

論文

[1203] **An Approach to Durability Design for RC Structures Subjected to Chloride Induced Reinforcement Corrosion**

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1. INTRODUCTION

Premature deterioration on account of chloride induced reinforcement corrosion in marine structures or bridge decks subjected to use of deicing salts has attracted a lot of attention recently. It has been found that durability of concrete structures is related closely with a wide spectrum of areas, such as, design considerations, materials used, workmanship, quality control, environmental conditions, etc. Thus it becomes difficult to develop an overall system to ensure the durability of a structure over its service life. But recently concerted attempts have been made to synthesize the knowledge gained thus far into a comprehensive philosophy for design of structures subjected to deterioration on account of chloride attack, etc. The Japan Society of Civil Engineers, JSCE, [1] and the Japan Concrete Institute, JCI, [2] have published the first draft proposals for "Durability Design".

Though the drafts [1,2] can provide a useful framework in developing methods to study the synergistic effects of diverse factors e.g., the w/c of concrete, type/amount of cement, flexural cracks, site conditions, etc., both the approaches are to a large extent empirical and do not necessarily reflect the mechanism of the corrosion process.

In this paper, a methodology, that rationally incorporates the deterioration mechanism into durability design of corrosion prone structures is discussed. Some results from parts of the research programme involving experimental and analytical work being done to study the effect and relative importance of various factors in the different stages of the deterioration process are also presented.

2. MECHANISM OF CHLORIDE INDUCED REINFORCEMENT CORROSION

It is believed [e.g.3-5] that reinforcing bars are prevented from corroding by the formation of a dense passivating film of gamma iron oxide in the high pH environment of concrete. However, under chloride attack, this film may be disrupted or destroyed, rendering the bars susceptible to

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corrosion. The corrosion process itself is electrochemical in nature involving the conversion of iron to its oxides and hydroxides in the presence of water and oxygen. Since these products are more voluminous than the parent metal, their formation and deposition on the bars, subjects the surrounding concrete to expansive pressures, and it ultimately cracks.

### 3. DURABILITY DESIGN FOR CORROSION PRONE STRUCTURES : A MECHANISM BASED MODEL

Durability design seeks to check that the level of deterioration in members does not exceed a certain level during the service life of the structure. It thus becomes important to not only correctly model the mechanism and determine the critical level of deterioration, but also understand the role of various factors in the different stages of deterioration.

	Model	Keywords	
		I	II
Stage 1		Surf. conc. (Co)	W/C
		Diffusion coeff. (D)	Cement type
Stage 2	General corrosion	Oxygen diffusion	Environment
	Flexural cracks	Width/spacing of cracks	Construction
	Macro-cell	Cathode:Anode ratio	W/C
Stage 2		Corrosion rate	Composition of corrosion products
		Mechanical prop. of corr. products	Creep of concrete

Figure 1 Deterioration model

Bazant [4,5] sought to provide a conceptual framework for durability design of corrosion prone structures based almost purely on theoretical and analytical considerations, including diffusion of chlorides and oxygen, electrochemistry, concrete resistivity, etc. The outline of such a model that reflects the actual mechanism of the deterioration process has been presented in Figure 1. Formation of corrosion induced longitudinal cracks causes not only accelerated deterioration, but also significantly changes the structural behavior of the members [6], and hence this level of deterioration has been taken as the maximum that can be "tolerated" during the service life. Assuming that the stages 1 and 2, take times  $t_0$  and  $t_1$ , respectively, the service life,  $T$ , of the structure should obviously be such that,  $T > t_0 + t_1$ .

The following section provides a broad overview of the work being carried out to be able to estimate these time periods. Some of the results have been discussed in greater detail elsewhere but an attempt has been made here to put them together within the framework described in Figure 1.

## 4. DESCRIPTION OF RESEARCH WORK AND RESULTS OBTAINED SO FAR

### 4.1 STAGE 1 : UPTO INITIATION OF CORROSION

#### (1) Penetration of chlorides

Assuming that the Fick's law of diffusion is valid for chloride penetration in concrete, the nomograms published by Browne [7] clearly indicate

the sensitivity of the time of initiation of corrosion to the diffusion coefficient, D. Experiments are thus directed to study the dependence of D on factors such as the type of cement, w/c, slump of concrete, etc.

This is being accomplished by, (a) studying the changes in the chloride concentration profiles under simulated field conditions [8] over time, and (b) directly estimating the D using modified rapid chloride penetration tests (T-277), diffusion cell type experiments, etc.

The concentration of total chlorides obtained in a slice 13-23mm from the surface under immersion in 3.3% NaCl solution for six months is given in Figure 2 [8]. The results highlight the importance of initial curing as it can be seen that under identical conditions, the concentration at 5 days curing is more than 3 times that after curing the specimens for 28 days. Further the results also indicate that higher slump could actually promote ingress of chloride ions.

The rapid chloride permeability test (AASHTO T-277) [9], offers a useful tool to directly estimate the chloride permeability since it can be carried out easily and quickly. Work is in progress to study the changes in the chloride permeability of the concrete matrix with time depending upon the type of the cement used, etc. The specimens were left in the molds for different lengths of time before being tested. Since the concrete tested was not fully mature, the RCPT test had to be carried out at a lower voltage i.e., 10V against the 60V specified. The results for some of the cases are plotted in Figure 3, showing the Coulombs (at 10V) against the compressive strength observed. It clearly shows that even at similar strength, the chloride permeability could be quite different, depending upon the cement type, with the slag cement providing the most impermeable matrix for a given strength. The data is being further analysed to study the effect of water-cement ratio, etc. and relate it to the hydration mechanism of the binder.

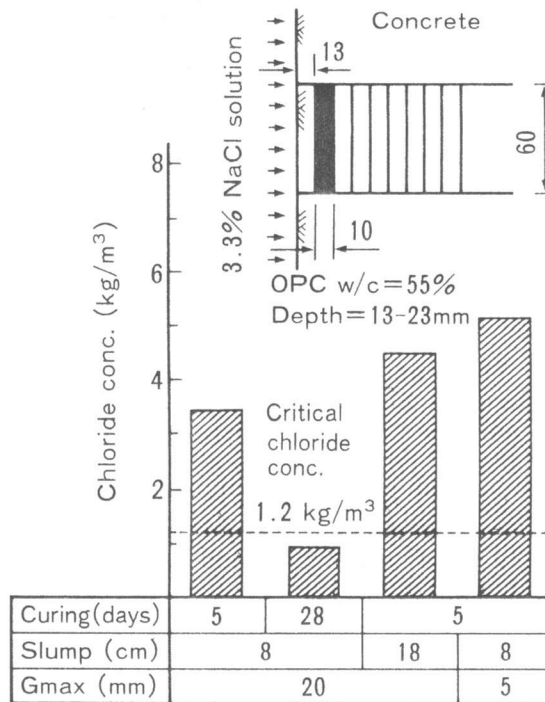


Figure 2 Observed chloride concentration

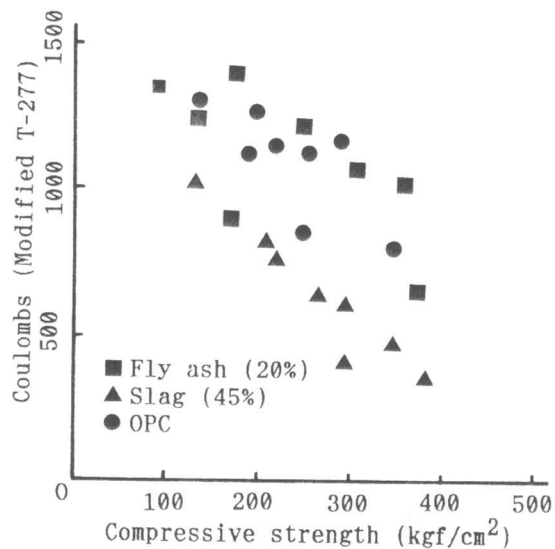


Figure 3 Coulombs (Modified T-277) versus compressive strength

(2) Initiation of corrosion

Experiments were carried out [10] by adding different amounts of chlorides to fresh concrete (0.5-2.1 kgs per m<sup>3</sup> of concrete as NaCl) and studying the extent of corrosion and the proportion of soluble chlorides, to obtain a better understanding of the actual chloride concentration that causes initiation of corrosion for different types of cement.

The results after a one-month exposure to 3.3% NaCl solution showed that even a 0.5Kg/m<sup>3</sup> chloride addition could initiate corrosion, provided oxygen was available relatively freely. Further, results of the finally observed total and soluble chlorides as shown in Figure 4 [10] show that the proportion of the latter depends upon the cement type. In this case a higher proportion of soluble chlorides was observed for slag cements.

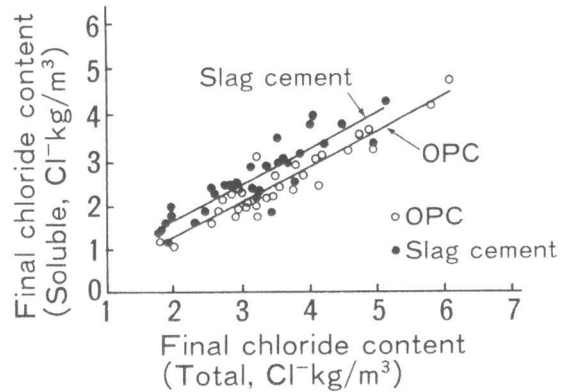


Figure 4 Total and soluble chlorides [Ref.10]

The results cited above suggest that the "critical chloride concentration" cannot be considered in isolation from the extent of oxygen availability and that the proportion of soluble chloride needs to be borne in mind separately from the ability of the cement to provide a dense matrix.

#### 4.2 STAGE 2 : UPTO FORMATION OF LONGITUDINAL CRACKS ON THE CONCRETE SURFACE

Once initiated, the rate of corrosion is a very complex phenomenon and could depend upon several factors as listed in Figure 1. It could be controlled by oxygen availability and/or macro-cell current flows, especially when the resistivity of concrete is low [11]. The affect of crack width (flexural, etc.) also needs to be taken into account when considering corrosion rates.

Further, it has been found [6] that the longitudinal cracking is induced even at a level of corrosion, which is structurally insignificant from the point of view of loss of sectional area of the reinforcing bars. Also, it is not enough to merely estimate the rate of metal dissolution (corrosion rate), because this value must then be related to the internal displacement and pressure which the cover concrete is subjected to on account of the expansive nature of the corrosion products. Obviously at this point, the properties of the corrosion products such as their expansion ratio and the Young's modulus ( $E_{\text{CORR}}$ ) become important.

Work is being carried out with the object of relating the corrosion rate to oxygen flux, existence and width of flexural cracks and macro-cell currents. At the same time another part of the research program deals with (a) studying the composition of the corrosion products in concrete, (b) relating the build up of internal pressure and the critical corrosion amount to induce longitudinal cracking to the mechanical properties of corrosion products, and (c) studying the formation and propagation of cracks in concrete, taking the creep of concrete under consideration.

In the limited space available here, all the aspects outlined above cannot understandably be dealt with in any detail, and hence only the salient features of some of them are mentioned below.

(1) General corrosion under oxygen diffusion control

Several papers [12] have been published studying the oxygen flux through concrete under different conditions (water-cement ratio, level of saturation, etc.). A conversion of these flux values to corrosion rates, assuming a perennial oxygen sink at the reinforcement location, the stoichiometry and the nature of oxidation reactions [13], show that a flux of  $10 \times 10^{-13}$  mol/cm<sup>2</sup>/sec corresponds to a dissolution of about  $3.5 \times 10^{-3}$  mm/year of the metal.

(2) Corrosion products formed within concrete

Corrosion products of iron within concrete [14] could be quite different from those observed in air, because of the high pH and relatively limited supply of oxygen. Analysis using X-ray diffraction and EPMA for RC specimens exposed in marine environment for 5 years show that only 30% of the rust within concrete is crystalline (Fe<sub>3</sub>O<sub>4</sub>-12%, α-FeOOH-15%, γ-FeOOH-3%), whereas the remaining 70% is amorphous. Based on the composition, an average expansion ratio has been worked out to be between 3.0 and 3.2.

(3) Critical corrosion amount

For a round bar with diameter 20mm, embedded in concrete ( $f_t=25$ kgf/cm<sup>2</sup>,  $E_c=3 \times 10^5$ kgf/cm<sup>2</sup>), with a 40mm cover, the internal displacement to induce longitudinal cracks is worked [15] out to be about  $6.5 \times 10^{-4}$ cm. Figure 5 [15] shows the sensitivity of critical corrosion amount under such conditions, to the expansion ratio and  $E_{corr}$  values. Further work to study the effect of cover thickness is presently in progress.

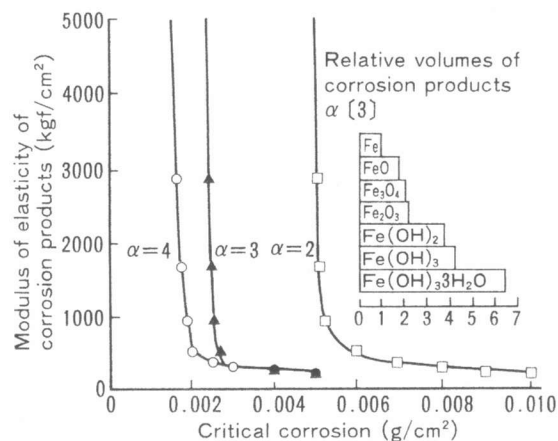


Figure 5 Effect of properties of corrosion products on critical corrosion [Ref. 15]

5. CONCLUDING REMARKS

An attempt has been made in this paper to put some of the individual results discussed in greater detail elsewhere [6, 8, 10, 14, 15] within the overall perspective of durability design of structures subjected to chloride induced reinforcement corrosion, considering the formation of longitudinal cracks along the bars as the limiting level of deterioration. The process has been assumed to proceed in two distinct stages :

- a) chloride penetration, and
- b) corrosion propagation.

Though the inter-relationship between the various factors is highly complex, the paper provides a general outline that can be followed to estimate the time spans involved in the two stages.

## 6. FURTHER WORK

The results indicate the need to do further work in several areas, especially, the variation of the diffusion coefficient and the proportion of soluble chlorides with time and the type and content of cement. Further, the role of pore water in, the transport (of chloride and oxygen) and providing a medium for dissolved oxygen during the corrosion process needs to be carefully looked into. Also, since the growth of internal pressure on account of corrosion could build up very slowly, effort has to be made to determine whether creep of concrete is an important factor in estimating parameters such as the critical internal displacement and the critical corrosion amount.

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