

THE CORROSION OF STEEL, AND ITS MONITORING, IN CONCRETE

INTRODUCTION

This Guide describes:

- (a) the circumstances in which steel reinforcement in concrete can corrode, and
- (b) methods of revealing whether corrosion is occurring and, if so, at what rate.

WHY STEEL IS USED IN CONCRETE

Concrete is a complex material of construction that enables the high compressive strength of natural stone to be used in any configuration. This is accomplished by breaking natural stone to suitable sizes and mixing the aggregates so formed with suitable proportions of water and cement. This mixture can then be moulded into any required shape while still fluid. The water and cement react chemically, forming a “glue” that bonds the pieces of stone aggregate together into a structural member, which becomes rigid and strong in compression when the chemical reaction is completed (i.e. the concrete is “cured”). In tension, however, concrete can be no stronger than the bond between the cured cement and the surfaces of the aggregate. This is generally much lower than the compressive strength of the concrete.

Most structures are subjected to loadings that create bending moments, producing both compression and tension stresses within the structure. Since concrete is comparatively weak in tension, arrangements have to be made for the tensile stresses in the structure to be transferred to another material that is strong in tension. Concrete is therefore frequently reinforced, usually with steel, but occasionally with glass fibres or polymer filaments.

Steel can be used for such reinforcement in one of two ways. When a system of steel bars or a steel mesh is incorporated in the concrete structure in such a way that the steel can support most of the tensile stresses and leave the immediately surrounding concrete comparatively free of tensile stress, then the complex is known as “reinforced concrete”. When the steel introduced is initially tensioned in such a manner that it applies a compressive stress to the surrounding hardened concrete such that no subsequent loading applied to the structure puts that concrete into tension, then the complex is known as “prestressed concrete”.

The steel introduced into concrete can occasionally serve both of these functions.

CONCRETE AS AN ENVIRONMENT FOR STEEL

The role of alkalinity

It is well known that if bright steel is left unprotected in the atmosphere a brown oxide rust quickly forms and will continue to grow until a scale flakes from the surface. This corrosion process will continue unless some external means is provided to prevent it. One method is to surround the steel with an alkaline environment having a pH value within the range 9.5 to 13.

Hydrated cement provides such an environment, the normal pH value being 12.6, at which steel is protected in the absence of aggressive anions. At this pH value a passive film forms on the steel that reduces the rate of corrosion to a very low and harmless value. Thus, concrete cover provides chemical as well as physical protection to the steel. However, circumstances do arise in which corrosion of reinforcement occurs. Since rust has a larger volume than the steel from which it is formed, the result can be cracking, rust-staining, or even spalling of the concrete cover. Such occurrences usually arise from loss of alkalinity in the immediate vicinity of the steel or from the presence of excessive quantities of aggressive anions in the concrete (normally chloride), or from a combination of both of these factors.

Loss of alkalinity by carbonation

Alkalinity can be lost as a result of:

(a) Reaction with acidic gases (such as carbon dioxide) in the atmosphere. The effects of sulphur dioxide are also included in the term “carbonation”.

Or –

(b) Leaching by water from the surface.

In practice both of these factors contribute to the reduction of alkalinity in the concrete. Concrete is permeable and allows the slow ingress of the atmosphere; the acidic gases react with the alkalis (usually calcium, sodium and potassium hydroxides), neutralising them by forming carbonates and sulphates, and at the same time reducing the pH value. If the carbonated front penetrates sufficiently deeply into the concrete to intersect with the concrete reinforcement interface, protection is lost and, since both oxygen and moisture are available, the steel is likely to corrode. The extent of the advance of the carbonation front depends, to a considerable extent, on the porosity and permeability of the concrete and on the conditions of the exposure.

For dense concretes, permeability and porosity are related to cement content, water/cement ratio, aggregate grading, degree of compaction, and adequacy of curing. Likewise, the permeability of lightweight concrete is determined mainly by the above factors and, to a lesser extent, by aggregate permeability where lightweight concretes are used. For aerated concretes, permeability is a function of the amount of air entrainment and the type of bubble formation; interconnecting bubbles allow easier ingress of the atmosphere than do discrete bubbles. (Methods of air entrainment for dense concrete should not permit the formation of other than discrete bubbles.) The extent of carbonation is likely to be greater in lightweight concretes than in dense concretes, and the depth of cover should be increased accordingly. Indeed, where carbonation or loss of alkalinity (in, for example, autoclaved aerated concrete) is expected to extend to the steel, additional protection to the reinforcement, or the use of a more corrosion-resistant material such as stainless steel, is necessary.

It is normal to accept, in the long term, a degree of carbonation in the concrete according to the above factors of porosity, permeability and degree of exposure. To provide the steel with an effectively permanent protective alkaline environment, the designer therefore ensures that the depth of cover to the reinforcement nearest the surface is sufficiently greater than the depth of carbonation penetration.

Cracks in concrete formed as a result of tensile loading, shrinkage or other factors can also allow the ingress of the atmosphere and provide a zone from which the carbonation front can develop. If the crack penetrates to the steel, protection can be lost. This is especially so under tensile loading, for debonding of steel and concrete occurs to some extent on each side of the crack, thus removing the alkaline environment and so destroying the protection in the vicinity of the debonding. The extent of subsequent corrosion will be determined by a number of factors, including width of crack, loading conditions, degree of exposure and atmospheric pollution. In some circumstances the cracks will be closed by the product of carbonation reactions, ingress of dust or other solid airborne matter, or combinations of both of these influences, so restricting further oxygen and moisture access and minimising further corrosion. Where, however, cracks are not closed in this manner (especially cracks subject to movement resulting from fluctuating load conditions), oxygen and moisture still have access to the unprotected steel surface and corrosion is likely to progress.

Effect of chloride in the concrete

The passivity provided by the alkaline conditions can also be destroyed by the presence of chloride ions, even though a high level of alkalinity remains in the concrete. The chloride ion can locally de-passivate the metal and promote active metal dissolution. Chlorides react with the calcium aluminate and calcium aluminoferrite in the concrete to form insoluble calcium chloroaluminates and calcium chloroferrites in which the chloride is bound in non-active form; however, the reaction is never complete and some active soluble chloride always remains in equilibrium in the aqueous phase in the concrete. It is this chloride in solution that is free to promote corrosion of the steel. At low levels of chloride in the aqueous phase, the rate of corrosion is very small, but higher concentration increases the risks of corrosion. Thus the amount of chloride in the concrete and, in turn, the amount of free chloride in the aqueous phase (which is partly a function of cement content and also of the cement type) will influence the risk of corrosion. While the concrete remains in an uncarbonated state the level of free chloride in the aqueous phase remains low (perhaps 10% of the total Cl). However, the influence of severe carbonation is to break down the hydrated cement phases and, in the case of chloroaluminates, the effect is to release chloride. Thus more free chloride is available in carbonated concrete than in uncarbonated materials.

The properties of the concrete (controlled by water/cement ratio, cement content, aggregate grading and degree of compaction) have two influences on the effect of chloride in stimulating the corrosion of reinforcement. As the cement content of the concrete increases (for a fixed amount of chloride in the concrete), more chloride reacts to form solid phases, so reducing the amount in solution (and the risk of corrosion), and as the physical properties improve, the extent of carbonation declines, so preventing further liberation of chloride from the solid phase.

When corrosion is a hazard

The great majority of reinforced concrete structures are built to guidelines given in British Standard Codes of Practice and are in situations where they given very long maintenance-free lives. There are, however, certain circumstances in which the concrete cannot be expected to give the desired, almost indefinite, protection to the steel reinforcement. These circumstances are:

- (a) Where, because of error of construction, the full thickness of concrete cover was not given to the reinforcement.
- (b) Where the concrete contains damaging amounts of chloride, either present in high concentration in the materials from which the concrete is made or added deliberately to accelerate setting.
- (c) Where the concrete is exposed to sea water, to de-icing salts or to acid.

In these circumstances it is very desirable to know whether or not the steel may be corroding.

METHODS OF DETECTING AND MONITORING CORROSION

General

Detection methods reveal whether corrosion is taking place, but not the rate of corrosion or how much has already occurred. Monitoring methods tell either the rate of corrosion or the total amount of corrosion that has already taken place.

Method A – Detection by electrode potential

The electrode potential of steel in concrete is an indicator of corrosion activity; the value reveals whether the steel is in a thermodynamically active or passive state.

The half-cell shown is that usually used as a reference electrode, i.e. the saturated copper/copper sulphate electrode (CSE). The following values of potential of reinforcement are generally accepted as revealing the active and passive conditions

<i>CSE potential : volts</i>	<i>Condition</i>
0.20	Passive
0.20 to 0.35	Active or passive
0.35	Active

This method can be applied to existing structures provided that electrical connection can be made to the reinforcement.

Method B – Detection by the constant anodic current polarisation method

The corrosive or inhibitive character of alkaline media such as concrete can be predicted by anodic polarisation measurements. This involves the application to the reinforcement of a small fixed anodic (oxidising) current in the range 5-20 $\mu\text{A cm}^{-2}$ and observing how the electrode potential of the steel changes with time. If the concrete environment is inhibitive the passive film formed on the steel will be stable and, on application of the constant anodic current, the electrode potential will rise to a steady value in the region of 0.6 V SCE (standard calomel electrode), representing the evolution of oxygen from the passivated steel surface. If the concrete environment is corrosive to steel the passive film will be unstable; rusting can occur and the potential will not attain the oxygen-evolution value of 0.6 V SCE.

This method is used in laboratory tests on the corrosion of steel in concrete. It could be adapted for use on structures, in which case electrical connection to the reinforcement or to probes would be required.

Method C – Monitoring by the electrical resistance probe

In this method the loss of section of a probe by corrosion is determined by measuring its electrical resistance. The resistance of the probe is given by:

$$R = \frac{\rho l}{A} = \frac{\rho l}{w} \left(\frac{1}{t} \right) = \frac{K}{t}$$

where R denotes the resistance of the specimen
 ρ denotes the resistivity of the specimen
 l denotes the length of the specimen
 w denotes the width of the specimen
 A denotes the cross-sectional area of the specimen
 t denotes the thickness of the specimen
 K is a constant.

In order to use this phenomenon to measure corrosion rates two conditions must be satisfied:

1. The probe must be made from the same metal or alloy as the reinforcement and must be sufficiently thin for corrosion to cause a significant loss of metal thickness in a convenient time interval.
2. Compensation for the variation of resistance with temperature is essential because resistance changes resulting from changes in temperature can swamp those caused by loss of section through corrosion. This compensation can be achieved by incorporating in the resistance probe a reference element, which experiences the same temperature variation as the test element and is protected from corrosion by a suitable coating.

The reference and test elements of the probe are incorporated as two arms of an AC bridge network, which enables the resistance ratio of the reference and test elements of the probe to be measured. Schematic diagrams of the probe and electrical circuit are shown in.

$$\frac{R_T}{R_R} = \frac{K_T / t_T}{K_R / t_R} = \frac{K}{t_T}$$

where R_T denotes the resistance of the test element
 R_R denotes the resistance of the reference element
 t_T denotes the thickness of the test element
 t_R denotes the thickness of the reference element
 K, K_T, K_R are constants.

The main advantages of this method are that measurements can be made continuously and at a position remote from the probe location, and that the measurements are not affected by the conductivity of the concrete. Each reading shows the total corrosion to date; rates of corrosion can be readily calculated.

Method D – Monitoring by the polarisation resistance probe

In this method instantaneous corrosion rates are determined from measurements of small currents and potentials between two probe electrodes made of the same metal as the reinforcement and set in the concrete or between two pieces of isolated reinforcement. The results take into account all the corrosion processes that are taking place.

In electrochemical terms the method gives a semi-logarithmic plot of potential versus log. current for any polarisation that is linear. The polarisation resistance relates the slope of the polarisation curve in the vicinity of the corrosion potential to the corrosion current by the following equation:

$$\left(\frac{\Delta E}{\Delta i} \right)_{\Delta E \rightarrow 0} = \frac{b_a b_c}{2.3 i_{\text{corr}} (b_a + b_c)}$$

where b_a denotes the Tafel slope of the anodic reaction
 b_c denotes the Tafel slope of the cathodic reaction
 i_{corr} denotes the corrosion current
 $\left(\frac{\Delta E}{\Delta i} \right)_{\Delta E \rightarrow 0}$ is the polarisation resistance.

In order to measure precise corrosion rates it is necessary to know the values of the Tafel slopes b_a and b_c , but it has been shown that an estimate of the corrosion rate within a factor of two can be obtained even if the Tafel slopes are not known. The above equation is valid provided that E lies in the range 5-20 mV. Experimentally the simplest circuit for measuring polarisation resistance involves a two-electrode probe.

A limitation of this method is that it can be applied only in a conducting medium (maximum resistivity 10^5 ohm cm). Somewhat higher resistivities can be tolerated if a three-electrode probe is used. This can be a problem in concrete that has dried out to a very low moisture content, because dry concrete has a high resistivity.

Monitoring by AC impedance measurement

This method is being developed in the laboratory. It shows promise for use on steel in concrete and has the advantage that it is independent of the resistivity of the concrete.

Application to *in situ* measurement

All four methods can be applied *in situ*, but methods B and C require wired probes to be cast in suitable positions in the concrete. This is preferable also for method D. Method A can be applied to existing structures provided that electrical connection can be made to the reinforcement.

For future designs of structures that may be at hazard (for reasons given under the heading “When corrosion is a hazard”), full consideration should be given to casting-in suitably wired

probes on which measurements can be made. Owners of existing structures should consider using method A to find out if corrosion is occurring.

PROTECTION OF REINFORCEMENT AND REPAIR

Designers of structures that may be at hazard are urged to consider protecting the reinforcement or using a corrosion-resistant reinforcement, such as austenitic stainless steel.