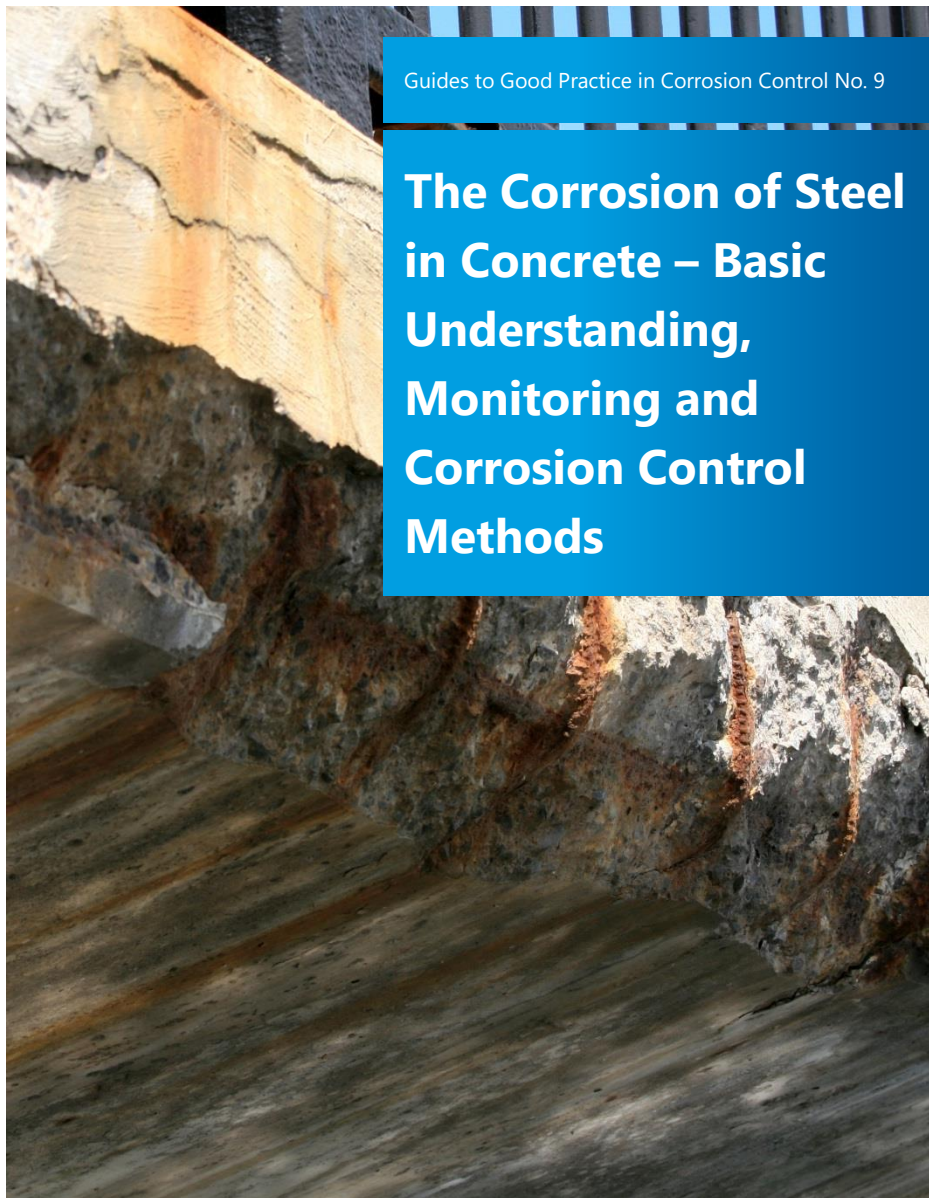


Guides to Good Practice in Corrosion Control No. 9

The Corrosion of Steel in Concrete – Basic Understanding, Monitoring and Corrosion Control Methods





For more information on corrosion research
and testing contact Gareth.hinds@npl.co.uk
Or visit our website:
www.npl.co.uk/electrochemistry

This is a 2018 update of a DTI publication first issued in 1981. This new version has been prepared by John P Broomfield, FICorr FNACE FIMMM FCS, on behalf of NPL.

Although every effort is made to ensure that the information contained in this document is accurate and up to date, NPL does not make any representations or warranties, whether express, implied by law or by statute, as to its accuracy, completeness or reliability. NPL excludes all liabilities arising from the use of this brochure to the fullest extent permissible by law. NPL reserves the right at any time to make changes to the material, or discontinue the brochure, without notice. The NPL name and logo are owned by NPL Management Limited. Any use of any logos must be authorised in writing.

This content and design is protected by copyright. Written permission must be obtained from NPL before copying, reproducing and distributing any its parts

© NPL Management Limited, 2020

This page was intentionally left blank

Contents

1. Introduction	1
2. Why Steel in Used Concrete?.....	1
3. Concrete as an Environment for Steel	2
3.1 The role of alkalinity.....	2
3.2 Loss of alkalinity by carbonation	2
3.3 Effect of chloride in the concrete.....	3
3.4 Cracks in Concrete	4
3.5 When corrosion is a hazard	4
4. Methods for Detecting and Monitoring Corrosion	5
4.1 General	5
4.2 Method A – Detection by electrode potential	5
4.3 Method B – Monitoring by the electrical resistance probe.....	5
4.4 Method C – The polarisation resistance probe	7
5. Monitoring Structures.....	8
6. Protection of Reinforcement and Repair	8
6.1 Design codes.....	8
7. Post Tensioned Structures	10
8. Further Reading	10
9. References	11
10. Bibliography	12

1. Introduction

This Guide describes:

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

2. Why Steel in Used Concrete?

Mankind uses more concrete than any other material other than water. Concrete is a complex construction material 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. Other cementitious materials may be partially substituted for the Portland cement such as pulverised fuel ash, ground granulated blast furnace slag or silica fume. These tend to reduce the porosity of the concrete. Other additives such as water reducers and plasticisers can be added to change the properties when fluid to improve compaction. This mixture can then be moulded into any required shape while still fluid. The water and cement react chemically, forming a “glue” or “gel” 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.

Many 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 fibres such as glass fibres or polymer filaments.

Steel can be used for such reinforcement in one of two ways. The most common method is to incorporate a system or cage of steel bars or a steel mesh directly into 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 this composite material is known as “reinforced concrete”. An alternative method is known as prestressing. This can be done in two ways. Either steel bars, rods or cables are stressed and the concrete is poured around the, known as pre-tensioning, or after the concrete is cast, cables, rods or bars are introduced into or around the concrete and tensioned up. This is post tensioning. Prestressing can allow longer spans, slimmer members and higher loads on a structure than conventional reinforcement.

3. Concrete as an Environment for Steel

Many things can attack concrete either physically such as wear, erosion or impact or chemically such as acids to remove the protective concrete around embedded steel. However, despite the fact that concrete is porous and can have high levels of moisture in it, it usually offers a high level of protection to steel embedded in it.

3.1 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 or more. This means that the steel is protected from corrosion in the absence of damage to the concrete cover to the steel or aggressive chemicals. 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, tensile forces occur and 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.

There are a number of substances or environments that will damage the concrete cover exposing the steel such as impact, wear, erosion, and acid attack. There are also internal chemical reactions that can damage concrete with the wrong constituents. However, there are two substances that can penetrate concrete cover to the steel without damaging the concrete but will then attack the steel.

3.2 Loss of alkalinity by carbonation

The primary cause of loss of alkalinity in concrete is atmospheric carbon dioxide (CO₂). Other acid gasses will attack the cement paste in concrete at the surface but CO₂ is unique in its ability to react with the cement without damaging it but changing the environment around the steel making it susceptible to corrosion.

Concrete is permeable and allows the slow ingress of the atmosphere; the CO₂ reacts 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 carbonation 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 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 types and content, water/cement ratio, aggregate grading, degree of compaction, and adequacy of curing.

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.

3.3 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. If chlorides are cast into concrete (by contaminated constituents such as unwashed marine aggregates, or, historically as set accelerators), if the concrete cover remains in a relatively 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 concrete so corrosion can occur once the carbonation starts to increase.

However, the major source of chlorides is from external ingress. In the UK this is principally from marine exposure or from de-icing salt ingress on or around highways or walkways.

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 the reservoir of hydroxyl ions increases so there must be a higher proportion of chloride to exceed the corrosion threshold. Also, as the

physical properties improve, the extent of carbonation declines, the rate of external chloride ingress declines, delaying the onset of corrosion.

3.4 Cracks in Concrete

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 as 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.

A discussion of cracking in reinforced concrete and its impact on durability is given in Concrete Society Technical Report 44¹.

3.5 When corrosion is a hazard

The great majority of reinforced concrete structures are built to guidelines given in British and International Standard Codes of Practice and are in situations where they given very long maintenance-free lives. However, the latest codes are comparatively new so many structures constructed in the mid to late 20th century were not built to high enough performance standards for their environments. Additionally, there are 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 or details reduce the cover or the compaction of concrete around the steel
- b) Where the concrete contains damaging amounts of chloride, either present in high concentration in the materials from which the concrete is made or historically added deliberately to accelerate setting
- c) Where the structure has reached its original design life for its environment and especially if the concrete is exposed to sea water, to de-icing salts or to acid

As stated previously, the expansive corrosion product usually leads to cracking delamination and ultimately spalling of the concrete cover to the steel. This can be hazardous if unchecked.

However, if a structure is under a suitable maintenance regime this provides early warning long before loss of steel section becomes a structural issue. However, there are circumstances where the corrosion product stays in solution and precipitates away from the steel/concrete interface, leading to loss of steel section without any observable signs at the surface. This usually occurs when the concrete is saturated locally so there is insufficient oxygen to form solid rust products. This can happen under poorly detailed or damaged waterproofing membranes and has also been seen where impermeable jackets are used to repair concrete columns in marine conditions.

4. Methods for Detecting and Monitoring Corrosion

4.1 General

There is a range of methods for detecting corrosion or of determining whether conditions are likely to be causing corrosion. Portable, battery operated instruments are available and some can be attached to permanently installed probes to monitor conditions long term.

4.2 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. An electrical connection is made to the steel and, using a voltmeter, the electrode potential of the steel is measured with respect to a suitable reference electrode (half-cell) in wet contact with the concrete. The details of applying this technique are given in ASTM C876 and Concrete Society technical report 54². This standard is based on measurement of the electrode potential using the saturated copper/ copper sulphate electrode (CSE) and the following values of potential of reinforcement are generally accepted as revealing the active and passive conditions:

CSE potential: volts	Condition
0.20	Passive
0.20 to 0.35	Active or passive
0.35	Active

However, the saturated copper/copper sulphate electrode is now not recommended for concrete; the silver/silver chloride/potassium chloride electrode is preferred.

4.3 Method B – 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

This is a monitoring technique rather than a portable detection technique. 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. However, the probe is most effective when cast directly into the concrete during construction. Retrofitting resistance probes in concrete puts them into a cementitious grout that is a very different environment from the reinforcement. See NACE Report 05107³.

4.4 Method C – 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:

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

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. Practical application and devices are described in Concrete Society Technical Report 54⁴.

5. Monitoring Structures

There are two aspects to corrosion monitoring of reinforced concrete structures. The first is inspection and testing of an existing structure to determine whether there is deterioration; carried out with portable equipment and requiring contact with the surface. The second is the installation of permanent probes either during construction or after the identification of problems that require long term monitoring.

In the UK there is a significant number of test houses with the UK Accreditation Service (UKAS) who can carry out condition surveys on reinforced concrete structures using British and international standard methods to quantify damage, defects and corrosion condition. Methods and their application are discussed in Concrete Society Technical Reports 54⁴ and 60².

There is a comprehensive review of permanent corrosion monitoring systems for reinforced concrete structures in CIRIA report C661⁵.

6. Protection of Reinforcement and Repair

6.1 Design codes

The international design code, BS EN 206⁶ categorises environments and provides methods of determining suitable mix designs and minimum concrete cover depth over the steel to achieve required lives. Table of mix designs and cover depths to achieve given design lives for different exposure conditions are provided in BS 8500⁷. These cover most environments and durability requirements encountered in the UK and the resto of Europe.

The current design codes for reinforced concrete^{6,7,8} provide adequate corrosion control to new structures if correctly applied. However, errors in construction or in understanding the severity of the exposure conditions and microclimates around the structure can lead to problems. The codes deal with the mix designs and minimum cover to steel required to achieve a given design life. There is passing reference to other corrosion control methods such as the use of stainless steel reinforcement or impressed current cathodic protection.

Austenitic stainless steel such as A316 (UNS S31600) have been shown to be very successful in resisting corrosion in concrete but the initial cost limits their application despite their reduced life cycle cost over the full life of a structure. Highways England recommends their use in parts of structures with very severe exposure and long design life. Other corrosion resistant reinforcement is also available. The most widely used is fusion bonded epoxy coated reinforcement. This is widely used in North American bridge decks exposed to de-icing salts where waterproofing membranes are not applied from new. However its use and availability elsewhere is limited. Other than galvanized reinforcement⁹, which has limited use in Europe and North America, most other corrosion resistant rebars are either still experimental or in the

early stages of demonstration projects. Further alternatives include the use of fibres, usually polymer, glass or steel. These are popular in flooring where they reduce the risk of cracking.

The Saudi Basic Industries Corporation (SABIC) frequently applies impressed current cathodic protection (ICCP) to new reinforced concrete structures and plant in severe chloride exposure. The combination of high temperatures, high chloride deposition rates and high risk of chloride contamination of the concrete and the steel surfaces means that they consider this a cost effective corrosion control measure. It is also used elsewhere in the Arabian Gulf region but is rarely used outside this region.

The main problems of reinforcement corrosion are with older structures that have either exceeded their design life or were inadequately designed and constructed for their environment. There is a series of concrete repair standards, BS EN 1504 parts 1 to 10 that cover conventional concrete repair materials such as mortars, coatings, sealers etc. Part 9 provides a methodology for ensuring that all options are considered for repairing structures depending on the cause of deterioration which includes a range of problems as well as reinforcement corrosion and Part 10 gives guidance for site activities for conventional repair.

Impressed current cathodic protection (ICCP) is now widely used once corrosion damage is discovered, especially in high chloride environments. The international standard BS EN ISO 12696¹⁰ covers both impressed current and galvanic cathodic protection applied to atmospherically exposed, buried and immersed reinforced concrete. This standard is extensively used especially in Europe along with the certification of designers and installation technicians according to BS EN ISO 15257 which has a specific certification for steel in concrete. In North America NACE SP0290¹¹ covers cathodic protection of atmospherically exposed reinforced concrete. NACE also has its own training and certification system, but no separate certification for steel in concrete. A separate NACE standard covers buried and submerged applications¹². Further electrochemical techniques such as electrochemical chloride removal and electrochemical realkalization are also covered by European and North American standards^{13,14,15}.

Galvanic anodes are widely used as additional corrosion protection at patch repairs. When corrosion occurs at anodic sites on the reinforcement, it induces cathodes around the site, effectively cathodically protecting the adjacent area. If a patch repair is carried out at the anodic corrosion site, it can then become the cathode and, especially if chloride contamination is widespread in the concrete cover, new anodes are created around the patch. This “incipient” or “ring” anode problem is a major cause for the development of cathodic protection for steel in concrete. By inserting zinc based anodes into the repair, the incipient anode problem can be mitigated, extending the life of the patch repair.

7. Post Tensioned Structures

As stated previously, the alternative to conventional reinforcement is using high tensile steel which is pre- or post-tensioned. Pre-tensioned bars or strands are usually cast directly into concrete under tension and can be treated like conventional reinforcement except that there is a potential risk of catastrophic failure due to pitting corrosion combined with, fatigue and possibly hydrogen induced embrittlement.

For post-tensioned structures, the cables are in ducts which may contain grease or cementitious grout. Problems have occurred with the sealing of the ducts and the performance of the grout. Corrosion has occurred at anchorages due to ingress of chlorides or atmospheric CO₂ and water and there have been problems of chloride contaminated grouts and bleed water from the setting grout accumulating in anchorages.

The use of impressed current cathodic protection on prestressed structures is problematic due to the potential risk of hydrogen evolution on the steel and some high tensile steel being susceptible to hydrogen embrittlement. Galvanic anodes are less likely to generate hydrogen.

The enclosure of the strands in ducts also makes corrosion detection difficult. However, since many problems are at the anchorages, close inspection of this area often shows whether there is a problem or not. The inspection of prestressed structures requires close cooperation between structural and corrosion engineers familiar with the problems and the particular structure.

8. Further Reading

The bibliography contains publications providing overviews and reviews of the principles of corrosion of steel in concrete as well as techniques for investigation and treatment of reinforcement corrosion problems. A series of Technical Notes covering many aspects can be downloaded from the www.corrosionprevention.org.uk website. The UK Concrete Society, NACE International and ACI International provide guidance documents and standard practice documents on concrete repair, inspection and corrosion control.

9. References

¹ The relevance of cracking in concrete to corrosion of reinforcement - 2nd Edition TR44 Concrete Society, Camberley, Surrey

² Electrochemical tests for reinforcement corrosion TR60 Concrete Society, Camberley, Surrey

³ NACE Report 05107 Report on Corrosion Probes in soil & concrete, NACE International Houston Texas.

⁴ Diagnosis of deterioration in concrete structures TR54 Concrete Society, Camberley, Surrey

⁵ Intelligent monitoring of concrete structures Report C661, CIRIA, London

⁶ BS EN 206-1 Concrete – Part 1: Specification, performance, production and conformity, British Standards Institute, London

⁷ BS 8500-1 Concrete – Complementary British Standard to BS EN 206. Part 1 Method of specifying and guidance for the specifier

⁸ Eurocode 2: Design of Concrete Structures – General Rules and rules for Buildings BS EN 1992-1-1, British Standards Institute, London

⁹ Galvanized steel reinforcement in concrete” Ed. S.R. Yeomans, Publ. Elsevier 2004

¹⁰ BS EN ISO 12696 Cathodic protection of steel in concrete , British Standards Institute, London

¹¹ NACE SP 0290 Cathodic protection of atmospherically exposed

¹² NACE SP0408-2014, Cathodic Protection of Reinforcing Steel in Buried or Submerged Concrete Structures

¹³ SP0107-2007, Electrochemical Realkalization and Chloride Extraction for Reinforced Concrete NACE International Houston Texas

¹⁴ BS EN 14038-1 Electrochemical realkalization and chloride extraction treatments for reinforced concrete. Part 1 Realkalization , British Standards Institute, London

¹⁵ BS EN TS 14038-2 Electrochemical realkalization and chloride extraction treatments for reinforced concrete. Part 2 Electrochemical Chloride Extraction , British Standards Institute, London

10. Bibliography

ACI 222R-01: Protection of Metals in Concrete Against Corrosion (Reapproved 2010) ACI International

BRE Digest 444 Parts 1 to 3 Corrosion of steel in concrete, Building Research Establishment, Watford (2000)

Broomfield, J.P. Corrosion of steel in concrete, understanding, investigation and repair, 2nd Edition Publ. Taylor and Francis, London (2007)

Chess, P.M. & Broomfield, J.P. Cathodic Protection of Steel in Concrete and Masonry 2nd Edition, Ed, CRC Press (2014).

Concrete Society Technical Report 54 Diagnosis of deterioration in concrete structures. Concrete Society, Bracknell UK. (2000).

Concrete Society Technical Report 69 Repair of concrete structures with reference to BS EN 1504, Concrete Society, Bracknell (2009)

Contact NPL

The National Physical Laboratory

The National Physical Laboratory (NPL) is the UK's National Measurement Institute. The heart of our mission is to deliver science with impact by disseminating research and measurement best practice for economic and social benefit.

National Physical Laboratory
Hampton Road
Teddington
Middlesex
TW11 0LW

Switchboard **020 8977 3222**

www.npl.co.uk/contact

Keep in touch with us

Follow NPL on Twitter:

www.twitter.com/npl

Become a Facebook fan:

www.facebook.com/npldigital

Subscribe on YouTube:

www.youtube.com/npldigital

Follow NPL on LinkedIn:

www.linkedin.com/company/national-physical-laboratory