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Predicting degradation of the anode–concrete interface for impressed current cathodic protection in concrete

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HIGHLIGHTS

- Accelerated tests were done to exam degradation at the anode-concrete interface.
- A power-relation conversion model was proposed to predict the service life of ICCP.
- An acceleration factor was introduced to the power-relation model.
- Degradation of mortar containing GGBS was less than those containing fly ash.

ARTICLE INFO

ABSTRACT

Impressed current cathodic protection and prevention techniques are efficient methods to stop or prevent corrosion in steel reinforced concrete structures. The inevitable side effect of the current exchange is acidification at the anode–concrete interface. Accelerated test methods can be used to investigate the long-term performance of the system. However, a linear relation will not hold between the accelerated and normal conditions because of the influence of the current density. This paper presents results of an accelerated test. A power-relation conversion model is proposed and an acceleration factor is introduced.

1. Introduction

Corrosion of the reinforcement in concrete infrastructures, such as highway bridges and tunnels, is the major cause of unplanned maintenance and costs billions of dollars each year [1]. Impressed current cathodic protection (ICCP) is an efficient method to stop or control corrosion of the steel reinforcement in concrete structures [2], which normally is the subject of repair techniques. Cathodic prevention, which has the same fundamental electrochemical principles as ICCP, is commonly considered as a preventative techniques to prevent or postpone the onset of corrosion and extend significantly the service life of the structure. The principles and applications of cathodic protection (CP) and cathodic prevention (CPre) have been reviewed and studied previously [3–5]. Many studies have been devoted to monitoring and investigating the long-term performance of CP and CPre systems [6–10]. Innovative anode material, such as carbon fiber reinforced polymer (CFRP), has been studies and successfully demonstrated its great potential as anode material for the purpose of corrosion control [11,12]. However, being limited in time and resources, such long-term studies can hardly last more than 15 years, which is not sufficient compared to the desired service life, which is in a range of 50–100 years. Therefore, there is the need to apply accelerated tests to evaluate or predict the performance of ICCP systems for the whole service life.

One of the major reasons that cause an ICCP system to fail is the degradation at the anode–concrete interface due to acid formation in the bond plane, which is associated with calcium leaching [10,13–15]. Previous studies have shed light on the mechanism of degradation in relation to calcium leaching, cement type, and especially the current density [16–19]. Qualitative numerical models have been proposed to describe concrete acidification and the transport of calcium hydroxide under cathodic protection [20,21]. It is well accepted that the formation of acid at the anode is associated to the current density and the total amount of charge

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passage [14,22,23]. Many researchers have reported the physical and mechanical properties of cementitious materials subjected to natural leaching or accelerated leaching [24,25]. It has been observed that the leached cement paste was made up of different zones, which are delimited by different dissolution or precipitation fronts from the sound concrete [26,27]. However, the failure mechanism of an ICCP system and the degradation of the anode–concrete interface due to current exchange have not been fully investigated. Moreover, there is a lack of methods to link accelerated testing to real-life applications.

Therefore, this paper presents the results of an accelerated test and discusses the combined process of chemical reaction and mass transport in the concrete. Finally, a conversion model and an acceleration factor are proposed for estimating the service life of a cathodic prevention system from the results of an accelerated test method.

2. Electrochemical acceleration test method

In an electrochemical cell, such as an ICCP system, chemical reactions occur at both the anode and cathode, and ions are current carriers that are transported through the concrete. Concrete is not only a transport medium, but also actively reacts with these processes: this is because concrete is porous and highly alkaline, so when the pH is decreased, the cement hydrates dissolves and releases hydroxide ions, which is associated with calcium leaching.

From a thermodynamic point of view, if the concentration of the calcium ions decreases, calcium hydroxide ($Ca(OH)_2$) crystals dissolve to replenish the calcium ions to maintain equilibrium. After a complete dissolution of the calcium hydroxide crystals, calcium ions are supplemented by the calcium silicate hydrates (C-S-H) and the C-S-H finally degrades to silica (SiO_2) gel [28]. The equilibrium between $Ca(OH)_2$ and C-S-H and their component ions in the pore solution are described by the following reactions [17]:

$$Ca(OH)_2 \rightleftharpoons Ca^{2+} + 2OH^- \tag{1}$$

$$C - S - H \rightarrow Ca^{2+} + 2OH^- + SiO_2 \tag{2}$$
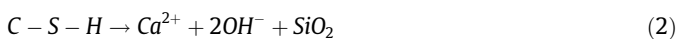
The calcium leaching process will be accelerated if an electric current is applied. Because the calcium leaching is an direct indicator of the chemical reactions and is also associated with the applied current, that the depth of calcium leaching can be used to indicate the anode–concrete interface degradation.

Under alkaline conditions, the chemical reaction occurring at the anode surface is mainly the oxidation of hydroxide ions (OH^-), as given in Reaction (3). As this reaction progresses and the anode–concrete interface loses its basic character, the oxidation of water takes place to produce hydrogen ions (H^+), as given in Reaction (4) [29]. Both reactions consume hydroxide ions and tend to lower the pH at the anode–concrete interface, which can be considered as acid formation at the anode.

Chlorine gas is produced when chloride is present, as shown in Reaction (5a). At a pH of 8 or lower, an equilibrium of chloride acid and hypochlorous acid is also present, as given in Reaction (5b) [30].

$$4OH^- \longrightarrow 2H_2O + O_2 + 4e^- \tag{3}$$

$$2H_2O \longrightarrow O_2 + 4H^+ + 4e^- \tag{4}$$

$$2Cl^- \longrightarrow Cl_2 + 2e^- \tag{5a}$$

$$Cl_2 + H_2O \rightleftharpoons HCl + HClO \tag{5b}$$

The type of anode reaction depends on the electrical potential, the availability of the reactants, and the type of anode material. The reaction rates mainly depend on the current density and the concentrations of the ions.

Under an electrical field, positive ions (Na^+, K^+ and Ca^{2+}) in the concrete pore solution migrate towards the reinforcement steel as the cathode, and negative ions (OH^-, Cl^- if available) migrate towards the anode. The migration flux of ions depends on the concentration of the ions, which can be calculated from the applied current density and the transference number. The transference number is described as the fraction of current carried by a certain type of ion.

The current density has a great influence not only on the chemical reaction rate but also on the transport mechanisms in an ICCP system, because the transport mechanisms make up a coupled process with both migration and diffusion. The overall effect of the migration is that the hydroxide and sodium ions become depleted at the anode and accumulate at the cathode. When the concentration gradient is built up, it will cause these ions to diffuse from elsewhere in the concrete towards the anode, and from the cathode to elsewhere [13]. This means that, for normal ICCP current densities (below 20 mA/m²), the diffusion flux has the same order of magnitude as the migration flux, so that the consumption rate of OH^- at the anode is relatively low and the calcium leaching is also slow [13]. However, for significantly higher current densities, such as for accelerated tests, the contribution of diffusion is smaller and the pH reduction as well as the degradation of the anode–concrete interface caused by calcium leaching is greater.

This type of extra damage brought about by the acceleration method should be noted and quantified when the accelerated test result is converted to a normal ICCP operating condition.

For the purpose of cathodic protection, the current density has to be sufficient to protect the reinforcement, and at the same time as low as possible to mitigate the acidification at the anode–concrete interface. Therefore, because acidification is inevitable, it is important to investigate the long-term performance for CP and CPre systems. Hence, an accelerated method and a conversion model are needed to examine the long-term effects and provide insight that can be used for ICCP design.

3. Experiment

3.1. Materials and specimens

Swedish structural cement CEM I 42.5N-SR3 MH/LA was used in this study as ordinary Portland cement (OPC). Two types of supplementary cementitious materials were also included: an ASTM class F siliceous fly ash (FA), manufactured by Noecem AS (Norway) and ground-granulated blast-furnace slag (GGBS), commercially available as Merit 5000, supplied by Merox (Sweden). The chemical compositions of OPC, FA and GGBS are given in Table 1.

The test specimens were divided into two categories: the paste specimens and the mortar specimens. Table 2 presents the mix proportions and the equivalent CaO content of all groups of specimens. The plain cement pastes were mixed for the paste specimens with a water/cement ratio (w/c) of 0.4, and are denoted by the group name P. For the mortar specimens, the w/c was 0.6 and the cement content was replaced either by 20% (by weight) of fly ash or by 25% (by weight) of slag, being then denoted by the group names M-F and M-G. The content of reactive calcium oxide (CaO) in the fly ash used in the tests was 5%, and 31% in the slag. The equivalent CaO content can be calculated accordingly.

Carbon fiber reinforced polymer (CFRP) mesh anodes were used for all specimens. The CFRP mesh was manufactured by SGL Group and was commercially available as SIGRATEX Grid. Fig. 1 shows the shape and dimensions of the mesh. The mass percentage of polymer was 15%, measured by thermogravimetric analysis (TGA).