

Prediction of reinforcement corrosion due to chloride ingress and its effects on serviceability



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ARTICLE INFO

Keywords:

Concrete
Corrosion
Propagation period
Chloride ingress
Serviceability

ABSTRACT

Concrete is the most common man-made material in today's world. Embedded steel reinforcement may corrode due to chloride presence from de-icing salts or salt water, having impact on structural serviceability and life design. The paper presents a chemo-mechanical model covering initiation and propagation periods of chloride steel corrosion, taking into account concrete mix design, supplementary cementitious materials, concrete cover, crack width and environmental conditions. First, a short-term fracture-plastic constitutive model predicts cracking prior to the chloride ingress. Second, 1D model of chloride ingress yields the time of concrete cracking, spalling and the effective steel area. Third, mechanical analysis assesses the load-bearing capacity of a structure in dependence on the state of reinforcement corrosion. Validation includes two load-bearing structures loaded by chlorides; a concrete strut of a prestressed bridge in Prague, Czech Republic and Nougawa bridge, Japan.

1. Introduction

Reinforcement corrosion due to chloride ingress and carbonation are considered to be the most damaging mechanism for reinforced concrete (RC) structures in the world [1]. They generally lead to decreased serviceability and durability, which has a further impact on the life cycle costs and the environment. Chloride ingress is mostly caused by de-icing salts, sea water and salts in coastal areas. Chloride ions diffuse through the binder in concrete and the ingress is controlled by several factors such as environmental boundary conditions, concrete cover thickness, cement type, cement content, water-to-binder ratio (w/b) [2,3].

The classical approach assumes that corrosion starts when the chloride concentration exceeds a critical value in the place of reinforcement [4, Tab. 8.7]. The critical chloride content approaches 0.6% by weight of the binder [5, p. 72]. Other sources give a range of 0.5–0.9% for a tidal and splash zone and 1.6–2.3% for submerged concrete [4, Tab. 8.7].

The initiation period t_i corresponds to no steel corrosion, see Fig. 1. After the initiation period, the propagation period t_p takes place, when the steel reinforcement corrodes and expanding corrosion products are formed. Chlorides often exhibit a pitting corrosion [6]. The times $t_{p,cr}$ and $t_{p,sp}$ in Fig. 1 correspond to the cracking and spalling time of the concrete cover. They are related to corrosion depths $x_{corr,cr}$ and $x_{corr,sp}$

[4].

There are several models predicting the chloride concentration during the ingress [1]. The Mejlbro-Poulsens model [7] assumes the concentration gradient as the driving force, operating on a time-dependent chloride concentration and diffusion coefficients. Kwon's model [8] extends the model for crack effects, which accelerate the ingress [2]. Their role is substantial for traditional cement-based materials, e.g. 0.3 mm cracks may decrease the initiation period approximately five times compared with uncracked concrete [9]. The more realistic ClinConc model decomposes chlorides into free and bound components [10]. This approach leads to a non-linear formulation affected by the binding chloride isotherm [11].

It has been found that the steel corrosion rate depends on the corrosion current density i_{corr} . The models addressing this problem include Liu and Weyer's model [3], models by Alonso [12], Yalçın and Eugen [13], Vu and Steward [14] or Scott [15] to mention a few.

This article combines Kwon's model [8] for the initiation period with the effect of cracking and Liu and Weyer's model [3] for the propagation period. The amalgamated models predict chloride profiles, the time for cracking and spalling and the decrease of the steel area due to chloride action with consequences for load-bearing capacity and structure reliability.

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<https://doi.org/10.1016/j.engstruct.2018.08.006>

Received 22 February 2018; Received in revised form 28 July 2018; Accepted 2 August 2018

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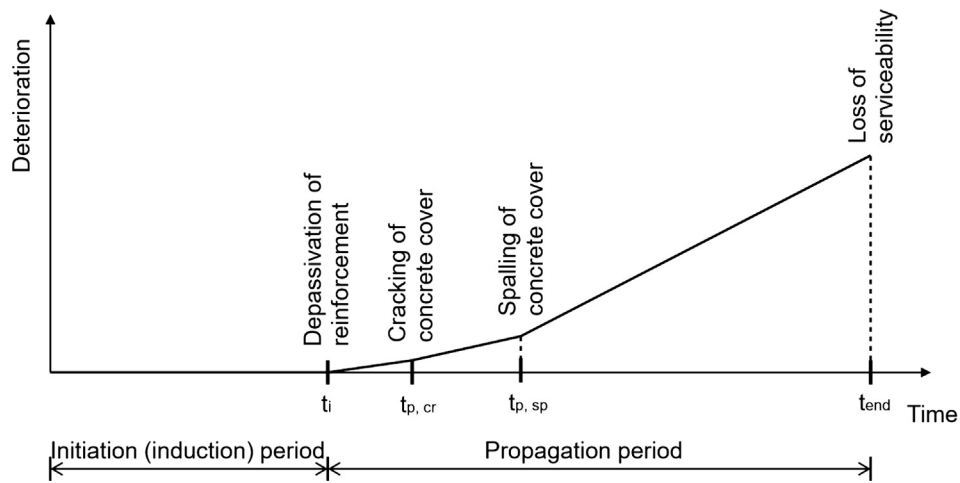


Fig. 1. Initiation and propagation periods.

2. Chemo-mechanical material models

2.1. Models for initiation period

Models for the initiation period assume that steel corrosion starts when the concentration of chloride ion exceeds a critical value [4, Tab. 8.7]. There is an analytical solution for 1D transient ingress with an initially zero chloride content

$$C(x, t) = C_s \left[1 - \operatorname{erf} \left(\frac{x}{2\sqrt{D_m(t)f(w)t}} \right) \right], \quad f(w) = 31.61w^2 + 4.73w + 1 \quad (1)$$

where C_s is the chloride content at surface (kg of chlorides/kg of a binder), $D_m(t)$ is the mean (averaged) diffusion coefficient at the time t (m^2/s) [2], x is the distance from the surface (m) and $f(w)$ includes acceleration by the crack width w (mm); e.g. a crack width of 0.3 mm increases the mean diffusion coefficient by a factor of 5.26. The preliminary results of the model have been described in detail previously [9]. The solution of Eq. (1) illustrates Fig. 2; a chloride profile with and without cracks from Section 2.1.2.

The instantaneous diffusion coefficient $D(t)$ for chloride ingress is assumed to decrease over the time t according to the power law

$$D(t) = D_{ref} \left(\frac{t_{ref}}{t} \right)^m \quad (2)$$

where m is the decay rate (also called the age factor). The same exponential form was employed in Model Code 2010 [5]. If $m = 0$, a constant value of $D(t) = D_{ref}$ is recovered; such a model was proposed by Collepardi et al. [16]. Nowadays, it has become clear that this assumption is too conservative and is not generally recommended.

The mean diffusion coefficient $D_m(t)$ is obtained by averaging $D(t)$ over the exposure time [17]

$$D_m(t) = \frac{D_{ref}}{1-m} \left(\frac{t_{ref}}{t} \right)^m, \quad t < t_R, \quad (3)$$

$$D_m(t) = D_{ref} \left[1 + \frac{t_R}{t} \left(\frac{m}{1-m} \right) \right] \left(\frac{t_{ref}}{t_R} \right)^m, \quad t \geq t_R \quad (4)$$

where t_R is the time, after which the diffusion coefficient remains constant and, which is generally taken as 30 years [18], t_{ref} corresponds to the time, when the diffusion coefficient was measured. Fig. 3 shows a characteristic evolution of the diffusion coefficient $D(t)$ and $D_m(t)$ through 100 years.

Once crack width changes over time, integration of derived Eq. (1) provides the mean diffusion coefficient $D_m(t)$ as

$$D_{m,w}(t, w) = D_m(t) \int_0^w 63.22w + 4.73 dw \quad (5)$$

2.1.1. Diffusion coefficients for chlorides

The proper determination of diffusion coefficients presents a challenging task, taking into account various cements, concretes, exposure conditions and inverse analysis. The DuraCrete model [4] provides the estimation of the apparent diffusion coefficient from the formula

$$D_a(t) = D_m(t) = k_e k_c D_{Cl}(t_0) \left(\frac{t_0}{t} \right)^m \gamma_{Da} \quad (6)$$

where $k_e \in \langle 0.27, 3.88 \rangle$ is the environment factor, $k_c \in \langle 0.79, 2.08 \rangle$ is the curing factor, $D_{Cl}(t_0)$ is the measured diffusion coefficient determined at the time t_0 , $m \in \langle 0.2, 0.93 \rangle$ is the decay rate factor and $\gamma_{Da} \in \langle 1.25, 3.25 \rangle$ is the partial factor. In our notation, $D_a(t) = D_m(t)$ and $t_0 = t_{ref}$. Table 1

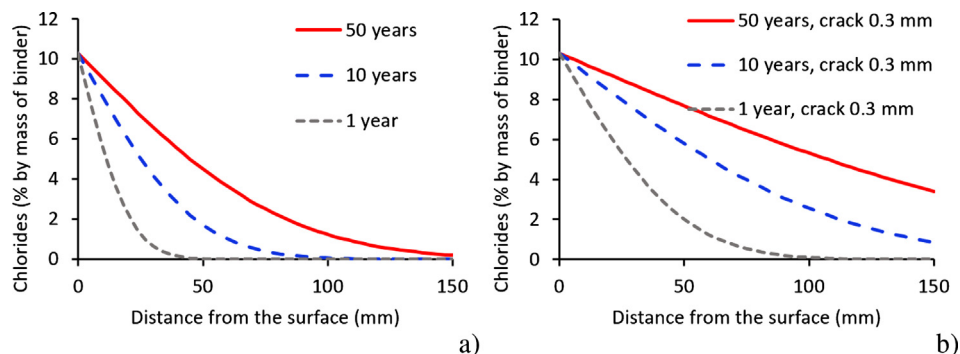


Fig. 2. Effect of cracking on chloride ingress. Chloride profile without cracks (a) and with 0.3 mm crack (b).

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