

# Chapter 2

## Durability of Reinforced Concrete Structures and Penetrability

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### 2.1 Introduction

In this chapter a brief overview is given on the mechanisms causing reinforcement corrosion, on the concrete properties relating to the ingress of aggressive agents (penetrability and transport properties) and on the principles for service life design and deterioration models.

### 2.2 Mechanisms Causing Reinforcement Corrosion

Reinforcement steel in concrete is passivated because of the alkaline environment at the steel surface. The steel cannot corrode as long as this passivation is prevailing. This passivation can be broken in two ways:

- carbonation causing a drop in pH in the carbonated part of the concrete;
- chloride ingress causing a chloride content at the steel surface above a certain critical chloride content, the “threshold level”.

After depassivation, and corrosion initiation, the rate of corrosion depends on the concrete properties, the thickness of the cover and the temperature and humidity conditions at the steel surfaces and in the cover. This “propagation process” is not dealt with here, since in most applications the service-life is defined to end at the

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start of the propagation period. Additionally, penetrability is not very relevant in the propagation period.

### 2.2.1 Carbonation

Carbonation is a combined process of diffusion of  $CO_2$  through the open pores of concrete into a carbonation “front” where a chemical reaction occurs where  $CO_2$  reacts with the cement paste hydrates. The carbonation of portlandite ( $Ca(OH)_2$ ) and calcium silicate hydrate ( $C-S-H$ ) leads to the formation of calcium carbonates and silica. The carbonation reaction of portlandite is shown in Eq. (2.1).



This chemical reaction must be “supplied” by  $CO_2$  to be able to continue. The two decisive parameters are the diffusion resistance of the carbonated concrete and the amount of  $CaO$  that can be carbonated.

### 2.2.2 Chloride Ingress

Chloride ingress is a combined process of three parts:

- a. diffusion of chloride ions in the pore liquid,
- b. convection of chloride ions in the pore liquid by liquid transport and
- c. binding of chloride to the cement gel.

Part ‘a’ and ‘b’ are “penetrability and transport properties” that are retarded by the chloride binding process ‘c’.

## 2.3 Concrete Properties Relating to the Ingress of Aggressive Agents

From Sect. 2.2 it is obvious that the concrete properties that are related to initiation of reinforcement corrosion are several:

- a. resistance against diffusion of  $CO_2$ ,
- b. amount and availability of  $CaO$  as a reactant in the carbonation reaction,
- c. moisture fixation properties of carbonated concrete, which influence the diffusion resistance,

- d. moisture fixation and moisture transport properties of carbonated and uncarbonated concrete, which affect the moisture conditions in the concrete cover and the convection of chloride ions,
- e. resistance against diffusion and convection of chloride ions,
- f. chloride binding properties and
- g. chloride threshold level.

Among these concrete properties only properties ‘a’, ‘d’ and ‘e’ are “penetrability and transport properties”, depending on the definition of “penetrability”. These are further described in the next sections. Properties that are binding and fixation properties are not covered.

### 2.3.1 Resistance Against Diffusion of $CO_2$

The flux of diffusing  $CO_2$  in carbonated concrete is based on Eq. (2.2),

$$J_{CO_2} = -D_{CO_2}(RH, \alpha) \frac{dc_{CO_2}}{dx} = \frac{c}{R_{CO_2}} \quad (2.2)$$

where the  $CO_2$ -diffusion coefficient  $D_{CO_2}$  depends on the humidity  $RH$  and degree of hydration  $\alpha$ . The concentration difference over the carbonated layer with thickness  $X_{CO_3}$  is  $\Delta c = c - 0 = c$ .

The resistance to diffusion of  $CO_2$  of the carbonated layer is  $R_{CO_2}$ , which is given by,

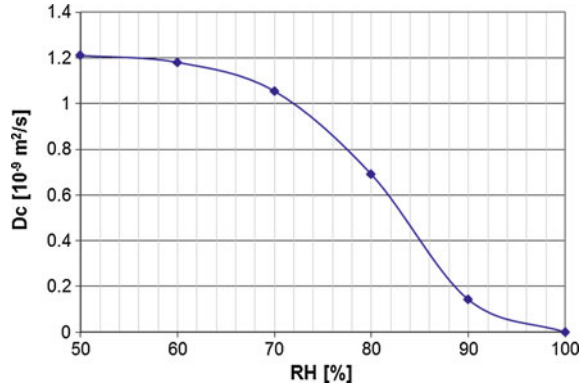
$$R_{CO_2} = \int_{x=0}^{x=X_{CO_3}} \frac{dx}{D_{CO_2}(RH(x), \alpha(x))} \quad (2.3)$$

The  $CO_2$ -diffusion coefficient varies with depth for two reasons; a humidity profile and a “curing profile” in the concrete cover. The moisture dependency is shown in principle in Fig. 2.1. Figure 2.2 shows examples of profiles of the degree of hydration and the corresponding  $CO_2$ -diffusion coefficient.

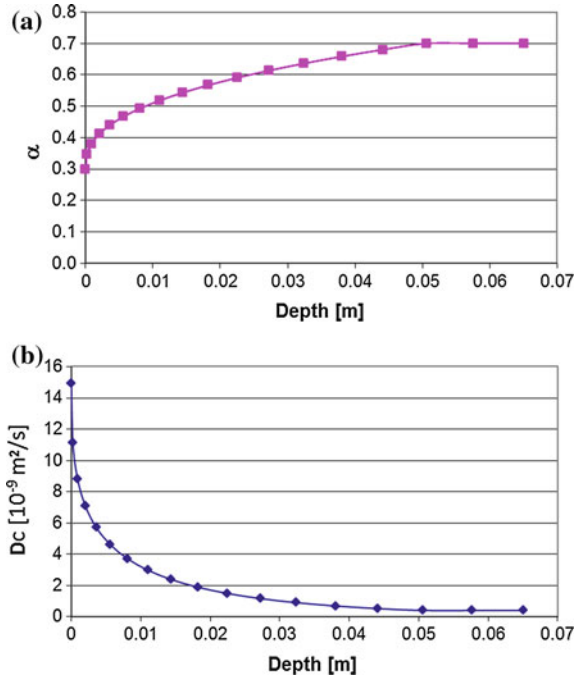
### 2.3.2 Moisture Transport Properties

Moisture is present in concrete as adsorbed in the gel at pore surfaces, physically bound by menisci in large gel pores and small capillary pores and as vapour in the “empty” pores. This moisture will be transported in the pore system due to differences in the state of water, usually described with the relative humidity, or pore humidity,  $RH$  or  $\phi$ . Since the different types of water, adsorbed, capillary and

**Fig. 2.1** The moisture dependency of the  $\text{CO}_2$ -diffusion coefficient; an example for a concrete with  $w/c = 0.4$  [1]



**Fig. 2.2** An example of a profile of **a** degree of hydration ( $\alpha$ ) after bad curing, and **b** the corresponding  $\text{CO}_2$ -diffusion coefficient [2]

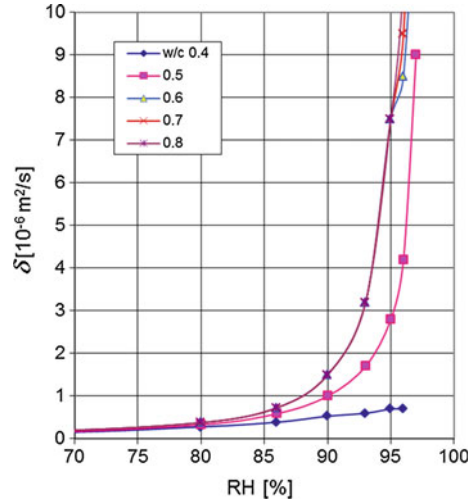


vapour, cannot be differentiated in a measurement, moisture transport properties are given as a total moisture transport coefficient  $\delta_{RH}$ , e.g. expressed as in Eq. (2.4).

$$J_w = -\delta_{RH}(RH, \alpha) \frac{d\varphi}{dx} \quad (2.4)$$

where  $J_w$  is the total flux of moisture,  $\alpha$  is the degree of hydration,  $\varphi$  is the moisture transport potential, and  $RH$  is the relative humidity.

**Fig. 2.3** The total moisture transport coefficient for various concretes [3]



The total moisture transport coefficient  $\delta_{RH}$  is moisture dependent, since the flux due to the different moisture transport mechanisms depends on the state of moisture and moisture content in the pore system. An example of this moisture dependency is shown in Fig. 2.3 for concretes with different water-binder ratios.

### 2.3.3 Resistance Against Chloride Diffusion and Convection

Transport of chloride ions due to convection, by ions being transported with the pore liquid transport, is given by that part of the total moisture transport that can “carry” ions. What portion of the total moisture flux can carry ions is not yet known; this is still a topic of research.

Transport of chloride ions as diffusion in the pore liquid is usually described with Fick’s 1st law or the Nernst-Planck equation. The latter considers the activity of various ions and the electrical field that is created by all the ions being present in the pore liquid. Fick’s 1st law is shown in Eq. (2.5).

$$J_{Cl} = -D_{F1}(RH, \alpha) \frac{dc}{dx} \quad (2.5)$$

where  $J_{Cl}$  is the flux of ions,  $D_{F1}$  is the chloride diffusion coefficient, and  $c$  is the concentration of chloride ions in the pore liquid.

The chloride diffusion coefficient depends on the degree of hydration and the pore humidity  $RH$  or the degree of saturation  $S$  of the pore system, since ions can only move in the liquid part of the total moisture content. The moisture dependency is not well known; only a few measurements are known. One example is shown in

Fig. 2.4. This example is for the chloride diffusivity in Fick's 2nd law, however, see Eq. (2.10) (Fig. 2.4).

## 2.4 Service Life and Deterioration Models (Principles)

The traditional service-life and deterioration model for reinforcement corrosion is the one proposed by Tuutti [1], see Fig. 2.5.

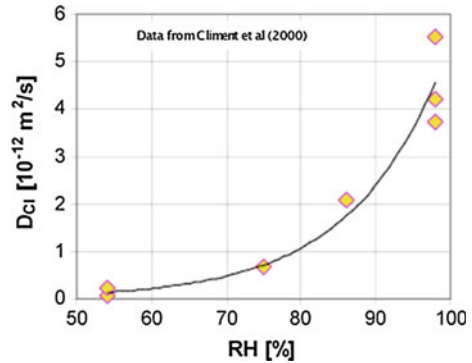
The most common definition of service-life being used by owners of buildings and infrastructures is the one that marks the end of the service-life as the end of the corrosion initiation period. Then the service-life and deterioration models are “simple”; they are models that give the length of the initiation period.

The principles of models for carbonation-initiated corrosion are simple; corrosion is first initiated when the carbonation “front” reaches the steel bar, see Eq. (2.6).

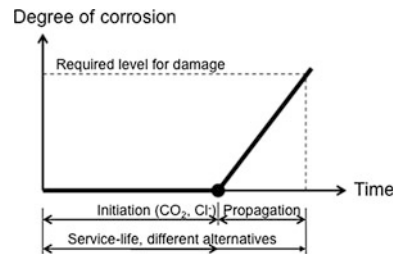
$$x_{CO_3}(t_{SL}) = d \quad (2.6)$$

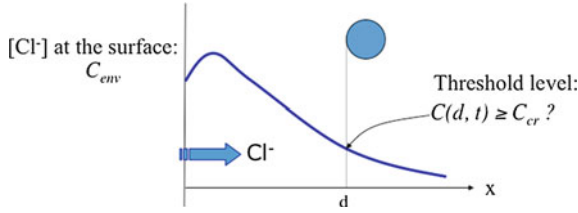
where  $x_{CO_3}$  is the depth of carbonation,  $t_{SL}$  is the service-life, and  $d$  is the thickness of the concrete cover.

**Fig. 2.4** An example of the moisture dependency of the chloride diffusivity  $D_{F2}$  [4]



**Fig. 2.5** The service-life model for reinforcement corrosion [1]





**Fig. 2.6** The principle of most common service-life models for chloride initiated reinforcement corrosion

The principles of models for chloride initiated corrosion are somewhat more complicated since chloride ingress must give a certain chloride level  $C(x = d, t_{SL})$  at the steel surface, above the chloride threshold level,  $C_{cr}$ , i.e. the principle of the service-life models is shown in Eq. (2.7) and Fig. 2.6.

$$C(x = d, t_{SL}) = C_{cr} \quad (2.7)$$

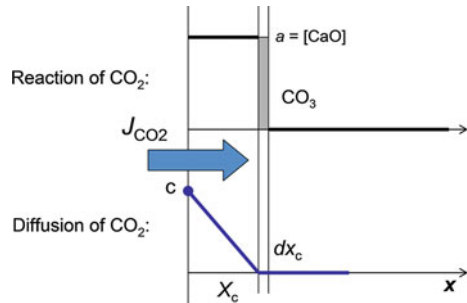
#### 2.4.1 Carbonation Models, in Principle

Several carbonation models are proposed in the literature. A simple carbonation model that includes a “penetrability and transport property” is the one in Eq. (2.8) [5], see Fig. 2.7.

$$x_{CO_3}(t) = \sqrt{\frac{2D_{CO_2}c_{CO_2}}{a}} \cdot \sqrt{t} \quad (2.8)$$

where  $x_{CO_3}$  is the depth of carbonation,  $D_{CO_2}$  is the diffusion coefficient for carbon dioxide,  $c_{CO_2}$  is the concentration of carbon dioxide at the surface of the concrete,  $a$  is the amount of carbon dioxide required to carbonate a unit volume of concrete, and  $t$  is the time.

**Fig. 2.7** A simple model for carbonation, with a diffusion and reaction process [5]



In the cover of a concrete structure exposed to real environmental actions, the moisture conditions are varying with time. This will affect the diffusion coefficient in such a way that it will vary with time and depth. To consider such effects, the carbonation process must be modelled with a “resistance” to diffusion of  $CO_2$ , i.e. Equation (2.8) must be differentiated and integrated over the carbonated part of the cover. This can be seen in [5].

### 2.4.2 Chloride Ingress Models, in Principle

A large number of models are proposed in literature [6]. All models could be said to be solutions to the mass balance equation for chloride, Eq. (2.9).

$$\frac{\partial C}{\partial t} = \frac{\partial c_b}{\partial t} + \frac{\partial c}{\partial t} = -\frac{\partial J_{Cl}}{\partial x} = \frac{\partial}{\partial x} D_{F1} \frac{\partial c}{\partial x} \quad (2.9)$$

where  $C$  is the total chloride content,  $c_b$  is the bound chloride content,  $c$  is the content of free chlorides,  $J_{Cl}$  is the flux of chlorides,  $D_{F1}$  is the diffusion coefficient in Fick’s 1st law,  $x$  is the depth, and  $t$  is the time. Here the flux is simplified in the right-hand part of the equation to Fick’s 1st law.

In its most simple form, the mass-balance Eq. (2.9) can be simplified to Fick’s 2nd law, Eq. (2.10).

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x} D_{F1} \frac{\partial c}{\partial x} \Leftrightarrow \frac{\partial C}{\partial t} = \frac{\partial}{\partial x} D_{F1} \frac{\partial C}{\partial x} \Leftrightarrow \frac{\partial C}{\partial t} = \frac{\partial}{\partial x} D_{F2} \frac{\partial C}{\partial x} \quad (2.10)$$

Note that the diffusivity  $D_{F2}$  is not only a “penetrability and transport property”. The chloride binding capacity  $dC/dc$  is included in that parameter. Consequently, the penetrability of chloride ions is not directly proportional to the chloride ingress.

In most service-life models one of the two parameters  $D_{F1}$  or  $D_{F2}$  is used.

### 2.4.3 Discussion on the Influence of Cracks

Most transport and penetrability test methods are used to characterize un-cracked concrete. Also, service life models are usually used without taking into account the eventual presence of cracks, and only un-cracked concrete properties are considered. However, in situ, the presence of cracks in concrete is not rare, whatever is the cause of these cracks: early-age, thermal loading, shrinkage, or a simple mechanical overloading. Cracked concrete allows the corrosion process to initiate much faster than un-cracked concrete. Cracks may adversely affect concrete durability by providing easy access to aggressive agents and especially to chloride ions. Data in the literature show the importance of this parameter since it can lead to a significant



increase of diffusivity. This increase depends on different parameters, among them the crack-width.

The quantification of this increase is not an easy task, however some data exists in the literature and one can expect that experimental data [7] and numerical simulations [8] on cracked concretes could be used to establish “correction factors” according to the type of the crack (self-healing or dynamic) and/or its geometrical properties (crack-width) and/or its density. These “correction factors” could be taken into account in the evaluation of the resistance against diffusion of  $CO_2$  or chloride ions.

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Performance-Based Specifications and Control of  
Concrete Durability

State-of-the-Art Report RILEM TC 230-PSC

Beushausen, H.; Fernandez Luco, L. (Eds.)

2016, XVIII, 373 p. 155 illus., Hardcover

ISBN: 978-94-017-7308-9