{\text{soln}}}{\delta r} \]

where \( C_{\text{O}_2, n} \) = oxygen concentration in element \( n \)
\( r \) = radius of element \( n \)
\( \delta r \) = width of element
\( d_{\text{soln}} \) = thickness of solution film
\( P_{\text{soln}} \) = permeability of solution

3. Electrochemical reaction

The oxygen in the solution beneath the epoxy film will react with the metal as a cathodic reaction that can be defined by normal electrochemical kinetics:
dependence of active region potential on crevice tip potential).

The lateral oxygen transport within the crevice is handled by a conventional relaxation process that occurs during the binary chop solution for the potential distribution. Essentially each pass of the potential solution allows diffusion between adjacent elements, and this process stabilizes during the repetitions of the potential solution. To provide a stable starting point the potential distribution is determined without lateral oxygen transport. Then the potential distribution is repeatedly solved with lateral oxygen transport until the maximum change in oxygen concentration in any one element is less than $10^{-5}$ of the oxygen concentration at the crevice tip, with a minimum of three repetitions. The number of diffusion steps that this approach entails is rather arbitrary, and is probably insufficient to fully relax the diffusion process. However, lateral oxygen diffusion in the solution is only significant over relatively small distances, and the errors resulting from this approach are thought to be small. This has been tested by running sample analyses for many more cycles, and the resultant potential and oxygen profiles were little different.

**CORROSION RATES IN THE ACTIVE REGION**

One of the objectives of this work was the comparison of the role of the disbonded region, the active region and the hole in the coating in determining the amount of corrosion occurring. In order to do this the corrosion directly associated with the latter effects must also be estimated. This is a rather complex problem, as there are many situations in which it is clearly inappropriate to use a linear approximation for the oxygen diffusion to the hole.

If the permeability of the epoxy coating is high relative to that of the concrete, the concrete will largely determine the oxygen distribution, and as diffusion to and through the coating will occur at a comparable rate to diffusion to the hole, it will be appropriate to use a linear approach to calculate the corrosion occurring due to the hole and the active region around it. However, when the permeability of the concrete is much higher than that of the coating, the oxygen concentration within the concrete will be close to that of the environment, and diffusion of oxygen to the hole will be controlled by spherical diffusion. The general solution of this problem has not yet been attempted, but it seems reasonable to assume that linear diffusion represents a lower bound to the possible rate of corrosion, while spherical diffusion represents an upper bound. Thus these cases have both been analyzed to give an indication of the rates to be expected.

For the case of linear diffusion the solution is essentially as that for the disbonded region, except that the oxygen concentration at the metal surface is assumed to be zero, and the permeability term associated with the film is omitted. For the spherical diffusion case the oxygen flux to the hole is

$$O_2 \text{ flux} = 2r P_{\text{oec}}$$

where $r$ = radius of hole

Note that this calculation ignores the effects of any solution film on the metal, and may therefore give an excessively high estimate of the oxygen flux, especially for diffusion through a high permeability concrete to a small hole. This is clearly unreasonable, and for this work this has been solved by arbitrarily limiting the maximum current density to 1 mA/m$^2$. This corresponds to a penetration rate (i.e. a corrosion rate in the active region) of approximately 1 mm/yr, which is a typical maximum corrosion rate for steel in neutral environments, such as the marine splash zone.
Solution Resistivity
We are not aware of any direct measurements of the resistivity or solution composition beneath a disbonded coating, but a simple consideration of osmotic pressure suggests that the ionic strength must be at least as high as the external solution (otherwise water will migrate through the coating to the pore solution), therefore we have taken a typical pore solution composition to estimate the conductivity. The solution contains 26.3 g/l NaOH, 10.74 g/l KOH, 34.35 g/l KCl and 2.15 g/l Ca(OH)₂. Calculation of the resistivity of this solution assuming dilute solution theory (which is not strictly applicable, but the errors will probably not be large) gives a resistivity of 0.034 Ω m.

Oxygen Reduction Kinetics
The kinetics of the oxygen reduction reaction in saturated calcium hydroxide solution have been studied by Hawkins.³ Analysis of her results gives the Tafel slope as 0.03606 V per unit natural logarithm of current (0.083 V/decade of current), with a current density at 0 V (SCE) of 3.6 x 10⁻⁸ A m⁻². The corrosion potential was around -0.22 V (SCE), which implies that the current density for the passive corrosion of iron was about 1.65 x 10⁻⁵ A m⁻².

The kinetics of the active region have not been explicitly considered, as it has been assumed that the reaction in this region is relatively non-polarizable, hence the conditions may be described in terms of a constant corrosion potential. It is open to some question as to the correct value to use for this. For the work undertaken to date a figure of -0.6 V (SCE) has been used, which is at the positive end of the range expected for steel corroding in neutral salt solutions (the solution pH in the region of the hole is expected to fall to somewhat less than neutral as a result of metal ion hydrolysis).

RESULTS
It is clear from the graphs of potential and oxygen concentration that are obtained from this analysis that the solution film in the crevice is effective at carrying current from the passive region to the active region, even with crevice widths of the order of 1 μm. Figure 1 shows a typical result (see Table 1 for details of the parameters used for Figures 1 to 6). Only for the thinnest crevice used (0.1 μm, see figure 2) does the potential rise to approach that of the freely-corroding passive surface, and then only for the larger crevice radii and the high permeability concrete. Thus the coupling between the passive metal in the crevice and the active metal near the hole should not be ignored in estimating the extent of corrosion expected.

The concrete permeability plays an important part in the general pattern of results obtained. When the permeability of the concrete is low, such that diffusion of oxygen through the concrete is significant in the control of the corrosion rate, the amount of oxygen reaching the crevice is large compared to that reaching the hole, and the area of disbonding dominates the behaviour (figures 3 and 4). In the case where the permeability of the concrete is high (figures 5 and 6), the transport of oxygen to the crevice is controlled by the coating, and the contribution of the coupling between the crevice and the active region is less important. However, even in this situation the corrosion attributable to the crevice may be comparable to that due to oxygen diffusion through the hole, especially for smaller hole sizes. The values that we have used for the high concrete permeability case are probably at the extreme of the range to be expected, as the coating will probably become more permeable as it absorbs water in service, and good-quality, well-cured concrete will probably be rather less permeable. Additionally the estimated current associated with spherical diffusion to the hole is probably rather high, as it ignores the diffusion through the liquid that will presumably be present at the corroding metal surface, and, particularly for the smaller holes, this will tend to reduce the corrosion rate (as noted above, this has been taken into account in part by limiting the maximum current...
possible (these two requirements will probably be linked, as the hydroxyl ions produced by the oxygen reduction reaction will be responsible for the disbonding process).

The area of hole in the coating will be important in determining the amount of corrosion occurring under some circumstances, particularly where processes in and around the hole are rate-controlling. This will include the situation when there is very widespread disbonding and/or the coating has a very high oxygen permeability. At the other extreme corrosion occurring as a result of oxygen transport through the hole (and hence the hole geometry) will be important when the coating is not disbonded and/or has a very low oxygen permeability.

ACKNOWLEDGEMENTS

This work was supported by Allied Bar Coaters.

REFERENCES


TABLE 1
PARAMETERS FOR FIGURES 1 TO 6

<table>
<thead>
<tr>
<th>Figure Number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell dimensions (microns)</td>
<td>50</td>
<td>50</td>
<td>10</td>
<td>50</td>
<td>10</td>
<td>50</td>
</tr>
<tr>
<td>Radius of hole (in mm)</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Radius of active region (in mm)</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Radius of passive region (in mm)</td>
<td>50</td>
<td>50</td>
<td>5</td>
<td>50</td>
<td>5</td>
<td>50</td>
</tr>
<tr>
<td>Thickness of epoxy (in microns)</td>
<td>200</td>
<td>200</td>
<td>200</td>
<td>200</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>Thickness of concrete (in mm)</td>
<td>25</td>
<td>25</td>
<td>25</td>
<td>25</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Thickness of solution (in microns)</td>
<td>1</td>
<td>0.1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>Permeability of epoxy (moles O\textsubscript{2}/m at 1 atm)</td>
<td>5.2\times10^{-12}</td>
<td>5.2\times10^{-12}</td>
<td>5.2\times10^{-12}</td>
<td>5.2\times10^{-12}</td>
<td>5.2\times10^{-12}</td>
<td></td>
</tr>
<tr>
<td>Permeability of concrete (moles O\textsubscript{2}/m at 1 atm)</td>
<td>5\times10^{-7}</td>
<td>7.5\times10^{-11}</td>
<td>7.5\times10^{-11}</td>
<td>5\times10^{-7}</td>
<td>5\times10^{-7}</td>
<td></td>
</tr>
<tr>
<td>Permeability of solution (moles O\textsubscript{2}/m at 1 atm)</td>
<td>1.5\times10^{-9}</td>
<td>1.5\times10^{-9}</td>
<td>1.5\times10^{-9}</td>
<td>1.5\times10^{-9}</td>
<td>1.5\times10^{-9}</td>
<td></td>
</tr>
</tbody>
</table>

Notes to Table 1
1. The cell dimensions refer to the cell size used for the finite difference analysis.
2. The oxygen permeability of the concrete is either high (5\times10^{-7}), corresponding to 'dry' concrete, or low (7.5\times10^{-11}), corresponding to 'wet' concrete.
3. For all cases, the solution resistivity was 0.0344 \Omega m, the potential of the active region was -0.6 V (SCE), and the bulk oxygen concentration was 0.2 atm (i.e. air-saturated)
FIGURE 7 Penetration rate as a function of the radius of the disbonded region

FIGURE 8 Metal loss as a function of time for low permeability concrete, varying rates of disbonding
FIGURE 1 Oxygen and Potential Distribution for 1 µm Crevice

FIGURE 2 Oxygen and Potential Distribution for 0.1 µm Crevice

FIGURE 3 Oxygen and Potential Distribution for 1 µm Crevice, Low Concrete Permeability. 5 mm Disbonded

FIGURE 4 Oxygen and Potential Distribution for 1 µm Crevice, Low Concrete Permeability. 50 mm Disbonded

FIGURE 5 Oxygen and Potential Distribution for 1 µm Crevice, High Concrete Permeability. 5 mm Disbonded

FIGURE 6 Oxygen and Potential Distribution for 1 µm Crevice, High Concrete Permeability. 50 mm Disbonded
density due to oxygen diffusion to the hole). On the other hand, our results for the low permeability concrete may overestimate the effect of the crevice, as the large current densities implied will result in a change of the corrosion potential at the hole, and this may be reflected in a reduction of the current produced within the crevice.

To put the results into a more practical perspective, the penetration rate at the active region has been plotted in figure 7 as a function of the area of disbonding. In real exposure conditions disbonding will frequently be progressive, and this is illustrated in figures 8 and 9, where the total metal loss as a function of time is plotted for two different rates of disbonding (assumed to take the form of a linearly-increasing radius of the disbonded region with time). At first sight these figures show two limiting behaviours. For the low permeability concrete the amount of oxygen reaching the metal (and hence the total metal loss) is controlled to a very large extent by the total area exposed, and the rate of disbonding therefore dominates the behaviour. For the high permeability concrete the disbonded region has a less significant effect on the behaviour, which is dominated by the oxygen diffusing through the hole. However, closer examination (figure 10) shows that there is a significant effect of the disbonding for the smaller (0.15 mm radius) hole.

**DISCUSSION**

This paper has described a simplified model that has been derived from first principles, with the objective of examining factors that might influence the rate of corrosion. While the parameters and assumptions appear reasonable, it is not yet possible to test the results of this model against experiments. This is partly due to the uncertainty of the correct parameters to use, and partly to the lack of experimental data for which sufficient information is available (particularly in respect of the extent of disbonding of the coating at different times in the test). It should be noted that this model is based on freely-corroding coated bar, and experiments in which the coated bar is coupled to uncoated bar can be expected to give markedly different results, as the uncoated bar (assuming that it is passive) will provide a large area cathode that negates many of the assumptions made in this model. In the latter case it may be assumed that the oxygen reduction reaction is no longer rate limiting (by virtue of the large cathode area), and the rate of corrosion will depend on anodic kinetic and/or mass transport processes occurring at the hole. It is perhaps also appropriate to note that coupling between coated and uncoated bar provides a very severe test of the coating integrity. If at all possible such a situation should be avoided in practice, and tests using such a configuration will have little relevance to the service behaviour of coated bar that is not connected to an uncoated cathode.

The ability of even thin solution layers in the crevice to transfer the current produced by oxygen reduction is somewhat surprising. Three main factors contribute to this; the high conductivity of the solution, the relatively low current density due to the low oxygen flux, and the insensitivity of the reaction kinetics to the electrochemical potential. However, this will become more difficult as the oxygen flux increases due to an increase in the permeability of the coating, or if the thickness of the solution layer is less than that assumed in this analysis. On the other hand, these factors will be countered by any tendency of the coating to allow ionic currents to flow, as this will allow the current to flow by the alternative path through the film and the concrete.

The failure of the concrete normally arises as a result of cracking due to the deposition of voluminous corrosion products. When the corrosion is occurring at a hole in an epoxy coating, the parameter that defines the amount of damage will presumably be the amount of metal ions that have been produced by corrosion, since it will be these that will precipitate the damaging corrosion products. On the basis of this model, it appears that for nominally dry concrete the oxygen permeability of the epoxy coating and the radius of disbondment of the coating will have an important influence on the total metal loss occurring. For best performance the epoxy should have a low oxygen permeability, and it should disbond as slowly as
For comparison purposes all oxygen fluxes have been converted to currents.

The active region surrounding the hole is subject to essentially the same diffusion conditions as the disbonded region, consequently the same linear assumption has been used in estimating the oxygen flux to this region.

**ESTIMATES OF REQUIRED DATA**

Several parameters are required for this model, and in many cases the information available is rather limited. The estimates that have been used in the analysis were obtained as follows:

**Oxygen Permeabilities**

In 'normal' diffusion terminology, that we shall use here, permeability is a measure of the ability of a substance to be transported through a membrane, and it is the product of the diffusion coefficient (which describes how fast each molecule will move) and the solubility (which describes how many molecules there will be). This terminology appears to be used somewhat differently in the concrete literature, where the term diffusion coefficient is sometimes used to refer to the permeability (as defined above), and permeability is used to refer to the transport of gas through the concrete under the influence of an applied pressure. Additionally the units used for reporting permeabilities may be rather obscure, and it is necessary to make assumptions (or perhaps guesses would be more accurate) about their meaning. For consistency, we have expressed all permeabilities in units of mole m\(^{-1}\) s\(^{-1}\) atm\(^{-1}\) (i.e. the number of moles that will pass through a 1 m cube of the material when the difference in oxygen partial pressure is 1 atmosphere). With these provisos, the oxygen permeabilities that have been used have been derived as follows:

(a) **Solution**

The oxygen diffusion coefficient in aqueous solutions has a reasonably well-defined value of the order of 1.2 \(\times\) 10\(^{-5}\) cm\(^2\) s\(^{-1}\), and the oxygen solubility is of the order of 40 ppm (for solution in contact with 1 atmosphere of oxygen). This leads to an oxygen permeability of 1.5 \(\times\) 10\(^{-9}\) mole m\(^{-1}\) s\(^{-1}\) atm\(^{-1}\).

(b) **Concrete**

The oxygen permeability of concrete will depend on whether it is nominally dry (i.e. the pores within the concrete contain gas) or wet (i.e. the pores are filled with liquid), since the oxygen permeability of gases and liquids are very different. For the case of wet concrete we have used an arbitrary estimate based on the assumption that liquid will constitute of the order of 5% of the volume of the concrete, hence the permeability will be 5% of that of solution, or 75 \(\times\) 10\(^{12}\) mole m\(^{-1}\) s\(^{-1}\) atm\(^{-1}\).

For the case of 'dry' concrete, typical values reported in the literature are in the region of 10\(^{-8}\) m\(^2\)/s (from reference 1). This implies that 10\(^{-8}\) m\(^3\) of oxygen per second permeate through a 1 metre cube, presumably with a 1 atmosphere partial pressure difference. This implies a permeability of approximately 5 \(\times\) 10\(^{-7}\) mole m\(^{-1}\) s\(^{-1}\) atm\(^{-1}\).

(c) **Epoxy Coating**

A typical permeability is of the order of 100 cm\(^3\) 100\(\mu\)m m\(^{-2}\) d\(^{-1}\) atm\(^{-1}\) (from Thomas\(^2\)). Converting this to our units gives a permeability of 5.2 \(\times\) 10\(^{-12}\) mole m\(^{-1}\) s\(^{-1}\) atm\(^{-1}\).
\[ i_{o_2} = i_o \times \exp \left( \frac{E - E_0}{\beta_c} \right) \times C_{O_2} \]

where \( i_{o_2} \) = local current density
\( i_o \) = exchange current density
\( E \) = local potential
\( E_0 \) = equilibrium potential
\( \beta_c \) = Tafel slope
\( C_{O_2} \) = local oxygen concentration

In addition the iron will be dissolving through the passive film at a rate that is largely independent of potential, although the rate is liable to fall with time as the passive film thickens. This is represented by a constant passive current density.

4. Flow of current between elements
Current will flow between elements as a result of potential differences between them. The effective resistance between elements will be given by

\[ R_{n,n-1} = \pi(2r - \delta r) \rho_{\text{solution}} \]

where \( R_{n,n-1} \) = resistance between elements n and n-1
\( \rho_{\text{solution}} \) = resistivity of solution

**BOUNDARY CONDITIONS AND SOLUTION METHODS**

Within an element, the requirements for stability are that the net current out of the element is equal to the net current due to the electrochemical reaction, and that the net flux of oxygen into the element (including the electrochemical oxidation of oxygen as an outward flux) is zero. This requirement was solved for using the secant method, with the oxygen concentration in the element as the control variable (in the secant method a new estimate for the control variable is made on the basis of the best two previous estimates, using linear interpolation or extrapolation to derive the next estimate). For a reasonably linear system this will find an accurate solution very rapidly, providing the initial estimates are sensible.

The potential distribution within the crevice will be such that the potential at the interface between the active and passive region is consistent with the fixed potential of the active region (i.e. the potential of the element next to the active region differs from that of the active region by the relevant IR drop), while at the outer end of the crevice the current must be zero. These boundary conditions are met by determining the potential next to the active element for selected potentials at the tip of the crevice, with the potentials of successive elements being calculated from the potential drop as a result of the current coming from the neighbouring element (starting from the crevice tip, where the incoming current is known to be zero). A binary chop was used to search for the crevice tip potential that gave the required potential at the active region (initial attempts to use the secant method suffered from instability due to the very sensitive
provide extended protection to the reinforcement, including galvanising and epoxy coating. Recent service problems with epoxy-coated reinforcement bar have given rise to questions about the role of coating defects in this application. This paper is concerned with a theoretical analysis of the current distribution around a defect in the coating, and in particular with the influence of disbonding of the coating around the defect on the rate of corrosion.

**THE MODEL**

For simplicity in analysis the physical model considered is based on a flat steel plate covered with layers of epoxy and concrete. The concrete coating is assumed to be continuous and homogeneous, while the epoxy coating has a small circular defect in it. It is assumed that disbonding has propagated radially from the defect, and that the region of active corrosion has extended a smaller distance below the coating, with the remaining disbonded region beneath the coating being passive. The model does not attempt to treat the chemical changes beneath the coating, hence the radius of the disbonded region and the region of active corrosion are provided as input parameters to the model.

Even with the simplifying assumptions made in respect of the geometry of the defect, the solution of the full two-dimensional problem is complex (the problem is inherently two-dimensional by virtue of the radial symmetry). It has therefore been further simplified by the use of a quasi one-dimensional analysis. In this the transport processes along the disbonded region beneath the coating are treated by means of a one-dimensional finite difference model, while transport of oxygen normal to the steel surface is treated by means of an analytical solution of the one-dimensional diffusion process (i.e. diffusion of oxygen in the concrete parallel to the metal surface is ignored). The significance of this assumption will depend on the importance of the diffusion of oxygen through the concrete in the overall corrosion process; this is discussed further below.

The active region of the metal is assumed to be corroding relatively rapidly, such that the oxygen concentration in the solution is essentially zero. This will also result in the potential in this region being reasonably unaffected by current flow from the neighbouring elements. Hence, for simplicity it is assumed that the potential in the active region is constant, and that the oxygen concentration in the active region is zero.

As a result of the simplifying assumptions, the processes considered are as follows:

1. **Oxygen diffusion through the concrete and the epoxy coating**
   This may be defined in terms of the permeability of the concrete, the epoxy coating and the layer of solution beneath the coating. There are a range of definitions and units used for permeability (these are discussed further below), but for the purposes of this paper, permeabilities are defined as the number of moles of oxygen passing through a one metre cube of the material per second when a difference in oxygen partial pressure of 1 atmosphere exists across opposite faces of the cube. With this definition, the flux of oxygen is given by: