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Deterioration of Concrete Structures

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Paper No 204

Structural Reliability Theory

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Deterioration of Concrete Structures

P. Thoft-Christensen

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DETERIORATION OF CONCRETE STRUCTURES

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Key words: Concrete deterioration, chloride ingress, rebar corrosion, diffusion coefficient

Abstract. *Chloride ingress is a common cause of deterioration of reinforced concrete bridges. Concrete may be exposed to chloride by seawater or de-icing salts. The chloride initiates corrosion of the reinforcement, which through expansion disrupts the concrete. In addition, the corrosion reduces the cross-section of the reinforcement and thereby influences the reliability of the structure.*

Modelling the chloride ingress is an important basis for designing reinforced concrete structures and for assessing the reliability of an existing structure. The modelling is also needed for predicting the deterioration of a reinforced structure. During the last 15 years the types of concrete have changed due to the use of plastisizers and mineral additives.

This report is based on fundamental chemical experimentation by Jensen[1] and by Jensen et al.[2]. The stochastic modelling of deterioration of reinforced concrete has been considered by many researchers, see e.g. Thoft-Christensen[3,4,5,6,7]. The purpose of the paper is to use the results obtained by Jensen[1] and by Jensen et al.[2] to make an improved stochastic modelling of the corrosion initiation time. It is emphasised in the paper that the diffusion coefficient D is not a real physical constant for a given concrete. It is strongly dependent on the water-cement ratio w/c, on the temperature Φ, and on the additives used.

1 INTRODUCTION

Corrosion of the reinforcement is one of the major reasons for deterioration of reinforced concrete structures. The corrosion process is very complex and the modelling is often based on observations or speculations rather than a clear understanding of the physical and chemical processes. In this paper the effect of corrosion of a structure is considered from the point of view of the rust production.

In brief, the main effect of the corrosion is generally a reduced strength of the structural element in question and, therefore, also a reduction of the structural reliability. However, a number of effects are of interest, such as: When is the corrosion initiated? What types of corrosion products are produced? How much corrosion is needed to form a corrosion crack? What kind of crack size may be accepted? What is a reasonable definition of service life for a given structure?

Corrosion of the reinforcement is not only a serious problem because of the reduction of the effective reinforcement and the corresponding strength reduction. The corrosion may also be serious, because the volume of the rust products is higher than the volume of the corroded steel. The porous zone around the steel/concrete surface can to some extent absorb the higher volume of the rust products. Some amount of rust products will diffuse into the capillary voids in the cement. However, at a certain time the total amount of corrosion products exceeds the amount of corrosion products needed to fill the porous zone around the steel. The rust products will then create expansive pressure on the surrounding concrete. To estimate these processes a clear understanding of the structure of the concrete near the reinforcement is necessary.

The expansion of the concrete near the reinforcement will initiate tensile stresses in the concrete. After some time with increasing corrosion the tensile stresses will reach a critical value and corrosion cracks may develop. With further production of rust, the crack width will increase and eventually often result in spalling. This last part of the corrosion process is still not well understood. More research is certainly needed to clarify these important problems for a corroded reinforced concrete structure.

In this paper the important role of the diffusion coefficients is emphasised, see also Thoft-Christensen[7].

2 RELIABILITY PROFILES

Reliability profiles (reliability as function of time) for reinforced concrete structures describe the deterioration as a function of time. They may be based directly on observations if such data are available using curve fitting and a given functional form with a number of parameters. If the functional form is chosen without any physical arguments then the parameters will also be without a physical meaning. This is a clear disadvantage since a direct estimation of the parameters is not possible in general. It is more satisfactory to use simple physical modelling as a basis for estimation of the reliability profiles, see e.g. Thoft-Christensen[5]. If only corrosion of the reinforcement due to chloride penetration of the concrete is considered then the reliability profile may be divided into the following steps, see figure 1:

1. Chloride penetration of the concrete
2. Initiation of the corrosion of the reinforcement
3. Evolution of corrosion of the reinforcement
4. Initial cracking of the concrete
5. Evolution of cracks in the concrete.
6. Spalling

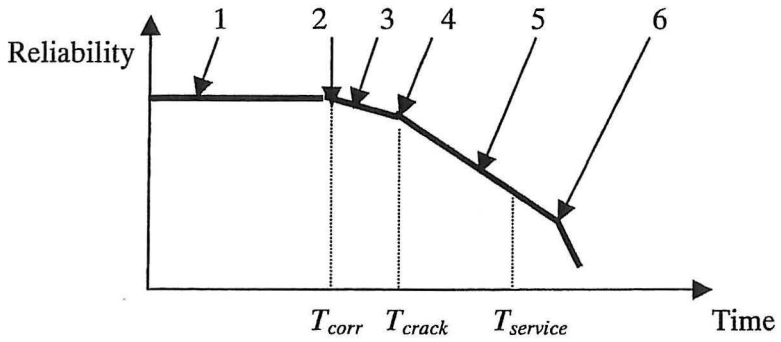

Figure 1. Deterioration steps.

Deterioration steps 1-3 are well understood, and are presented in numerous papers, e.g. Thoft-Christensen[3]. Step 4 has been addressed in Thoft-Christensen[4], and steps 5 and 6 have been addressed inThoft-Christensen[5].

3 FICK'S LAW

The corrosion initiation period T_{corr} refers to the time during which the passivation of steel is destroyed and the reinforcement starts corroding actively. Several techniques to estimate T_{corr} exist. However, there seems to be a general agreement that Fick's law of diffusion is superior to other techniques. Fick's law of diffusion can be written

$$\frac{dC(x,t)}{dt} = D \frac{d^2C(x,t)}{dx^2} \tag{1}$$

where $C(x,t)$ is the chloride ion concentration, given as % by weight of cement, at a distance of x m from the concrete surface after t seconds of exposure to the chloride source. D is the chloride diffusion coefficient expressed in m^2/sec. The solution of the differential equation (1) is given by

$$C(x,t) = C_0 \left\{ 1 - \text{erf}\left(\frac{x}{2\sqrt{D \cdot t}} \right) \right\} \tag{2}$$

where C_0 is the equilibrium chloride concentration on the concrete surface, given as % by weight of cement and erf is the error function.

Collepardi et al.[8] used Fick's law for diffusion as early as 1970 and they calculated diffusion coefficients for various concrete compositions. Since then, Fick's law has been the basis for chloride ingress modelling, but a large number of modifications have been introduced, such as, Jensen[1]:

- The diffusion coefficient is concentration dependent, perhaps as a result of hydration of chloride ions,
- The chloride diffusion has to be balanced either by co-diffusion of oppositely charged ions or by counter diffusion of identically charged ions.
- A significant amount of the ingressed chloride is immobilized through binding, either by adsorption on the C-S-H gel or by chemical reaction with the aluminate phases. More than 50% of the chloride in a cement paste may be bound. This delays the ingress.
- The chloride ingress may change the pore structure and, as a consequence, modify the effective diffusion coefficient as well.

4 BINDING MODIFIED FICK'S LAW

Jensen[1] and Jensen et al.[2] have investigated a single Fick's diffusion law modified with binding. They assume that the free chloride follows Fick's law. They also assume that the chloride binding follows a Freundlich isothermal equation, see Luping[8]

$$c_b = \alpha \times c_f^{\beta} \tag{3}$$

α and β are empirical constants. The chloride binding significantly modifies the shape of the chloride ingress profiles as well as the calculated chloride diffusion coefficient D. In figure 2 the principal difference between chloride ingress profiles with and without binding is shown. Without bonding the profile is strongly concave and with binding the profile is almost linear. In general measured profiles are almost linear so a modelling with binding seems to be a great improvement.

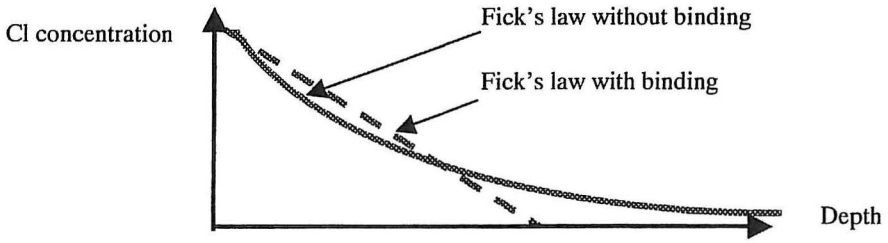

Figure 2. Chloride ingress profiles

In Jensen[1] an example is shown where this conclusion is strongly supported. A cement paste with w/c = 0.3 and with no additives was chloride exposed for 30 days at 35°. Without binding the diffusion coefficient is $1.5 \times 10^{-12} m^2/s$ and with binding included the diffusion coefficient for the free chloride is $3.7 \times 10^{-12} m^2/s$. If binding is included the description is substantially improved.

5 CORRODION INITIATION TIME

In a real structure, if C_{cr} is assumed to be the chloride corrosion threshold and d is the concrete cover thickness, then the corrosion initiation period T_{corr} can be calculated. The time T_{corr} to initiation of reinforcement corrosion is

$$T_{corr} = \frac{d^2}{4D}(erf^{-1}(\frac{C_{cr} - C_0}{C_i - C_0}))^{-2} \tag{4}$$

On the basis of equation (3) outcomes of the corrosion initiation time T_{corr} have been performed on the basis of the following data by simple Monte Carlo simulation (the unit of D is mm/year):

Initial chloride concentration:	0%
Surface chloride concentration:	Normal (0.650 ; 0.038)
Diffusion coefficient:	Normal (30 ; 5)
Critical concentration:	Normal (0.3 ; 0.05)
Cover:	Normal (40 ; 8)

A Weibull distribution can be used to approximate the distribution of the simulated data. The Weibull distribution is $W(x; \mu, k, \varepsilon)$, where μ = 63.67, k = 1.81 and ε = 4.79. The corresponding histogram and the density function are shown in figure 3.

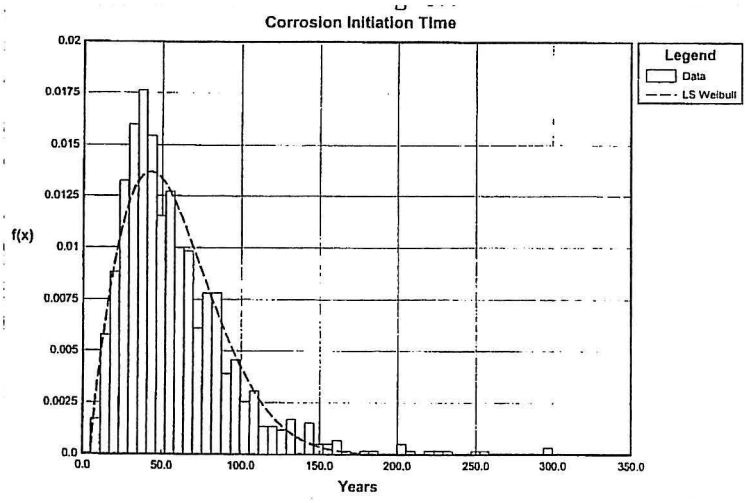

Figure 3. Density function of the corrosion initiation time T_{corr}.

6 THE DIFFUSION COEFFICIENT

The diffusion coefficient D is an important factor in all corrosion estimates. It follows from (4) that the time to corrosion imitation is inversely proportional in D. It is therefore of great interest to get a good estimate of D. For the example in section 4 the mean value of the time to corrosion initiation T_{cor} is estimated at 63.67 years. If chloride binding is included and

the ratio between the diffusion coefficients presented is used, the mean value of T_{corr} is reduced to 25.81 years. Clearly such a dramatic change is significant for the preventive maintenance strategies in this project.

The diffusion coefficient D is not a real physical constant for a given concrete structure since it depends on a number of factors. According to the extensive experimental investigations by Jensen[1] and by Jensen et al.[2] it can be concluded that the most important factors are the water/cement ratio w/c, the temperature Φ, and the amount of e.g. silica fume s.f. The data presented in this section are all based on Jensen[1] and Jensen et al.[2]. In figure 4 the diffusion coefficient D is shown as a function of the water-cement ratio w/c and the temperature Φ °C for cement pastes with 0% silica fume. It is clear from figure 3 that the diffusion coefficient D increases significantly with w/c as well as the temperature Φ. In the example illustrated in figure 3 the minimum value of D is 0.31 corresponding to w/c = 0.2 and the temperature Φ = 4°C. The maximum value 80.00 corresponding to w/c = 0.70 and Φ = 35 °C. In figure 5 the contour lines for the same data are shown.

The influence of w/c and the temperature Φ may be explained by the chloride binding. Only the free chloride is important for the diffusion coefficient D. With increased w/c ratio less chloride is bound and D is therefore increased. The strong influence of the temperature is mainly caused by thermal activation of the diffusion process, but may also be due to a reduced chloride binding when the temperature is increased. Taking the chloride binding into account also improves the modelling of the chloride ingress profiles.

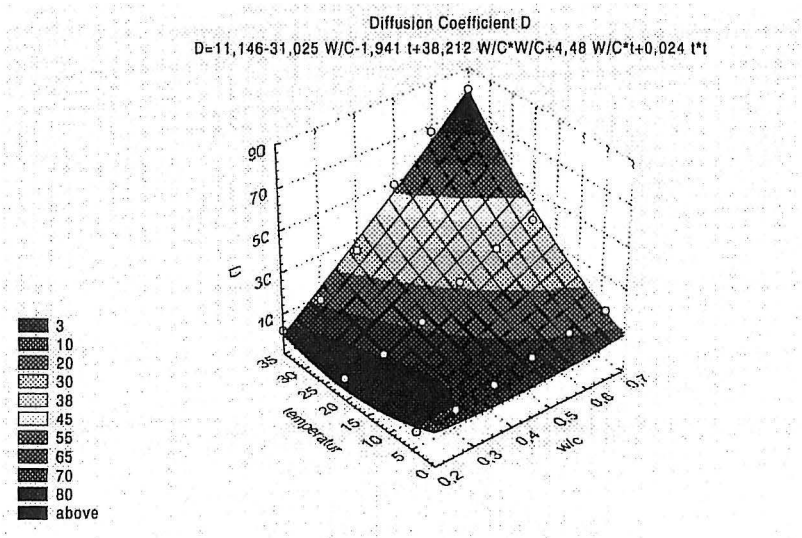

Figure 4. The diffusion coefficient D as a function of the water-cement ratio w/c and of the temperature t°C (Celsius).

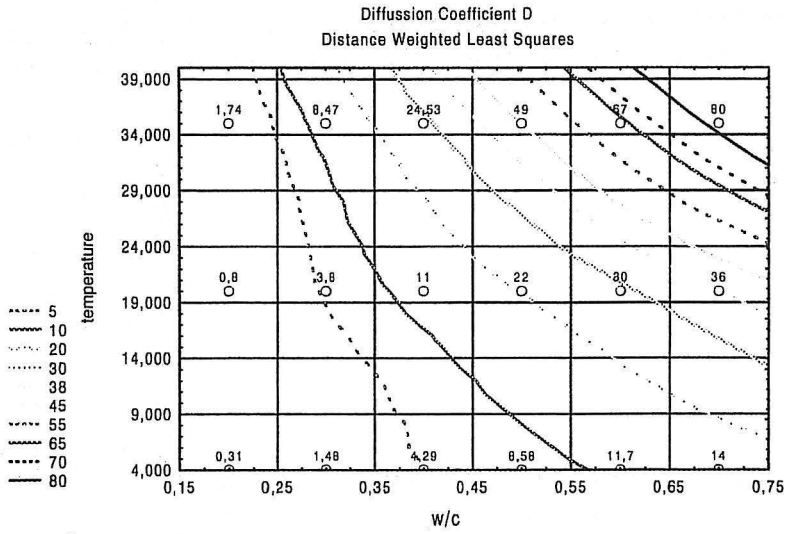

Figure 5. The diffusion coefficient D (10^{-12}m^2/s) as a function of the water-cement ratio w/c and the temperature Φ °C (Celsius).

It is clearly of great importance to get good estimates of w/c and Φ. The w/c value to be used is the original w/c value when the concrete was produced. If the original value of w/c is not available, then it can be estimated by testing of the concrete. Estimation of the temperature Φ is more complicated, since the temperature usually varies a lot. As a first estimate it is suggested to use an equivalent value based on information of the variation of the temperature during the year at the site of the structure. When relevant values of w/c and Φ are obtained, then an estimate of D may be obtained from figure 4 or figure 5.

The addition of silica fume is of great importance for the chloride ingress. Silica fume additions reduce the chloride ingress because of changes in the pore structure. This is illustrated in table 1, see Jensen[1].

w/c	% s.f.	D (10^{-12}m^2/s)
0.3	0	3.8
	3	2.0
	6	0.42
	10	0.12
	20	0.05
0.5	0	22
	3	13
	6	4.2
	10	1.6
	20	0.30

Table 1. The diffusion coefficient D as a function of % s.f. for two values of w/c and Φ =20 °C.

7 IMPLEMENTATION

It is clearly a significant improvement to include the findings presented in this paper in the estimation of reliability profiles. The data needed are:

- The average temperature at the sites of the bridges or perhaps a stochastic modelling of the average temperature in the area in question.
- The *w/c* ratios for the relevant bridges so that a distribution for *w/c* can be estimated.
- Information on additives used for the bridges in question.

Inclusion of these new findings in estimation of the time to corrosion initiation will significantly improve the modelling of the deterioration.

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