

ELECTROCHEMICAL REPAIR AND PROTECTION OF CONCRETE STRUCTURES

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ABSTRACT

Reinforced concrete has been used in structures since the beginning of the 19th century. Throughout the world, a major part of the infrastructure consists of reinforced concrete. The compressive strength of the concrete combined with the tensile strength of the steel makes the reinforced concrete efficient. Corrosion, however, reduces the cross section of the reinforcement bars and the load bearing capacity of steel, but it does not occur when the pH value of the surrounding environment is greater than 12.0. In general, the pH value of concrete is approximately 12.5 or greater and, for this reason, steel embedded in concrete does not corrode. The pH value of concrete changes over time due to carbonation and this allows for corrosion to occur. Moreover, the presence of chlorides at the reinforcement level causes corrosion even in non-carbonated concrete. Chloride induced corrosion may take place in the form of either pitting corrosion and/or non-expansive corrosion. These forms of corrosion reduce the load bearing capacity of steel rapidly and, thus, the structural element does not necessarily show signs of prior warning such as spalling of the cover concrete. Corrosion is the conversion from iron (or steel) to iron oxide (or rust). It is an electrochemical process and the best protection and rehabilitation measures for corroded reinforcement or concrete in aggressive environments are also electrochemical in nature. In a significant number of structures in the U.K., corrosion of reinforced concrete structures has occurred due to a combination of chloride contamination and poor workmanship. However, the budget allocated to repair and maintenance is limited. For this reason risk based methods of assessment have been used to determine the latest possible date of repair, particularly when this concerns a large number of structures. This paper analyses how repair can be prioritised and discusses the application of various forms of electrochemical protection measures that can be applied to structures to extend their service life. Electrochemical methods actively hinder the occurrence of corrosion and may, thus, extend the service life for a longer period of time when compared to a conventional repair. The advantages and disadvantages of these methods are also discussed in detail.

Introduction

Glass and Buenfeld (1995) claim that in the U.K. as much money is spent on rehabilitation of damage caused by corrosion as on the construction of new structures. Corrosion may cause severe damage to structures due to the reduction of the load bearing cross section of steel. In prestressed concrete the problem is intensified because hydrogen is generated during corrosion causing brittle fracture of the steel and leading to sudden failure of the structures. In the United Kingdom two cases of bridge collapse due to corrosion have been reported (Woodward, 1989 and Wouters et al, 1999). Chloride induced corrosion is one of the main causes of deterioration. Initially steel in concrete is passivated due to a protective,

non-soluble oxide film. After the passivation breaks down (depassivation), corrosion occurs. The *passivation* of steel in concrete is result of its high alkalinity (pH-value ≥ 12.5) due to calcium hydroxide and traces of sodium and potassium hydroxide in the concrete pore solution (Breit, 1997) increase the pH-value of the concrete pore solution to 14 (Andrade et al, 1995a). Iron forms an insoluble iron oxide film in this environment and further corrosion is thus prevented.

Depassivation theories comprise adsorption-induced pitting, ion penetration/migration pitting and mechanical film breakdown pitting. The second theory is the most applicable to chloride induced corrosion. It suggests that adsorbed chloride ions penetrate the passive film at the breakdown potential and form a chloride contaminated oxide, which allows rapid local dissolution of the underlying metal (Martin and Olek, 1996). Chloride acts as a reaction catalyst to a soluble iron salt that reacts with water to iron hydroxide and free chloride ions. These chloride ions can react with other iron ions and the process takes place in alkaline environments. Therefore, the rate of chloride induced corrosion is self-accelerating (Gofii and Andrade, 1990) and the passivation of steel is destroyed even at pH-values greater than 12.5 (Glass and Buenfeld, 1995).

Raupach (1996) categorises corrosion of reinforcement into three types: General corrosion in carbonated concrete with a high weight loss compared to pitting corrosion. However, its effects are less severe because the cross section of the steel is not reduced significantly at early stages. Chloride induced macro-cell corrosion occurs with the formation of pits. The anodic and cathodic sites on the steel can be located at a distance of more than one metre (Figure 1).

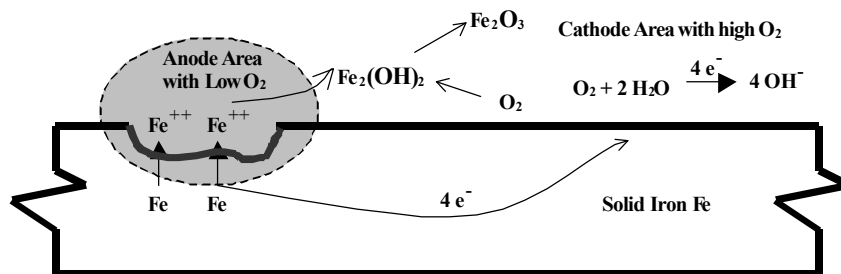


Figure 1 Chloride induced Macro Cell Corrosion

Micro-cell corrosion occurs where the anode and cathode are located in close proximity i.e. in crack tips. This type of corrosion is also called anodic dissolution and may lead to stress corrosion cracking. Unless corrosion is in an advanced state and cracking and spalling of the concrete cover has already occurred, it cannot be detected by visual inspection. Non-destructive inspection techniques have been developed to detect corrosion at an early stage.

Electrochemical Assessment of Condition

Corrosion is an electrochemical process and its presence can be detected at an early stage through non-destructive techniques (NDT) which are also electrochemical in nature. The oldest and most established electrochemical method is the halfcell potential measurement. There are different types of halfcell but most commonly the copper/copper sulphate (CSE) electrode is used. A copper rod of pure copper is placed in a saturated copper sulphate solution. At one end an

electrical connection is made to a potentiometer at the other end a membrane is attached to the chamber. This membrane is placed on top of the concrete to be investigated. The reinforcement of the concrete is connected to the potentiometer forming, thus, an electrical circuit. The electrode potential that is measured between the halfcell and the reinforcement can be used to determine the probability of corrosion. When the potential is less negative than $-350 \text{ mV}_{\text{CSE}}$ the probability of corrosion is greater than 90%.

The probability of corrosion is given by the potential, but this does not give any information about the intensity of corrosion i.e. the amount of iron that goes into solution. The intensity of corrosion (corrosion rate) obeys Faraday's law and can be characterised by the current between anode and cathode. Corrosion rates are considered to be significant when they exceed values between 1 and 2 mA/m^2 (Glass and Buenfeld, 1997). Hassanein et al (1999a) found current readings to be a better method of assessing the corrosion-state of reinforcement compared to potential readings because readings were established in a short period of time for the passive state compared to half-cell potential readings. Electrical current is transported through ions in the concrete pore water. Hence, the resistivity is a measure of the continuity of the pore solution through which chlorides migrate. For this reason Andrade (1993) and Bamforth (1999) use the resistivity of concrete as an indication of its chloride permeability. Dry concrete acts as an electrical insulator and the resistivity of oven-dry concrete is approximately $10^9 \Omega\text{m}$. Moist concrete in contrast is a good conductor with a resistivity of approximately $50 \Omega\text{m}$ (Buenfeld and Newman, 1987). Moreover, resistivity measurements of concrete were found to be less intrusive than the rapid chloride permeability test (Feldman et al, 1994 and 1999). It has also been suggested to use the conductivity of concrete, the reciprocal of resistivity, for measurements on chloride permeability (Xingying, 1997). Millard (1991) and Polder (2001) propose a non-destructive method for measuring concrete resistivity based on the Wenner-four-probe.

The method of linear polarisation resistance is based on the application of a direct potential shift of $\pm 10\text{mV}$ to $\pm 20\text{mV}$ about the rest potential (halfcell potential). A graph of the current required to cause this potential is plotted against the potential and from this the current at the rest potential is obtained. This current is also known as corrosion potential (I_{CORR}). This device can also be used to establish the halfcell potential and the concrete resistivity. Variations of this method are found when instead of the potential the current is shifted.

Use of Electrochemical Data for Maintenance Strategies

Owners of sets of reinforced concrete structures such as governments and local authorities have realised over the past two decades that a major part of their structures suffer deterioration problems. Very often the budget allocated for maintenance and repair of these structures would be overstretched if every structure suffering signs of deterioration would be repaired immediately and sometimes detailed and destructive analysis of structures is not possible because there are simply too many faulty structures.

In these cases it is possible to use electrochemical NDT tests that are calibrated against data from destructive tests to predict the present condition of a structure and to determine a possible future intervention date. For this reason, it is important that not only structural constraints are taken into consideration, but also related parameters such as traffic load. These can be summarised in key performance

indicators and may help to prioritise repair for budget reasons without encroaching safety.

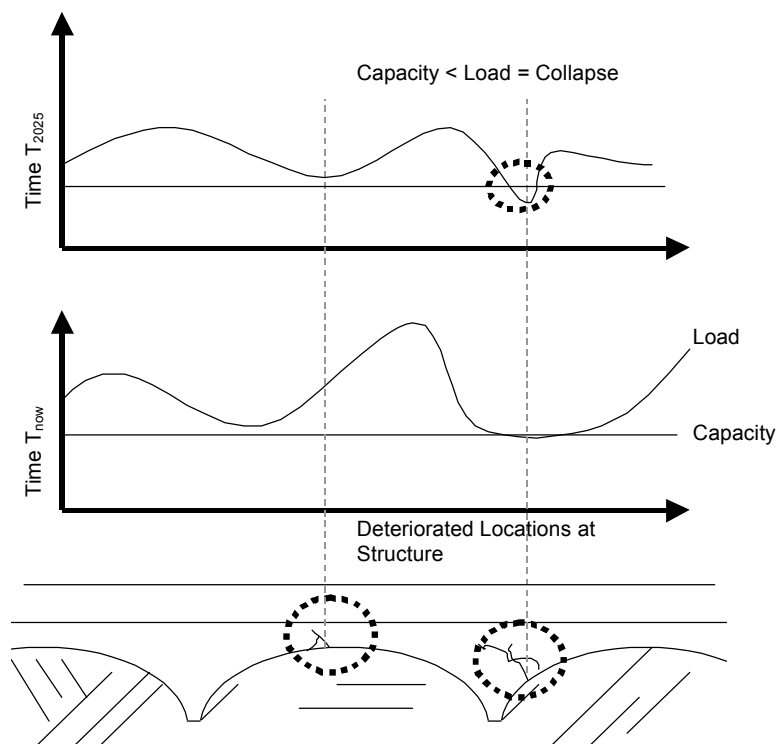


Figure 2 Structural Assessment comparing load to load capacity due to deterioration and prediction of intervention date

Figure 2 shows the output of a structural assessment (Risk Based Analysis) where the capacity is evaluated at certain intervals along the structure dependent on the (corroded) state of the reinforcement. This state is obtained from a series of electrochemical NDT tests such as halfcell potential readings and cover meter surveys from which the corrosion rate and subsequent loss of reinforcement over time is calculated. A series of destructive tests were conducted in order to derive this model and therefore its drawback is that it is only valid for structures on which it was calibrated. Latest developments in NDT techniques such as the LPR combined semi destructive tests could facilitate the expansion of the Risk Based Strategy to other structures. The corrosion rate is thereby be obtained directly and be calibrated against the weight loss of reinforcement taken from representative locations at structures.

Combined with the so-called key performance indicators the Risk Based Strategy can be an ideal tool for the management of bridge structures and will form a new Risk Management Strategy. This tool combines key performance indicators (safety, economical and environmental) with engineering factors to further prioritise repair when it is still in the safe range.

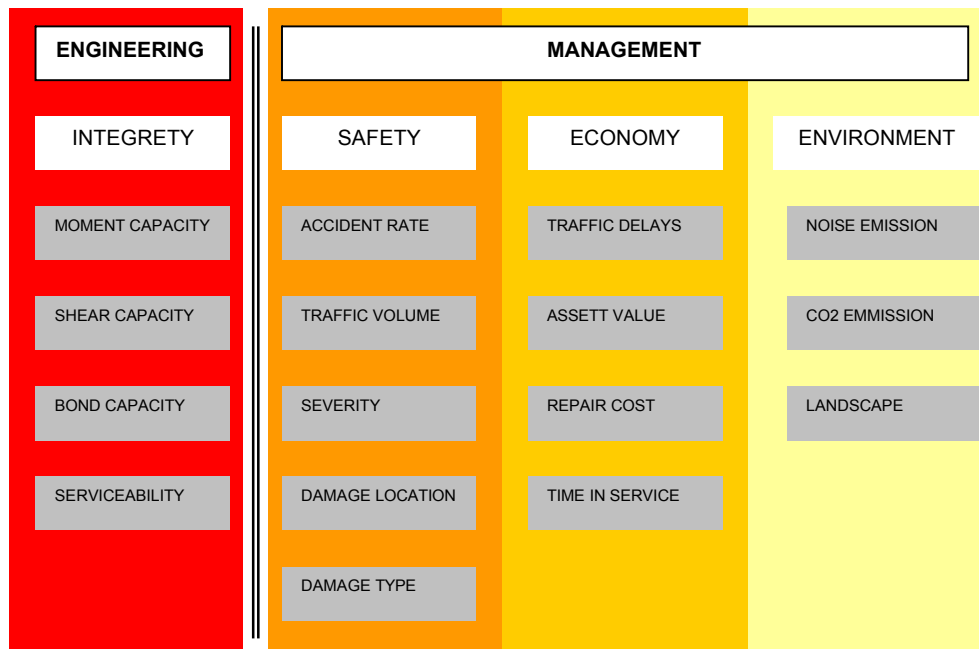


Figure 3 Risk Management Decision Factors that govern the Intervention Value

The concept of this strategy is shown in Figure 3. The final output of this new type of asset management will be the Intervention Value which determines the urgency of maintenance / repair measures. Repair must be carried out when the Intervention Threshold, a value below which the Intervention Value must not drop, is reached. This value must be governed by the engineering factors as these determine the structural integrity.

Electrochemical Repair and Monitoring

Structures suffering from chloride induced corrosion generally have high replacement costs and desired remaining design life so that more expensive long term protection and repair costs are justified. Traditional repair of concrete structures consists of patch repair where the concrete is mechanically removed from the structure and replaced with repair mortar. This form of repair is preferred for carbonated or physically damaged concrete with local damage in the concrete cover. Chloride contamination of a structure is in most cases environment related and exists throughout the lifetime of the structure. Therefore the damage is likely to reoccur. Furthermore, the removal of carbonated and otherwise sound concrete cover is cost, time and labour intensive. Where the concrete cover is still intact, and the aggressive environment permanent, electrochemical rehabilitation methods are the best and cheapest repair solution. Four types of electrochemical treatment may be applied to a structure namely cathodic protection, cathodic prevention, electrochemical chloride extraction and re-alkalisation.

The first application of cathodic protection is dated back to 1824 (Roberge, 2000). When cathodic protection is applied as a rehabilitation measure to corroded reinforcement, the steel surface potential is adjusted to a value where pitting corrosion is stopped (Funahashi and Bushman, 1991). The current density required for cathodic protection in concrete is between 0.010 and 0.020 A/m² of the steel

surface (Tvarusko, 1993). The application of cathodic protection to prestressed concrete structures has been investigated in the past (Wagner et al, 1993; Wagner et al, 1991; Wang et al, 1995), but it is rarely applied because of the inherent danger of hydrogen induced stress corrosion (HISCC). Cathodic prevention is used to prevent the initiation of corrosion of reinforcement in an aggressive environment, but it cannot stop corrosion and has to be used from the start of service life. The potential of the steel is shifted into the potential range where pitting corrosion is not initiated and, thus, lower current densities compared to cathodic protection, usually in the order of $0.001 - 0.002 \text{ A/m}^2$ of steel surface, are required (Bertolini, 2000). Cathodic prevention was first used in Italy in the 1990-ies. Both, cathodic prevention and protection are applied throughout the remaining service life of a structure and have to be controlled and monitored.

A side development of cathodic protection is galvanic repair, where a zinc based material coated with a conductive and porous mortar is placed in patch repaired concrete to avoid the occurrence of incipient anodes. A phenomenon that causes corrosion in previously non-corroding areas due to the shift of electrochemical balance in the concrete

The "hard form of cathodic protection, ECE was first investigated in the early 1970s in the United States by the Federal Highway Administration and later used in the U.S. under the Strategic Highway research program (SHRP) and in Europe by Norcure[®]. Re-alkalisation is the sister technique of electrochemical chloride extraction, but it is applied for much shorter duration (Mietz, 1998). The duration of ECE varies between 4 to 8 weeks. The applied current density is usually in the order of 1 A/m^2 of the concrete surface and the total charge varies between 650 and 2000 Amphrs/ m^2 of concrete surface. Different electrolytes such as water or lime solution are used. The duration of re-alkalisation is in the order of some days with sodium or potassium carbonate electrolyte being used and the total charge varies between 70 and 200 Amphrs/ m^2 (Velivasakis et al, 1998). Between one third and two third of externally penetrated chlorides can be removed during ECE (Stoop and Polder, 1999; Hope et al, 1995) and it reduces in particular the chloride content of the concrete of the immediate surrounding of the steel and corrosion is generally stopped (Broomfield, 1995). Experiences of the Highways Agency showed that it can save up to 50% of the cost compared to conventional repair.

The current density has a significant influence of the success on the treatment because it is the driving force in migration (Castellote et al, 1999). The applied current density also determines side effects (Ihekwaba and Hope, 1996) and 1 A/m^2 of concrete surface have been reported for laboratory studies on ECE. Current densities, based on the area of the concrete surface, are calculated on the assumption that in the treated structure the ratio of the reinforcement area to concrete area is equal to one. However, in most cases the reinforcement to concrete ratio is much less. This leads to unnecessary high current densities and undesired side effects. For some cases, 1 A/m^2 of concrete surface can be equal to 5 A/m^2 of steel surface (Ueda et al, 1995). Therefore, current densities for field applications have been calculated as current per square metre of steel surface and are in the range of 1 to 2 A/m^2 (Buenfeld and Broomfield, 2000).

Moisture is needed for corrosion to occur and lately electrochemical drying of concrete to reduce its moisture content and, thus, the susceptibility to corrode were developed. A pulsating current is passed between an embedded cell (X-cell), the reinforcement and an external anode.

Potential side effects are reduced bond strength (Buenfeld and Broomfield, 2000), altered concrete pore size (Hassanain et al, 1999), hydrogen embrittlement of high strength steel and alkali-silica reaction (Cromie, 1998). The author is also concerned about the applicability of the X-cell as he suspects it may induce anodic dissolution of the reinforcement, which is potentially dangerous.

Summary

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