



Carbonation and Chloride Penetration in Concrete with Special Objective of Service Life Modelling by the Factor Approach

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<p>Summary</p> <p>The objective of this research has been to develop a theoretical basis for practical service life models with respect to carbonation and chloride penetration in concrete structures. The interaction of degradation mechanisms is also considered.</p> <p>The cases addressed in this report are the following:</p> <ul style="list-style-type: none"> • Carbonation and chloride penetration on normal concrete surface • Carbonation and chloride penetration at cracks of concrete • Carbonation and chloride on a coated concrete surface • The effect of aging (hydration) on carbonation and chloride penetration • The effect of frost attack on carbonation and chloride penetration • Mutual effects of carbonation on chloride penetration. <p>The final aim has been to find ways to determine factors for service life design according to the "factor approach". The correct theoretical basis for factorizing the service life models has been searched as far as it is possible using simple mathematical formulations.</p>		
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Preface

This research is a part of the project “DuraInt” which began in 2008 with the objective of evaluating the effect of interacted deterioration parameters on the service life of concrete structures in cold environments. The project DuraInt includes both field and laboratory testing together with theoretical and computational efforts for the development of practical service life models. Especially the interaction of degradation mechanisms is studied. The DuraInt project is funded by TEKES (Finnish Funding Agency for Technology and Innovation) together with the Finnish Road Administration and other Finnish organisations and companies. During the project there has been much international cooperation on the topic of concrete durability.

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1 Introduction

Service life models are necessary in today's structural design. Present day structural engineers use service life models in the design of new structures, design of maintenance over time, life cycle analyses, predictive risk analyses etc. This research has been an attempt to develop a theoretical basis for practical service life models with respect to carbonation and chloride penetration in concrete structures. The interaction of degradation mechanisms is also considered.

The models have been developed starting from laws of diffusion and laws of chemical reactions - how the diffused agents, CO₂ and chloride ions, are chemically bound and stored in the porosity of concrete. Based on the fact that the agents cannot disappear the flux into concrete must be in balance with the material stored in concrete. The models are derived using different pre-assumptions starting from the simplest cases and ending in more demanding cases. The cases are the following:

- Carbonation and chloride penetration on normal concrete surface
- Carbonation and chloride penetration at cracks of concrete
- Carbonation and chloride on a coated concrete surface
- The effect of aging (hydration) on carbonation and chloride penetration
- The effect of frost attack on carbonation and chloride penetration
- The effect of carbonation on chloride penetration and the effect of chlorides on carbonation.

In some cases an analytical solution is not possible. In those cases the algorithms for numerically solution are presented.

The final aim has been to find ways to determine factors for service life design according to the "factor approach". A correct theoretical basis for factorizing the service life models has been searched as far as it is possible using simple mathematical formulations.

2 Carbonation on the Surface of Concrete

The experimental observation that the depth of carbonation is approximately proportional to the square root of time can be theoretically derived by applying the diffusion theory. In this theory the carbon dioxide is diffused into concrete and reacts with the non-carbonated calcium minerals at the 'moving boundary', that is at the distance of x_{ca} , depth of carbonation, from the surface of a structure. The carbon dioxide content between the surface and the moving boundary is assumed to be linear. Then the flux of carbon dioxide towards the moving boundary can be evaluated as [9]:

$$J = D \frac{\Delta c}{x_{ca}} \quad (1)$$

where J is flux of carbon dioxide into concrete, g/(m²s),

D	diffusion coefficient with respect to carbon dioxide, m ² /s,
x _{ca}	distance of the moving carbonation boundary from the surface of the structure, m,
Δc	= c _s - c _x , g(CO ₂)/m ³ ,
c _s	CO ₂ content of air at the surface of concrete, g(CO ₂)/m ³ , and
c _x	CO ₂ content of air at the moving boundary, g(CO ₂)/m ³ .

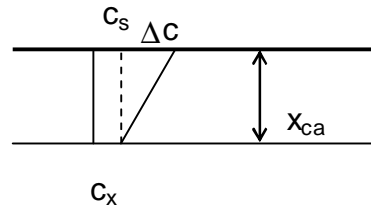


Figure 1. Carbonation on the surface of concrete.

The carbon dioxide flux into concrete must be in balance with the rate of mass growth of bound CO₂:

$$J = \frac{dQ_{ca}}{dt} \quad (2)$$

where Q_{ca} is the mass of chemically bound CO₂ in concrete, kgCO₂.

The mass of already bound CO₂ in concrete can be presented as

$$Q_{ca} = a \cdot x_{ca} \quad (3)$$

where a is the CO₂-binding capacity of concrete, kgCO₂/m³.

$$\frac{dQ_{ca}}{dt} = a \frac{dx_{ca}}{dt} \quad (4)$$

where t time, s.

By combining Equations 1 and 4 and integrating over time (x_{ca} = 0 when t = 0), the following solution is obtained:

$$x_{ca} = \sqrt{\frac{2D \cdot \Delta c \cdot t}{a}} \quad (5)$$

From Equation 5 it is seen that at constant conditions and with constant material properties the depth of carbonation is proportional to the square root of time. Thus the equation can be presented in a more simplified form as:

$$x_{ca} = k_{ca} \sqrt{t} \quad (6)$$

where t is the age of concrete, a, and

$$k_{ca} \text{ is coefficient of carbonation } \left(= \sqrt{\frac{2D \cdot \Delta c}{a}} \right), \text{ mm/a}^{0.5}.$$

The coefficient of carbonation depends on the permeability of concrete, quality of cement, possible cement replacements (blast furnace slag, silica fume etc.) and the environmental conditions. A less permeable concrete will yield a slower carbonation rate. In wet concrete, carbonation is much slower than in only slightly moist concrete.

Corrosion of reinforcement can start when carbonation attains the depth of reinforcement i.e. when the carbonated zone on the surface of the structure equals the concrete cover, C . So, from Eq. 5 the following equation for the “depassivation time” or “initiation time of corrosion” is obtained:

$$t_0 = \left(\frac{C}{k_{ca}} \right)^2 = \frac{C^2 \cdot a}{2D \cdot \Delta c} \quad (7)$$

where t_0 is initiation time of corrosion, a
 C concrete cover, mm.

Applying these results to the “factor method”, the initiation time can be presented as:

$$t_0 = t_{0r} \cdot A \cdot B \cdot E \quad (8)$$

where t_{0r} is reference initiation time of corrosion $\left(= \frac{C_r^2 \cdot a_r}{2D_r \cdot \Delta c_r} \right)$

A material factor $\left(= \frac{a}{a_r} \frac{D_r}{D} \right)$

B structural factor $\left(= \frac{C^2}{C_r^2} \right)$

E environmental factor $\left(= \frac{\Delta c_r}{\Delta c} \right)$.

The material factor A depends on the quality of concrete. i.e. the nominal strength of concrete and the quality of cement [7]. The material factor A can be divided into two factors ($A = A_1 \cdot A_2$) the other factor addressing the concrete strength (or w/c -ratio) and the other factor addressing the cement quality. The environmental factor E takes into account the moisture conditions of the environment as the diffusion of CO_2 in concrete depends much on the moisture content of concrete. The environmental factor as dependent on CO_2 content can be neglected if it is assumed that the CO_2 content is constant.

3 Chloride Penetration on the Surface of Concrete

The chloride penetration into concrete can be assumed to comply with the following equation according to Fick’s 2nd law of diffusion.

$$\frac{dc}{dt} = D \frac{d^2c}{dx^2} \quad (9)$$

where c chloride content, g/m^3 ,
 x distance from surface, m ,
 D diffusion coefficient with respect to chloride ion diffusion in concrete, m^2/s , and
 t time, s .

Actually a part of movable chlorides is chemically bound or adsorbed into concrete. So the equation for free chloride would be as follows:

$$\frac{dc_{free}}{dt} = D \frac{d^2c_{free}}{dx^2} - \frac{dc_{bound}}{dt} \quad (10)$$

where c_{free} is free chloride content, g/m^3 ,
 c_{bound} bound chloride content, g/m^3 ,

However, it is usually assumed that the amount of bound chloride is proportional to the amount of free chloride [3]:

$$c_{bound} = R \cdot c_{free} \quad (11)$$

where R is constant (depending on concrete).

Then the differential equation returns to Eq. 9. with following explanations:

c is total chloride content ($c_{free} + c_{bound}$), g/m^3 , and
 D apparent coefficient of diffusion with respect to chloride ions, m^2/s .

Although the free chloride gradient is the real driving potential for chloride penetration the total chloride content is used instead in the calculations and the (apparent) coefficient of diffusion is determined based on the total chloride gradient.

In the following it is assumed that the above mentioned rules are valid. This is important for practical reasons because the determination of free chloride content is extremely difficult. So, in practice the chloride content is determined as the total (acid soluble) chloride content and the surface chloride contents and critical chloride contents, which are essential parameters in service life models, are given as total chloride contents. Also the determination of the diffusion coefficient is based on total chloride content.

Having the differential equation 9 and assuming a semi-infinite wall with no time dependent changes in material properties the following solution can be derived for chloride content in concrete:

$$c = c_s \left(1 - \operatorname{erf} \left(\frac{x_{cl}}{2\sqrt{D \cdot t}} \right) \right) \quad (12)$$

c_s chloride content at the surface of concrete, g/m^3 ,

Although Equation 12 complies with the Fick's 2nd law of diffusion it cannot be considered exact in case of chloride penetration into concrete. That is because the assumptions made - constant surface content, constant environmental conditions and homogeneous quality of concrete (during the whole service life) - are practically never fulfilled. Also, the error-function solution is not very user friendly - especially considering differentiation of factors for the factor approach. That is why the use of a simpler model is justified. Next, the chloride content gradient is approximated with a parabola function which closely emulates the error-function model [2].

$$c = c_s \cdot \left(1 - \frac{x}{H}\right)^2 \quad x \leq H \quad (13)$$

where H is the depth of chloride ion penetration, m (the distance between the surface and the lowest point of the parabola).

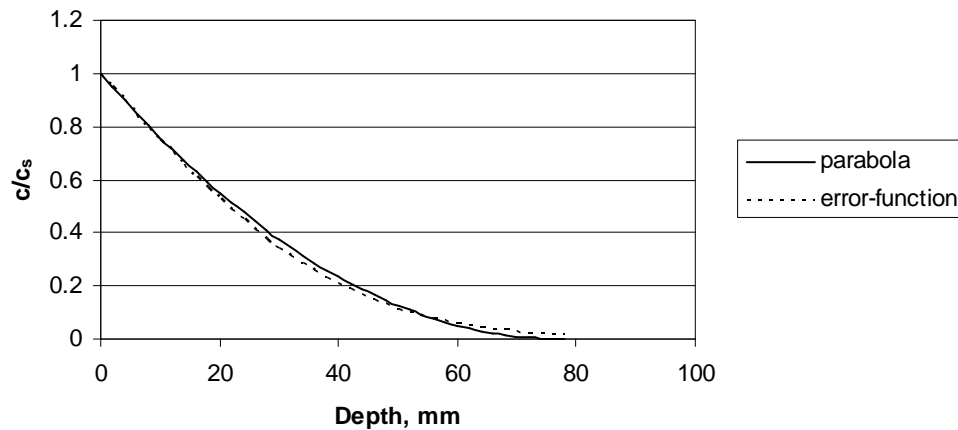


Figure 2. Parabola and error-function model for chloride penetration.

The parabola solution brings many benefits in practice. Not only the factorization for the factor approach is easier with the parabola solution but also the mathematical treatment of problems related to cracks, coatings, time-related changes in concrete quality and interaction with other degradation types are much easier to treat with the parabola model. The application of the error-function in the most simple case of chloride diffusion is not justified if it entails mathematical trade-offs in the more complicated cases.

So, starting from Eq. 13 an equation for the depth of chloride penetration, H, is derived by assuming that the chloride ion flux into concrete must be in balance with the mass growth of chloride ions in concrete. The flux of chloride ions into concrete can be presented as:

$$J = D \left(\frac{\partial c}{\partial x} \right)_s \quad (14)$$

where J is flux of chloride ions into concrete, g/m²s,
 D the diffusion coefficient of concrete with respect to chloride ion, m²/s,

$\left(\frac{\partial c}{\partial x}\right)_s$ gradient of the chloride content at the surface ($x = 0$), mol/m³/m.

Applying Eq. 13 to Eq. 14 the following solution is obtained:

$$J = D \frac{2c_s}{H} \quad (15)$$

The existing mass of chloride ions in concrete is:

$$Q_{cl} = \int_0^H c \, dx = \frac{c_s H}{3} \quad (16)$$

Thus the rate of mass growth is:

$$\frac{dQ_{cl}}{dt} = \frac{dH}{dt} \frac{c_s}{3} \quad (17)$$

By combining Equations 15 and 17, separating the variables, and integrating ($H = 0$ when $t = 0$) the equation becomes:

$$H = \sqrt{12 \cdot D \cdot t} \quad (18)$$

Inserting this to Equation 13 results in [2]:

$$c = c_s \cdot \left(1 - \frac{x}{2\sqrt{3 \cdot D \cdot t}}\right)^2 \quad (19)$$

The depth of the critical chloride content (with respect to initiation of corrosion) can be presented as a function of t by solving it from Eq. 19 and replacing c by the critical chloride content c_{crit} .

$$x_{Cl} = \left(1 - \sqrt{\frac{c_{crit}}{c_s}}\right) 2\sqrt{3 \cdot D \cdot t} \quad (20)$$

where x_{Cl} is depth of critical chloride content at moment t , m,
 c_{crit} critical chloride content, g/m³.

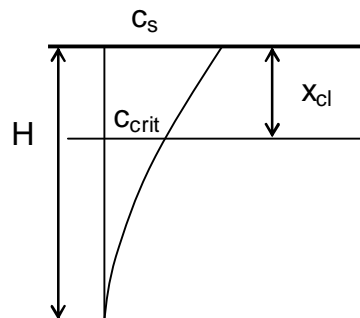


Figure 3. Chloride profile on concrete surface.

In this form it is obvious that the depth of the critical chloride content approximately complies with the "square-root-of-time"-law in the same way as the depth of carbonation:

$$x_{Cl} = k_{cl} \sqrt{t} \quad (21)$$

where k_{cl} coefficient of chloride penetration, mm/ $\sqrt{\text{year}}$ and
 t time, year.

The coefficient of chloride penetration can be determined as:

$$k_{cl} = 2\sqrt{3D} \cdot \left(1 - \sqrt{\frac{c_{crit}}{c_s}}\right) \quad (22)$$

Corrosion starts when the critical chloride content reaches the reinforcement. From Equations 21 and 22 the initiation time of corrosion can be determined as follows.

$$t_0 = \left(\frac{C}{k_{cl}}\right)^2 = \frac{C^2}{12D \cdot \left(1 - \sqrt{\frac{c_{crit}}{c_s}}\right)^2} \quad (23)$$

The critical chloride content, c_{crit} , is usually expressed as a percentage of the weight of cement [% (Cl) by weight of cement]. The corresponding amount as [g(Cl)/m³] is obtained as follows:

$$c_{crit} = 0.01 \cdot M_{cem} \cdot p_{crit} \quad (24)$$

where c_{crit} is critical chloride content, g[Cl]/m³
 M_{cem} amount of cement in concrete, g/m³,
 p_{crit} critical chloride content, % (Cl) by weight of cement.

Using the "factor approach" the initiation time can be presented as:

$$t_0 = t_{0r} \cdot A \cdot B \cdot E \quad (25)$$

where t_{0r} is reference initiation time of corrosion $\left(= \frac{C_r^2}{12D_r \cdot \left(1 - \sqrt{\frac{c_{crit}}{c_{sr}}}\right)^2} \right)$

A material factor $\left(= \frac{D_r}{D} \right)$

B structural factor $\left(= \frac{C^2}{C_r^2} \right)$

E environmental factor $\left(= \frac{\left(1 - \sqrt{\frac{c_{crit}}{c_{sr}}}\right)^2}{\left(1 - \sqrt{\frac{c_{crit}}{c_s}}\right)^2} \right)$.

4 Carbonation at a Crack of Concrete

Carbonation rate at a crack of concrete can be derived using the same principles as those applied in the case of a normal concrete surface. The CO₂-gas first diffuses into a crack and then to concrete at the sides of the crack. The flux of the diffused CO₂ mass must equal the chemically bound CO₂ mass at the sides of the crack. In the following the problem is applied only to one side of the crack.

The CO₂ flux through half of a crack can be presented as (ref. Eq. 1). The axis y denotes the distance from the surface at the crack and the axis z denotes the distance from the crack surface into the concrete:

$$J_{Ry} = D_R \frac{\Delta c_R}{y_{ca}} \frac{w}{2} \quad (26)$$

where J_R is flux of carbon dioxide into concrete, g/m²s,
 D_R the diffusion coefficient of concrete with respect to CO₂, m²/s,
 y_{ca} depth of carbonation at the crack, m,
 w width of the crack, m
 $\Delta c_R = c_s - c_x$, g(CO₂)/m³,
 c_s CO₂ content of air at the surface of concrete, g(CO₂)/m³ and
 c_x CO₂ content of air at the depth y_{ca} , g(CO₂)/m³.

The diffusion to concrete at one side of the crack is (ref. Eq. 1)

$$J_{Rz} = \int_0^{y_{ca}} D \frac{\Delta c_{Ry}}{z_y} dy \quad (27)$$

where Δc_{Ry} is CO₂-content in the crack at the distance y from the origin, g(CO₂)/m³
 z_y is depth of carbonation at the crack at the distance y from the origin, m.

The CO₂-content in the crack is assumed to reduce linearly to 0 at the depth of y_{ca} . More difficult is to know the depth of carbonation at the side of the crack. Next, it is assumed that the depth of carbonation changes as related to $(y/y_{ca})^n$ where n is an unknown exponent (solved later). For simplification the origin is assumed to be at the tip of the carbonated wedge at the crack, i.e. at y_{ca} from the surface. Thus Δc_{Ry} and z_y can be expressed as functions of y :

$$\Delta c_{Ry} = \Delta c_R \cdot \left(\frac{y}{y_{ca}} \right) \quad (28 a)$$

$$z_y = z_{ca} \left(\frac{y}{y_{ca}} \right)^n \quad (28 b)$$

where Δc_R is CO₂-content at the crack at the surface of the structure, g(CO₂)/m³,
 z_{ca} is depth of carbonation at the side of the crack at the surface of the structure, m.

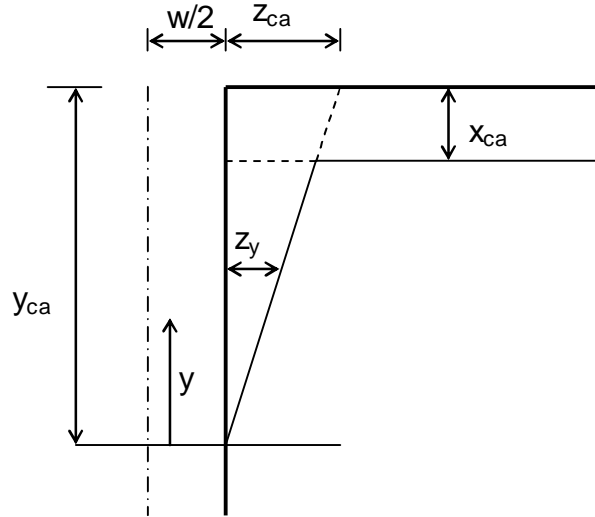


Figure 4. Carbonation at a crack of concrete.

Eq. 27 will then be:

$$J_{Rz} = \int_0^{y_{ca}} D \frac{\Delta c_R}{z_{ca}} \left(\frac{y}{y_{ca}} \right)^{1-n} dy = D \frac{\Delta c_R}{z_{ca}} \frac{y_{ca}}{2-n} \quad (29)$$

The mass of already carbonated concrete at one side of the crack is:

$$Q_{ca} = a \cdot \int_0^{y_{ca}} z_y dy = a \cdot z \int_0^{y_{ca}} \left(\frac{y}{y_{ca}} \right)^n dy = \frac{a \cdot z_{ca} \cdot y_{ca}}{n+1} \quad (30)$$

where Q_{ca} is the mass of bound CO_2 at one side of the crack, g,
 a CO_2 -binding capacity of concrete, $\text{g}(\text{CO}_2)/\text{m}^3$.

Both y_{ca} and z_{ca} are time-related variables. So, the rate of mass growth in y and z directions is divided as follows:

$$\frac{dQ_{ca}}{dt} = \left(\frac{dQ_{ca}}{dt} \right)_y + \left(\frac{dQ_{ca}}{dt} \right)_z \quad (31)$$

As combined with the fluxes of CO_2 in y and z directions there is the requirement:

$$J_{Ry} + J_{Rz} = \left(\frac{dQ_{ca}}{dt} \right)_y + \left(\frac{dQ_{ca}}{dt} \right)_z \quad (32)$$

It is now assumed that the diffusion in the y direction corresponds to the mass growth in the y direction and the diffusion in the z direction corresponds to mass growth in the z direction. From Eq. 26 the y direction becomes:

$$D_R \frac{\Delta c_R}{y_{ca}} \frac{w}{2} = \frac{a \cdot z_{ca}}{n+1} \frac{dy_{ca}}{dt} \quad (33)$$

Correspondingly from Eq. 29 in the z direction:

$$D \frac{\Delta c_R}{z_{ca}} \frac{y_{ca}}{2-n} = \frac{a \cdot y_{ca}}{n+1} \frac{dz_{ca}}{dt} \quad (34)$$

From 34 by differentiating the variables and integrating ($t = 0, z_{ca} = 0$)

$$z_{ca} = \sqrt{\frac{n+1}{2-n} \frac{D \cdot \Delta c_R}{a} \cdot t} \quad (35)$$

This equals to Eq. 5 assuming $\Delta c = \Delta c_R$ and $n = 1$. Thus, the previously made assumptions related to the carbonation in z -direction can be considered proven correct. The sides of the carbonated wedge are proven to be linear ($n = 1$) and $z_{ca} = x_{ca}$.

In the y -direction (Eq. 33) the origin is then set to the mouth of crack. Thus finding ($n = 1, z = x_{ca} = k_{ca}\sqrt{t}$):

$$\int_0^{y_{ca}} y_{ca} dy_{ca} = \frac{D_R \cdot \Delta c_R \cdot w}{a \cdot k_{ca}} \cdot \int_0^t \frac{1}{\sqrt{t}} dt \quad (36)$$

from which it can be solved:

$$y_{ca} = \sqrt{\frac{4 \cdot D_R \cdot \Delta c_R \cdot w}{a \cdot x_{ca}} \cdot t} \quad (37)$$

and further noting Eq. 5.

$$y_{ca} = \sqrt{\frac{2 \cdot D_R \cdot w \cdot 2 \cdot D \cdot \Delta c_R \cdot t}{D \cdot a \cdot x_{ca}}} = \sqrt{\frac{2 \cdot D_R \cdot w}{D} x_{ca}} \quad (38)$$

This is the same function as that derived by Schiebl [9]. Thus y_{ca} is proportional to the square root of x_{ca} . By inserting Eq. 5:

$$y_{ca} = \sqrt{\frac{2 \cdot D_R \cdot w}{D} k_{ca} \cdot \sqrt[4]{t}} \quad (39)$$

From 39 the initiation time of corrosion at a crack can be solved ($y_{ca} = C$ when $t = t_0$):

$$t_{0R} = \frac{C^4}{\left(\frac{2 \cdot D_R \cdot w}{D} k_{ca}\right)^2} \quad (40)$$

Noting Eq. 7 a practical solution results:

$$t_{0R} = \frac{C^2}{\left(\frac{2 \cdot D_R \cdot w}{D}\right)^2} \cdot t_0 \quad (41)$$

The initiation time of corrosion at a crack can be determined by multiplying the initiation time of corrosion at a normal concrete surface by a crack factor, F_R , which is

$$F_R = \left(\frac{C}{2 \cdot w} \right)^2 \cdot \left(\frac{D}{D_R} \right)^2 \quad (42)$$

5 Chloride Penetration at a Crack of Concrete

A mathematical model for the penetration of chloride ions at the crack of concrete is derived based on the same principles as those applied in the case of carbonation. The flux of chloride ions into a crack and then into concrete at the sides of the crack must equal the mass growth of chloride ions in concrete. The axis y denotes the distance from the surface at the crack and the axis z denotes the distance from the crack surface into concrete. The parabola model is assumed for the chloride gradient at the crack:

$$c_{Ry} = c_{Rs} \cdot \left(1 - \frac{y}{H_R} \right)^2 \quad y \leq H_R \quad (43)$$

where c_{Ry} is chloride content at the crack at the distance of y from the surface, g/m^3 ,
 c_{Rs} chloride content at the mouth of the crack (at surface level of structure), g/m^3 ,
 y distance from surface, m,
 H_R the depth of chloride penetration at the crack, m.

Thus the chloride ion flux into one wall of the crack is (comparing Eq. 15 and Eq. 26):

$$J_{Ry} = D_R \frac{2c_{Rs}}{H_R} \cdot \frac{w}{2} \quad (44)$$

where J_{Ry} is flux of chloride ions into crack, $\text{g/m}^2\text{s}$,
 D_R the diffusion coefficient of the crack with respect to chloride ions, m^2/s ,
 w width of the crack, m.

As in the case of chloride diffusion at the concrete surface, an equation for the mass growth of chloride ions at a crack can be presented (compare Equations 16 and 17):

$$\frac{dQ_{cl}}{dt} = \frac{dH_R}{dt} \frac{c_{Rs}}{3} \cdot \frac{w}{2} \quad (45)$$

However, the chloride ions are assumed to further diffuse into concrete at the sides of the crack. The diffusion through concrete at one side of the crack is (compare Eq. 27):

$$J_{Rz} = \int_0^{H_R} D \frac{2 \cdot c_{Ry}}{H_{zy}} dy \quad (46)$$

where c_{Ry} is chloride ion content at the crack at the distance y from the origin, g/m^3 ,
 H_{zy} depth of chloride penetration in z -direction at the crack at the distance y from the origin, m.

The chloride ion content at the crack is assumed to reduce according to Eq. 43. The depth of chloride penetration into the wall of the crack (in z -direction) is unknown, but it is assumed that H_{zy} (the depth of chloride penetration as a function of y) is related to $(1-y/H_R)^n$ where n is an unknown exponent. To make the calculations easier the origin is changed to the tip of the chloride contaminated wedge at the crack, i.e. at H_R from the surface. Thus c_{Ry} and H_{zy} are presented as:

$$c_{Ry} = c_R \left(\frac{y'}{H_R} \right)^2 \quad (47 \text{ a})$$

$$H_{zy} = H_z \left(\frac{y'}{H_R} \right)^n \quad (47 \text{ b})$$

where H_{zy} depth of chloride ion penetration at the side of the crack in z -direction, m,
 y' distance from the tip of the chloride contaminated wedge ($= H_R - y$), m,
 H_z depth of chloride ion penetration in z -direction at the mouth of the crack, m.

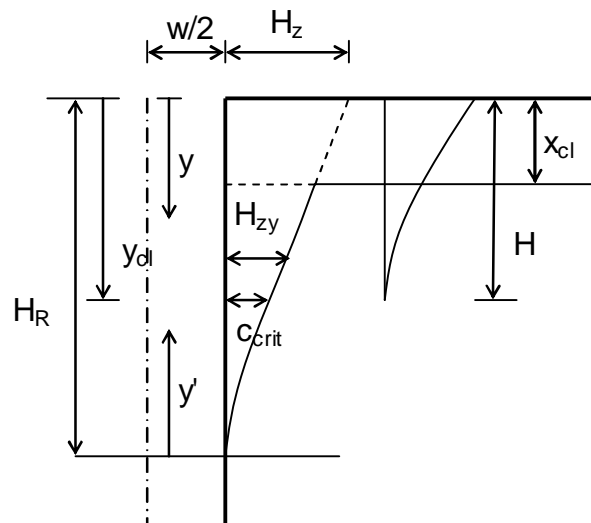


Figure 5. Chloride penetration at a crack of concrete.

Then from Eq. 46 follows:

$$J_{Rz} = \int_0^{H_R} D \frac{c_R}{H_z} \left(\frac{y'}{H_R} \right)^{2-n} dy' = D \frac{c_R}{H_z} \frac{H_R}{3-n} \quad (48)$$

The mass of chlorides ions in concrete is:

$$Q_{cl} = \int_0^{H_R} \frac{c_y \cdot H_z}{3} dy' = c_R \cdot H_z \int_0^{H_R} \left(\frac{y'}{H_R} \right)^{2+n} dy' = \frac{c_R \cdot H_z \cdot H_R}{n+3} \quad (49)$$

where Q_{cl} is the mass of chloride ions at one side of the crack, g/m.

Both H_z and H_R are time dependent variables. So the rate of mass growth is determined as follows:

$$\frac{dQ_{cl}}{dt} = \left(\frac{dQ_{cl}}{dt} \right)_y + \left(\frac{dQ_{cl}}{dt} \right)_z = \frac{c_R \cdot H_z}{n+3} \frac{dH_R}{dt} + \frac{c_R \cdot H_R}{n+3} \frac{dH_z}{dt} \quad (50)$$

It is now assumed (as in the case of carbonation) that the diffusion in the y direction corresponds to the mass growth in the y direction and the diffusion in the z direction corresponds to mass growth in the z direction. Then by taking Eq. 44 it is determined in the y-direction:

$$D_R \frac{2 \cdot c_R \cdot w}{H_R \cdot 2} = \frac{c_R \cdot H_z}{n+3} \frac{dH_R}{dt} \quad (51)$$

And correspondingly in the z-direction (Eq. 48):

$$D \frac{c_R \cdot H_R}{H_z \cdot 3-n} = \frac{c_R \cdot H_R}{n+3} \frac{dH_z}{dt} \quad (52)$$

From 52 by differentiating the variables and integrating ($t = 0, H_z = 0$) it is found that:

$$H_z = \sqrt{\frac{n+3}{3-n} \cdot 2 \cdot D \cdot t} \quad (53)$$

This is equal to Equation 18 assuming that $n = 15/7 \approx 2.14$. The sides of the chloride contaminated wedge are curved and related approximately to the function $(y'/H_R)^{2.14}$. The depth of the chloride content at the mouth of the crack can be assumed to be the same as the depth of the chloride content on an uncracked concrete surface ($H_z = H = \sqrt{12Dt}$).

In the y-direction the origin is set back to the surface. Thus it is obtained (ref. Eq. 51):

$$\int_0^{H_R} H_R dH_R = (n+3) \frac{D_R \cdot w}{\sqrt{12D}} \cdot \int_0^t \frac{1}{\sqrt{t}} dt \quad (54)$$

from which it can be solved:

$$H_R = \sqrt{\frac{2 \cdot (n+3) \cdot D_R \cdot w}{\sqrt{3} \cdot \sqrt{D}} \cdot \sqrt{t}} \quad (55)$$

and further noting Eq. 15.

$$H_R = \sqrt{\frac{n+3}{3} \frac{D_R \cdot w \cdot \sqrt{12 \cdot D \cdot t}}{D}} = \sqrt{\frac{12}{7} \frac{D_R \cdot w \cdot H}{D}} \quad (56)$$

Thus H_R is proportional to the square root of H . The critical depth of chloride content at a crack, y_{cl} , can also be presented as a function of x_{cl} :

$$y_{cl} = \left(1 - \sqrt{\frac{c_{crit}}{c_s}}\right) \cdot H_R = \left(1 - \sqrt{\frac{c_{crit}}{c_s}}\right) \sqrt{\frac{12}{7} \frac{D_R \cdot w \cdot x_{cl}}{D \left(1 - \sqrt{\frac{c_{crit}}{c_s}}\right)}} \quad (57)$$

or as a function of t .

$$y_{cl} = \left(1 - \sqrt{\frac{c_{crit}}{c_s}}\right)^{\frac{1}{2}} \cdot \left(\frac{12}{7} \frac{D_R \cdot w \cdot k_{cl}}{D}\right)^{\frac{1}{2}} \cdot t^{\frac{1}{4}} \quad (58)$$

Finally from Eq. 58 the initiation time of corrosion at a crack can be solved:

$$t_{0R} = \frac{C^4}{\left(\frac{12 \cdot D_R \cdot w \cdot k_{cl}}{7 \cdot D}\right)^2 \left(1 - \sqrt{\frac{c_{crit}}{c_s}}\right)^2 \cdot k_{cl}^2} \quad (59)$$

However, noting still Eq. 23, it is found:

$$t_{0R} = \frac{C^2}{\left(\frac{12 \cdot D_R \cdot w}{7 \cdot D}\right)^2 \left(1 - \sqrt{\frac{c_{crit}}{c_s}}\right)^2} \cdot t_0 \quad (60)$$

The initiation time of corrosion at a crack can be determined by multiplying the initiation time of corrosion on a normal concrete surface by a crack factor, F_R , which is

$$F_R = \left(\frac{7 \cdot C}{12 \cdot w}\right)^2 \cdot \left(\frac{D}{D_R}\right)^2 \cdot \left(\frac{1}{1 - \sqrt{\frac{c_{crit}}{c_s}}}\right)^2 \quad (61)$$

6 Carbonation on a Coated Concrete Surface

Coatings retard the penetration CO_2 into concrete. Thus they reduce the rate of carbonation of concrete and lengthen the initiation time of corrosion. In the following a “coating factor” is derived for the initiation time of corrosion at a coated concrete surface. The flux of CO_2 through the coating is [3]:

$$J_c = D_c \frac{(c_s - c_g)}{h_c} \quad (62)$$

where J_c is flux of carbon dioxide through coating, $\text{g}/\text{m}^2\text{s}$,
 D_c the diffusion coefficient of the coating with respect to CO_2 , m^2/s ,
 h_c thickness of the coating, m ,
 c_s CO_2 content of air at the surface of the coated concrete, $\text{g}(\text{CO}_2)/\text{m}^3$, and
 c_g CO_2 content of air at the concrete side of the coating, $\text{g}(\text{CO}_2)/\text{m}^3$.

The CO_2 flux in concrete assuming that c_0 is approximately 0 is:

$$J_1 = D \frac{(c_g - c_0)}{x_1} \approx D \frac{c_g}{x_1} \quad (63)$$

where J_1 is flux of CO_2 into concrete, $\text{g}/(\text{m}^2\text{s})$,
 D diffusion coefficient of concrete, m^2/s ,
 c_0 CO_2 content at the depth of x_1 in concrete, $\text{g}(\text{CO}_2)/\text{m}^3$
 x_1 depth of carbonation (behind the coating), m .

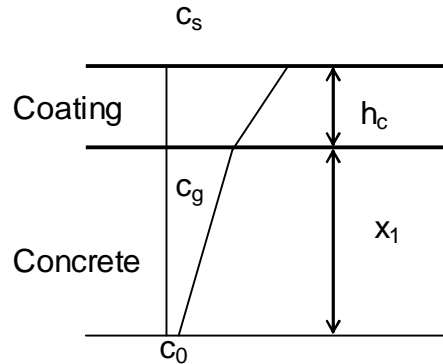


Figure 6. Carbonation under a coating.

By setting $J_c = J_1$ the CO_2 content immediately behind the coating (c_g) can be solved as follows [3]:

$$c_g = \frac{c_s}{1 + \frac{D}{x_1} \cdot \frac{h_c}{D_c}} \quad (64)$$

Thus the rate of mass growth of bound CO_2 in concrete is:

$$\frac{dQ_{ca}}{dt} = a \frac{dx_1}{dt} \quad (65)$$

where t time, s .

By combining Equations 63 and 65, it is found that:

$$D \frac{c_s}{x_1 + \frac{D \cdot h_c}{D_c}} = a \frac{dx_1}{dt} \quad (66)$$

By separating the variables and integrating ($t = 0, x_1 = 0$) it is seen that:

$$t = \frac{a \cdot x_1^2}{2 \cdot D \cdot c_s} \left(1 + 2 \frac{D \cdot h_c}{x_1 \cdot D_c} \right) \quad (67)$$

when t is the initiation time of corrosion, t_{0c} , x_1 is C :

$$t_{0c} = \frac{a \cdot C^2}{2 \cdot D \cdot c_s} \left(1 + 2 \frac{D \cdot h_c}{C \cdot D_c} \right) \quad (68)$$

By noting Eq. 7 we get:

$$t_{0c} = t_0 \cdot \left(1 + 2 \frac{D \cdot h_c}{C \cdot D_c} \right) \quad (69)$$

where t_{0c} is initiation time of a coated structure, a
 t_0 initiation time of uncoated structure.

Thus the coating factor of initiation time is:

$$B_c = 1 + 2 \frac{D \cdot h_c}{C \cdot D_c} \quad (70)$$

where B_c is the coating factor.

The coating factor can be easily tabulated by the concrete parameter D/C and the coating parameter D_c/h_c .

7 Chloride Penetration on a Coated Concrete Surface

In the case of chloride penetration on a coated concrete surface the first step is to solve the chloride content immediately beneath the coating. The flux through the coating is:

$$J_c = D_c \frac{(c_s - c_g)}{h_c} \quad (71)$$

where J_c is flux of chloride ions through coating, $\text{g/m}^2\text{s}$,
 D_c the diffusion coefficient of the coating with respect to chloride ions, m^2/s ,
 h_c thickness of the coating, m ,
 c_s chloride content at the surface of the coated concrete, g/m^3 , and
 c_g chloride content immediately behind the coating, g/m^3 .

The flux under the coating is according to Eq. 15:

$$J_1 = D \frac{2c_g}{H_1} \quad (72)$$

where J_1 is flux of chloride ions towards concrete, $\text{g/m}^2\text{s}$,
 H_1 depth of chloride penetration, m.

By setting J_c equal to J_1 it is found that:

$$c_g = \frac{c_s}{1 + \frac{2D \cdot h_c}{H_1 \cdot D_c}} \quad (73)$$

The rate of mass growth of chloride ions in concrete is according to Eq. 17:

$$\frac{dQ_{cl}}{dt} = \frac{dH_1}{dt} \frac{c_s}{3} \quad (74)$$

By setting this equal to J_1 and separating factors it is seen that:

$$\left(H_1 + \frac{2D \cdot h_c}{D_c} \right) dH_1 = 6D \cdot dt \quad (75)$$

By integrating ($t = 0, H_1 = 0$) it is found that:

$$t = \frac{H_1^2}{12 \cdot D} \left(1 + \frac{4D \cdot h_c}{H_1 \cdot D_c} \right) \quad (76)$$

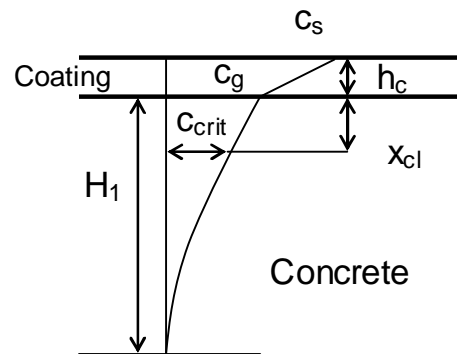


Fig 7. Chloride penetration under a coating.

The solution of the interaction factor is not so easy as in the case carbonation because the service life is not determinable based on the total penetration of chloride but on the critical chloride content. It is also seen that the surface content of chlorides in concrete is lowered by the coating so that the efficient surface content is c_g instead of c_s . From equation 76 the total depth of chloride penetration can be solved as follows.

$$H_1 = \sqrt{\left(\frac{2 \cdot D \cdot h}{D_c}\right)^2 + 12 \cdot D \cdot t} - \frac{2 \cdot D \cdot h}{D_c} \quad (77)$$

The depth of critical chloride content can then be determined as follows:

$$x_{cl} = \left(1 - \sqrt{\frac{c_{crit}}{c_g}}\right) \cdot H_1 \quad (78)$$

where c_g is the chloride content of concrete immediately behind the coating and is determined from Eq. 73, and,
 x_{cl} the depth of critical chloride content.

The time equals to the initiation time of corrosion, t_{0c} , when the depth of critical chloride content attains the depth of concrete cover, C . An arithmetical solution is difficult to present but the problem can be solved by Goal Seek or Solver. Finally the relationship t_{0c}/t_0 is determined (t_0 is the initiation time of corrosion at a non-coated surface). The results can be tabulated by factors c_{crit}/c_s , D/D_c and h/C representing environmental conditions (factor E), material properties (factor A) and structural measures (factor B).

8 The Effect of Aging on Carbonation of Concrete

Some properties of concrete improve with age because of continuous hydration of cement minerals. Such properties are the strength, diffusion resistance, electric resistivity etc. When studying diffusion problems like carbonation the actual diffusion coefficient reduces with time as follows [1, 5, 6, 10]:

$$D = D_N \left(\frac{t_N}{t}\right)^n \quad (79)$$

where D diffusion coefficient of concrete with respect to CO_2 , m^2/s ,
 D_N diffusion coefficient of concrete at the nominal age of concrete t_N , m^2/s ,
 t age of structure, years,
 t_N nominal age of concrete (= 28 d = 0.0767 years),
 n exponent depending on the quality of cement.

Thus CO_2 flux through the surface of the structure is dependent on time:

$$J = D_N \cdot \left(\frac{t_N}{t}\right)^n \frac{\Delta c}{x_{ca}} \quad (80)$$

Setting this equal to the mass growth of bound CO_2 (ref. Eq.4) it is found that:

$$D_N \cdot \left(\frac{t_N}{t}\right)^n \frac{\Delta c}{x_{ca}} = a \frac{dx_{ca}}{dt} \quad (81)$$

where t is time (or age of the structure), s.

By integrating over time ($x_{ca} = 0$ when $t = 0$) the following solution is obtained:

$$x_{ca} = \sqrt{\frac{2D_N \cdot \Delta c \cdot t_N}{a \cdot (1-n)}} \cdot \left(\frac{t}{t_N}\right)^n \quad (82)$$

For initiation time of corrosion it is then found ($t = t_0$ when $x_{ca} = C$)

$$t_0 = \left(\frac{C^2 \cdot a \cdot (1-n)}{2D_N \cdot \Delta c \cdot t_N}\right)^{\frac{1}{1-n}} \cdot t_N \quad (83)$$

As applied to the factor method one can write:

$$t_0 = t_{0r} \cdot A \cdot B \cdot E \quad (84)$$

where t_{0r} is reference initiation time of corrosion

$$= \left(\frac{C_r^2 \cdot a_r \cdot (1-n_r)}{2D_{Nr} \cdot \Delta c_r \cdot t_N}\right)^{\frac{1}{1-n_r}} \cdot t_N,$$

$$A \quad \text{material factor} = \frac{\left(\frac{a}{D} \cdot (1-n)\right)^{\frac{1}{1-n}}}{\left(\frac{a_r}{D_r} \cdot (1-n_r)\right)^{\frac{1}{1-n_r}}},$$

$$B \quad \text{structural factor} = \frac{C^{\frac{2}{1-n}}}{C_r^{\frac{2}{1-n_r}}},$$

$$E \quad \text{environmental factor} = \frac{\Delta c_r^{\frac{1}{1-n}}}{\Delta c^{\frac{1}{1-n_r}}}.$$

The parameter n depends partly on the cement partly on the environment [10]. Thus it is impossible to completely separate environmental factors from material factors and structural factors.

9 The Effect of Aging on Chloride Penetration in Concrete

As in the case of carbonation also diffusion coefficient with respect to chloride diffusion is considered to be reduced with time [1, 5, 6, 10]:

$$D = D_N \left(\frac{t_N}{t}\right)^n \quad (85)$$

where D diffusion coefficient of concrete with respect to Cl^- , m^2/s ,
 D_N diffusion coefficient of concrete at the nominal age of concrete
 t_N , m^2/s .

By setting $J = dQ_{cl}/dt$ (ref Eq. 15 and 17) it is found that:

$$D_N \left(\frac{t_N}{t} \right)^n \cdot \frac{2 \cdot c_s}{H} = \frac{dH}{dt} \frac{c_s}{3} \quad (86)$$

By combining separating variables H and t , and integrating ($H = 0$ when $t = 0$):

$$H = \sqrt{\frac{12}{1-n} \cdot D_N \cdot t_N} \cdot \left(\frac{t}{t_N} \right)^{\frac{1-n}{2}} \quad (87)$$

The depth of the critical chloride content (with respect to initiation of corrosion) is thus:

$$x_{Cl} = \left(1 - \sqrt{\frac{c_{crit}}{c_s}} \right) \sqrt{\frac{12}{1-n} \cdot D_N \cdot t_N} \left(\frac{t}{t_N} \right)^{\frac{1-n}{2}} \quad (88)$$

The initiation time of corrosion is:

$$t_0 = \left(\frac{C^2}{\left(1 - \sqrt{\frac{c_{crit}}{c_s}} \right)^2} \cdot \frac{1-n}{12} \frac{1}{D_N \cdot t_N} \right)^{\frac{1}{1-n}} \cdot t_N \quad (89)$$

Using the “factor method” the initiation time can be presented as:

$$t_0 = t_{0r} \cdot A \cdot B \cdot E \quad (90)$$

where t_{0r} is reference initiation time of corrosion

$$= \left(\frac{C_r^2 \cdot (1-n_r)}{12 D_{Nr} \cdot t_N \cdot \left(1 - \sqrt{\frac{c_{crit}}{c_{sr}}} \right)^2} \right)^{\frac{1}{1-n_r}} \cdot t_N,$$

A material factor = $\frac{\left(\frac{(1-n)}{12 D_N \cdot t_N} \right)^{\frac{1}{1-n}}}{\left(\frac{(1-n_r)}{12 D_{Nr} \cdot t_N} \right)^{\frac{1}{1-n_r}}},$

B structural factor = $\frac{\left(\frac{C^{\frac{2}{1-n}}}{C_r^{\frac{2}{1-n_r}}} \right)}{\left(\frac{C^{\frac{2}{1-n}}}{C_r^{\frac{2}{1-n_r}}} \right)},$

E environmental factor = $\frac{\left(\frac{\left(1 - \sqrt{\frac{c_{crit}}{c_{sr}}} \right)^{\frac{2}{1-n_r}}}{\left(1 - \sqrt{\frac{c_{crit}}{c_s}} \right)^{\frac{2}{1-n}}} \right)}{\left(\frac{\left(1 - \sqrt{\frac{c_{crit}}{c_s}} \right)^{\frac{2}{1-n}}}{\left(1 - \sqrt{\frac{c_{crit}}{c_s}} \right)^{\frac{2}{1-n}}} \right)}.$

As with carbonation, the exponent n depends on both environmental conditions and cement types [10]. So the separation of environmental factors from material factors and structural factors is not possible.

10 The Effect of Frost Attack on Carbonation of Concrete

There are two forms of frost attack: one - internal attack - causing internal cracks in concrete, and the other - frost scaling - causing cracking and disintegration of concrete at the surface of a structure. Internal frost attack reduces the compressive strength and other physical properties of concrete. The diffusion coefficient with respect to both CO_2 and chlorides increases as a result of internal frost attack. Assuming that the increase of the diffusion coefficient can be expressed as a function of time the following model for the effective diffusion coefficient would be applied:

$$D_{\text{eff}} = D_N \cdot k_{\text{IntFrost}}(t) \quad (91)$$

where D_{eff} effective diffusion coefficient of concrete with respect to CO_2 , m^2/s ,
 D_N diffusion coefficient of concrete without the effect of frost, m^2/s ,
 k_{IntFrost} reduction coefficient taking into account the effect of internal frost action on the diffusion coefficient
 t age of structure, years.

The other type of frost attack which is usually associated with chloride salts causes scaling of concrete surface. Thus the thickness of concrete cover is diminished as a result of frost scaling [4]:

$$x_{\text{ca,eff}} = x_{\text{ca}}(t) - x_{\text{frSc}}(t) \quad (92)$$

where $x_{\text{ca,eff}}$ effective depth of carbonation, m,
 x_{ca} original depth of carbonation, m,
 x_{frSc} depth of scaled concrete from the surface of the structure, m,
 t age of structure, years.

Applying Equations 91 and 92 to Equation 1, setting it equal to Eq. 4, and adding coefficients for temperature and moisture variations and hydration of cement, the following differential equation is obtained:

$$D_N \cdot \left(\frac{t_N}{t} \right)^n \cdot k_T(t) \cdot k_{RH}(t) \cdot k_{\text{IntFrost}}(t) \cdot \frac{\Delta c}{x_{\text{ca}}(t) - x_{\text{frSc}}(t)} = a \frac{dx_{\text{ca}}}{dt} \quad (93)$$

This function cannot be solved analytically because the variables cannot be separated. So, the problem can only be solved by numerical methods. The numerical solution can be formulated as follows:

$$x_{ca} = \sum \Delta x_{ca} \quad (94)$$

$$\Delta x_{ca}(t + \Delta t) = \frac{D_N}{a} \cdot \left(\frac{t_N}{t} \right)^n \cdot k_T(t) \cdot k_{RH}(t) \cdot k_{IntFrost}(t) \cdot \frac{\Delta c}{x_{ca}(t) - x_{FrSc}(t)} \cdot \Delta t$$

where k_T is coefficient taking into account the effect of the momentary temperature on the diffusion coefficient, and
 k_{RH} coefficient taking into account the momentary relative humidity on the diffusion coefficient.

The numerical simulation can be conducted in a simple or a more profound way. Here a simple way, in which only the effects of frost attack are considered, is presented. Thus the diffusion coefficient is not assumed to reduce with time as a result of hydration. Also the temperature and moisture coefficients are ignored as the calculations are performed on annual bases (daily and hourly fluctuations of temperature and moisture can be ignored). The increase of the diffusion coefficient (as a result of internal frost attack) is assumed to occur linearly. Likewise the frost scaling is assumed to proceed linearly with time. Then the Eq. 94 can be simplified in the following form [11]:

$$x_{ca} = \sum \Delta x_{ca} \quad (95)$$

$$\Delta x_{ca}(t + \Delta t) = \frac{k_{ca}^2}{2} \cdot \frac{k_{IntFr} \cdot t}{x_{ca}(t) - k_{FrSc} \cdot t} \cdot \Delta t$$

where k_{IntFr} is a coefficient of linear internal frost attack, and
 k_{FrSc} a coefficient of linear frost-salt attack.

Considering, for example, that the diffusion coefficient of CO_2 is doubled when the limit state of service life with respect to frost attack is reached, then the coefficient of internal frost attack would be:

$$k_{IntFr} = \frac{2}{t_{L;IntFr}} \quad (1/\text{year}) \quad (96)$$

where $t_{L;IntFr}$ is the predicted service life of the structure with respect to internal frost attack.

Likewise considering that the limit depth of scaling is 20 mm at the end of the service life of the structure. Then the coefficient k_{FrSc} for frost scaling is:

$$k_{FrSc} = \frac{20}{t_{L;FrSc}} \quad (\text{mm}/\text{year}) \quad (97)$$

where $t_{L;FrSc}$ is the predicted service life of the structure with respect to frost-salt attack.

Considering further that the original predicted initiation time of corrosion with respect to carbonation is $t_{0;ca}$. Then the coefficient of carbonation is:

$$k_{ca} = \frac{C}{\sqrt{t_{0;ca}}} \quad (mm/\sqrt{a}) \quad (98)$$

where $t_{0;ca}$ is the original predicted initiation time of corrosion with respect to carbonation, and,
 C concrete cover, mm.

In the following first the determination of the interaction factor of initiation time of corrosion interacted by internal frost attack is presented. This interaction factor, $I_{t_{0;ca};IntFr}$, is calculated as the relation of the reduced initiation time of corrosion due to internal frost attack to the original initiation time (without interaction). The original initiation time of corrosion, $t_{0;ca}$, and the service life with respect to internal frost attack, $t_{L;IntFr}$, are assumed to be known and they are parameters with which the interaction factor is tabulated. The calculation procedure goes on as follows:

- 1) Give the original $t_{0;ca}$ and $t_{L;IntFr}$
- 2) Calculate the corresponding k_{ca} (Eq. 98) and k_{IntFr} (Eq. 96)
- 3) Calculate in a table as a function of time from 0 to 250 years the annual (1) carbonation depth without interaction, (2) internal frost attack and (3) carbonation as interacted by internal frost attack using Eq. 95 (the frost scaling is now ignored).
- 4) Determine (1) $t_{0;ca}$ as the time when the carbonation depth exceeds the concrete cover (should be the same as that given at stage 1), (2) $t_{L;IntFr}$ as the time when the internal frost attack exceeds the limit state of service life (should be the same as that given at stage 1), and (3) time when the carbonation depth exceeds the concrete cover with interaction ($t_{0;ca;Int}$).
- 5) Determine the ratio $I_{t_{0;ca};IntFr} = t_{0;ca;Int}/t_{0;ca}$.

Table 1 shows the calculation table. The initiation time of corrosion is reached when the figure in the carbonation columns attains 1. Likewise the service life with respect to internal frost attack corresponds to the value 1 for internal frost attack. Concrete cover is not an essential parameter in this case. The interaction parameters are presented in Table 2.

Table 1. Calculation table of interaction parameters Internal Frost -> Carbonation.

	Carbonation	Internal Frost	Int Carbonation	
Cover, mm	25		100 %	=Increment of carbonation
Service life, year	50	40		at the end of Int Frost SL
Coefficient	3.54	0.025	0.025	
t_L (analysis), year	49	40	34	
			0.69	=Interaction Factor
t				
0	0.00	0.00	0.00	
1	0.14	0.03	0.14	
2	0.21	0.05	0.22	
3	0.26	0.08	0.27	
4	0.30	0.10	0.31	
5	0.33	0.13	0.34	
6	0.36	0.15	0.38	
7	0.39	0.18	0.41	
8	0.41	0.20	0.44	
9	0.44	0.23	0.47	
10	0.46	0.25	0.49	
11	0.48	0.28	0.52	
12	0.50	0.30	0.54	
13	0.52	0.33	0.57	
14	0.54	0.35	0.59	
15	0.56	0.38	0.62	
16	0.58	0.40	0.64	
17	0.60	0.43	0.66	
18	0.61	0.45	0.68	
19	0.63	0.48	0.70	
20	0.65	0.50	0.73	
21	0.66	0.53	0.75	
22	0.68	0.55	0.77	
23	0.69	0.58	0.79	
24	0.71	0.60	0.81	
25	0.72	0.63	0.83	
26	0.73	0.65	0.85	
27	0.75	0.68	0.87	
28	0.76	0.70	0.89	
29	0.77	0.73	0.91	
30	0.79	0.75	0.93	
31	0.80	0.78	0.95	
32	0.81	0.80	0.96	
33	0.82	0.83	0.98	
34	0.84	0.85	1.00	
35	0.85	0.88	1.02	
36	0.86	0.90	1.04	
37	0.87	0.93	1.06	
38	0.88	0.95	1.08	
39	0.89	0.98	1.09	
40	0.91	1.00	1.11	
41	0.92	1.03	1.13	
42	0.93	1.05	1.15	
43	0.94	1.08	1.17	
44	0.95	1.10	1.19	
45	0.96	1.13	1.20	
46	0.97	1.15	1.22	
47	0.98	1.18	1.24	
48	0.99	1.20	1.26	
49	1.00	1.23	1.27	
50	1.01	1.25	1.29	
51	1.02	1.28	1.31	
52	1.03	1.30	1.33	
53	1.04	1.33	1.34	
54	1.05	1.35	1.36	
55	1.06	1.38	1.38	

Table 2. Interaction factor, $I_{t_{0;ca};IntFr}$, as a function of the original initiation time of corrosion ($t_{0;ca}$) and the service life with respect to internal frost attack ($t_{L;IntFr}$).

$t_{0;ca}$	$t_{L;IntFr}$									
	20	40	60	80	100	120	140	160	180	200
10	0.80	0.90	0.90	0.90	0.90	0.90	1.00	1.00	1.00	1.00
20	0.70	0.80	0.85	0.90	0.90	0.90	0.90	0.95	0.95	0.95
30	0.67	0.77	0.80	0.83	0.87	0.90	0.90	0.90	0.90	0.93
40	0.60	0.73	0.78	0.83	0.85	0.85	0.88	0.90	0.90	0.90
50	0.59	0.69	0.78	0.82	0.84	0.86	0.88	0.88	0.90	0.90
60	0.54	0.68	0.73	0.78	0.81	0.83	0.85	0.86	0.88	0.88
70	0.52	0.64	0.71	0.75	0.78	0.81	0.83	0.86	0.86	0.87
80	0.51	0.62	0.68	0.73	0.77	0.80	0.81	0.84	0.85	0.86
90	0.48	0.60	0.66	0.72	0.75	0.78	0.80	0.82	0.83	0.84
100	0.46	0.58	0.65	0.70	0.74	0.76	0.79	0.80	0.82	0.83
110	0.45	0.56	0.63	0.68	0.72	0.74	0.77	0.79	0.81	0.82
120	0.44	0.55	0.62	0.66	0.71	0.73	0.76	0.77	0.79	0.81
130	0.42	0.53	0.60	0.65	0.69	0.72	0.74	0.77	0.78	0.80
140	0.41	0.53	0.59	0.64	0.68	0.71	0.73	0.76	0.77	0.78
150	0.40	0.51	0.58	0.63	0.66	0.70	0.72	0.74	0.76	0.78
160	0.39	0.50	0.57	0.62	0.65	0.69	0.71	0.74	0.75	0.77
170	0.38	0.49	0.56	0.61	0.64	0.67	0.70	0.72	0.74	0.76
180	0.37	0.48	0.55	0.60	0.64	0.66	0.69	0.72	0.73	0.75
190	0.37	0.47	0.54	0.59	0.63	0.66	0.68	0.70	0.72	0.74
200	0.36	0.46	0.53	0.58	0.62	0.65	0.67	0.70	0.71	0.73

The interaction factor for initiation time of corrosion as interacted by frost-salt attack is calculated in the same way. The process goes on as follows:

- 1) Give the original $t_{0;ca}$ and $t_{L;FrSc}$.
- 2) Calculate the corresponding k_{ca} (Eq. 98) and k_{IntFr} (Eq. 97)
- 3) Calculate as a function of time from 0 to 250 years the annual (1) carbonation depth without interaction, (2) depth of frost scaling, and (3) carbonation depth as interacted by frost scaling using Eq. 95 (the internal frost attack is now ignored).
- 4) Determine (1) $t_{0;ca}$ as the time when the carbonation depth exceeds the concrete cover (should be the same as that given at stage 1), (2) $t_{L;FrSc}$ as the time when the internal frost attack exceeds the limit state of service life (should be the same as that given at stage 1), and (3) time when the carbonation depth exceeds the concrete cover with interaction ($t_{0;ca;FrSc}$).
- 5) Determine the ratio $I_{t_{0;ca};FrSc} = t_{0;ca;FrSc}/t_{0;ca}$.

Now, concrete cover is an influencing factor and must be given together with the results. The calculation table is presented in Table 3. The results of calculation are presented in Table 4 (for $C = 25$ mm).

Table 3. Calculation table of interaction parameters Frost-Salt Scaling -> Carbonation.

	Carbonation	Frost Scaling	Int Carbonation	
Cover, mm	25	20		
Service life, year	50	40		
Coefficient	3.54	0.5		
t _L (analysis), year	49	40	29	
			0.59	=Interaction Factor
t				
0	0.00	0.00	0.00	
1	0.14	0.03	0.14	
2	0.21	0.05	0.22	
3	0.26	0.08	0.28	
4	0.30	0.10	0.32	
5	0.33	0.13	0.37	
6	0.36	0.15	0.40	
7	0.39	0.18	0.44	
8	0.41	0.20	0.47	
9	0.44	0.23	0.50	
10	0.46	0.25	0.53	
11	0.48	0.28	0.56	
12	0.50	0.30	0.59	
13	0.52	0.33	0.62	
14	0.54	0.35	0.65	
15	0.56	0.38	0.68	
16	0.58	0.40	0.70	
17	0.60	0.43	0.73	
18	0.61	0.45	0.75	
19	0.63	0.48	0.78	
20	0.65	0.50	0.81	
21	0.66	0.53	0.83	
22	0.68	0.55	0.85	
23	0.69	0.58	0.88	
24	0.71	0.60	0.90	
25	0.72	0.63	0.93	
26	0.73	0.65	0.95	
27	0.75	0.68	0.97	
28	0.76	0.70	1.00	
29	0.77	0.73	1.02	
30	0.79	0.75	1.04	
31	0.80	0.78	1.06	
32	0.81	0.80	1.09	
33	0.82	0.83	1.11	
34	0.84	0.85	1.13	
35	0.85	0.88	1.15	
36	0.86	0.90	1.18	
37	0.87	0.93	1.20	
38	0.88	0.95	1.22	
39	0.89	0.98	1.24	
40	0.91	1.00	1.26	
41	0.92	1.03	1.28	
42	0.93	1.05	1.31	
43	0.94	1.08	1.33	
44	0.95	1.10	1.35	
45	0.96	1.13	1.37	
46	0.97	1.15	1.39	
47	0.98	1.18	1.41	
48	0.99	1.20	1.43	
49	1.00	1.23	1.45	
50	1.01	1.25	1.48	
51	1.02	1.28	1.50	
52	1.03	1.30	1.52	
53	1.04	1.33	1.54	
54	1.05	1.35	1.56	
55	1.06	1.38	1.58	

Table 4. Interaction factor $I_{t_{0;ca};FrSc}$ as a function of the original initiation time of corrosion ($t_{0;ca}$) and the service life with respect to frost-salt attack ($t_L; FrSc$). Concrete cover $C = 25$ mm.

$t_{0;ca}$	$t_{L;FrSc}$									
	20	40	60	80	100	120	140	160	180	200
10	0.80	0.90	0.90	0.90	0.90	0.90	1.00	1.00	1.00	1.00
20	0.65	0.80	0.85	0.85	0.90	0.90	0.90	0.95	0.95	0.95
30	0.53	0.70	0.77	0.83	0.87	0.87	0.90	0.90	0.90	0.90
40	0.45	0.63	0.73	0.78	0.83	0.85	0.85	0.88	0.88	0.90
50	0.39	0.59	0.69	0.76	0.80	0.82	0.86	0.86	0.88	0.90
60	0.34	0.53	0.64	0.71	0.76	0.80	0.81	0.83	0.85	0.86
70	0.30	0.49	0.59	0.67	0.72	0.75	0.78	0.81	0.83	0.84
80	0.28	0.44	0.56	0.63	0.70	0.73	0.76	0.78	0.81	0.82
90	0.25	0.42	0.53	0.61	0.66	0.71	0.74	0.76	0.79	0.81
100	0.22	0.38	0.49	0.58	0.64	0.68	0.72	0.75	0.77	0.79
110	0.21	0.36	0.47	0.55	0.61	0.65	0.69	0.72	0.74	0.77
120	0.19	0.34	0.45	0.52	0.59	0.63	0.67	0.71	0.73	0.75
130	0.18	0.32	0.42	0.50	0.57	0.61	0.65	0.68	0.71	0.74
140	0.17	0.30	0.40	0.48	0.54	0.59	0.63	0.66	0.69	0.72
150	0.15	0.28	0.38	0.46	0.52	0.57	0.61	0.65	0.68	0.70
160	0.15	0.27	0.36	0.44	0.50	0.55	0.60	0.63	0.66	0.69
170	0.14	0.25	0.35	0.43	0.49	0.54	0.58	0.62	0.64	0.67
180	0.13	0.25	0.34	0.41	0.47	0.52	0.56	0.60	0.63	0.66
190	0.13	0.23	0.32	0.40	0.46	0.51	0.55	0.59	0.62	0.65
200	0.12	0.22	0.31	0.38	0.44	0.49	0.54	0.57	0.60	0.63

11 The Effect of Frost Attack on Chloride Penetration

The effects of frost attack on chloride penetration are very similar to those in the case of carbonation. The internal frost attack reduces the diffusion coefficient as presented in Eq. 91:

$$D_{eff} = D_N \cdot k_{IntFr}(t) \quad (99)$$

where D_{eff} diffusion coefficient of concrete with respect to Cl^- , m^2/s ,
 D_N diffusion coefficient of concrete at the nominal age of concrete t_N , m^2/s ,
 $k_{IntFrost}$ reduction coefficient taking into account the effect of internal frost on the diffusion coefficient.

Frost scaling removes concrete material from the surface. So the depth of chloride penetration is reduced accordingly:

$$H_{eff} = H - x_{FrSc}(t) \quad (100)$$

where H_{eff} effective depth of chloride penetration, m,
 H original depth of chloride penetration, m.

Salt scaling causes the depth of chloride penetration to reduce. Thus the differential equation for interaction of chloride diffusion and frost scaling would be presented as follows:

$$D_N \cdot \left(\frac{t_0}{t}\right)^n \cdot k_T(t) \cdot k_{RH}(t) \cdot k_{IntFrost}(t) \cdot \frac{2 \cdot c_s}{H - x_{FrSc}(t)} = \frac{dH}{dt} \frac{c_s}{3} \quad (101)$$

Equation 101 cannot be solved analytically, as the variables cannot be separated, However, numerical solution is possible. The formulation would be as follows:

$$H = \sum \Delta H \quad (102)$$

$$\Delta H(t + \Delta t) = D_N \cdot \left(\frac{t_0}{t}\right)^n \cdot k_T(t) \cdot k_{RH}(t) \cdot k_{IntFrost}(t) \cdot \frac{6}{H(t) - x_{FrSc}(t)} \cdot \Delta t$$

$$x_{Cl} = \left(1 - \sqrt{\frac{c_{crit}}{c_s}}\right) \cdot H$$

Or:

$$x_{cl} = \sum \Delta x_{cl} \quad (103)$$

$$\Delta x_{cl}(t + \Delta t) = D_N \cdot \left(\frac{t_0}{t}\right)^n \cdot k_T(t) \cdot k_{RH}(t) \cdot k_{IntFrost}(t) \cdot \frac{6 \cdot \left(1 - \sqrt{\frac{c_{crit}}{c_s}}\right)^2}{x_{cl}(t) - x_{FrSc}(t)} \cdot \Delta t$$

Noting Eq. 22 and making the same simplifications as for carbonation initiated corrosion (the diffusion coefficient is not assumed to reduce with time as a result of hydration and the temperature and moisture coefficients are ignored), the following equation is obtained for numeric simulation.

$$x_{cl} = \sum \Delta x_{cl} \quad (104)$$

$$\Delta x_{cl}(t + \Delta t) = \frac{k_{cl}^2}{2} \cdot \frac{k_{IntFr} \cdot t}{x_{cl}(t) - k_{FrSc} \cdot t} \cdot \Delta t$$

Comparing Eq. 104 to Eq. 95 one can observe complete consistency. So the interaction coefficients are the same for carbonation and chloride initiated corrosion. Thus Tables 1 and 2 can be used also for chloride initiated corrosion. In Table 3 the values for $I_{t_0cl;FrSc}$ with respect to frost-salt attack have been presented when the concrete cover is 50 mm.

Table 5. Interaction factor $I_{0cl;FrSc}$ as a function of the original initiation time of corrosion ($t_{0;cl}$) and the service life with respect to frost-salt attack ($t_{L;FrSc}$). Concrete cover $C = 50$ mm.

$t_{0;ca}$	$t_{L;FrSc}$									
	20	40	60	80	100	120	140	160	180	200
10	0.90	0.90	0.90	1.00	1.00	1.00	1.00	1.00	1.00	1.00
20	0.80	0.85	0.90	0.95	0.95	0.95	0.95	0.95	0.95	0.95
30	0.70	0.83	0.87	0.90	0.90	0.93	0.93	0.93	0.93	0.93
40	0.63	0.78	0.85	0.88	0.90	0.90	0.93	0.93	0.93	0.95
50	0.59	0.76	0.82	0.86	0.90	0.92	0.92	0.94	0.94	0.94
60	0.53	0.71	0.80	0.83	0.86	0.88	0.90	0.92	0.93	0.93
70	0.49	0.67	0.75	0.81	0.84	0.87	0.88	0.90	0.91	0.91
80	0.44	0.63	0.73	0.78	0.82	0.85	0.87	0.89	0.90	0.91
90	0.42	0.61	0.71	0.76	0.81	0.83	0.85	0.88	0.89	0.90
100	0.38	0.58	0.68	0.75	0.79	0.82	0.84	0.86	0.87	0.89
110	0.36	0.55	0.65	0.72	0.77	0.80	0.83	0.84	0.86	0.87
120	0.34	0.52	0.63	0.71	0.75	0.78	0.81	0.83	0.85	0.87
130	0.32	0.50	0.61	0.68	0.74	0.77	0.80	0.82	0.84	0.85
140	0.30	0.48	0.59	0.66	0.72	0.76	0.78	0.81	0.83	0.84
150	0.28	0.46	0.57	0.65	0.70	0.74	0.77	0.79	0.81	0.83
160	0.27	0.44	0.55	0.63	0.69	0.72	0.75	0.78	0.81	0.82
170	0.25	0.43	0.54	0.62	0.67	0.71	0.75	0.77	0.79	0.81
180	0.25	0.41	0.52	0.60	0.66	0.70	0.73	0.76	0.78	0.80
190	0.23	0.40	0.51	0.59	0.65	0.69	0.72	0.75	0.77	0.79
200	0.22	0.38	0.49	0.57	0.63	0.67	0.71	0.74	0.76	0.78

12 The Effect of Carbonation on Chloride Penetration

The effect of carbonation to chloride penetration is complex because so many phenomena occur as a result of this action [12]. Carbonation pushes the chloride front forward by liberating chlorides that were bound in non-carbonated concrete. The actual driving force of chlorides in concrete is the gradient of free chlorides, not the gradient of total chlorides as was assumed in the previous analyses. As long as the relationship of free chloride content to total chloride content is constant no error is made as the apparent diffusion constant takes into account the relationship of free chlorides to total chlorides (ref. Chapter 3). The reason why total chloride content and the apparent diffusion coefficient are used in calculations is that the measurement of total chloride content is much easier than the measurement of free chloride content.

However, as a result of carbonation the relationship of free chloride content to total chloride content is changed. This is because concrete loses its capacity to bind chlorides when CO_2 reacts with cement minerals. Accordingly, a part of already bound chlorides is set free during carbonation (carbonation is assumed to proceed slower than chloride penetration.). The liberated chlorides increase the free chloride content in the carbonated zone of concrete and the gradient of free chlorides grows. When using the apparent diffusion coefficient in calculations the apparent total chloride content (assuming that the relationship of free chloride content to total chloride content is the same as in non-carbonated concrete) is increased as presented in Figure 8 b.

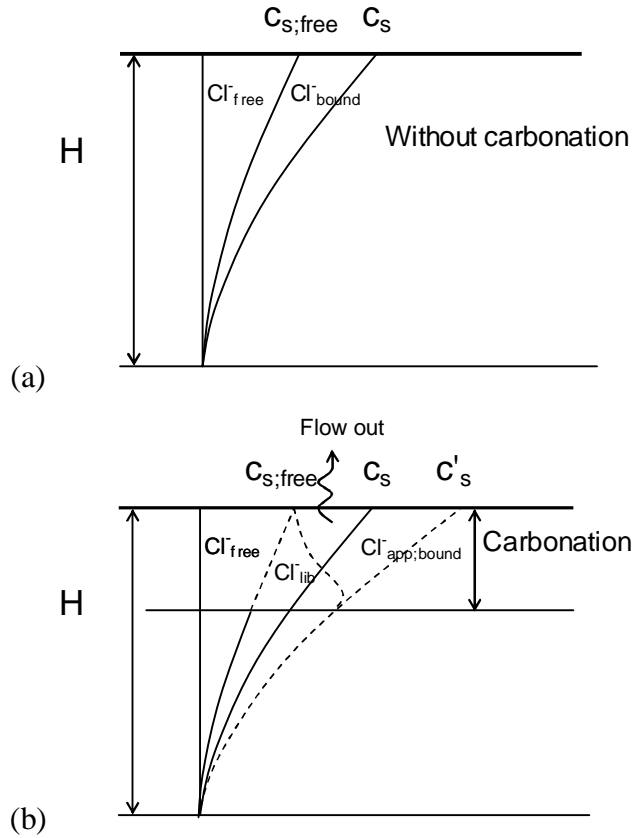


Fig 8. (a) Free and bound chloride content in non-carbonated concrete. (b) Free, bound and apparent bound chloride content in carbonated concrete.

Assuming that the increase of the (apparent) total chloride content i.e. the apparent bound chloride content at the surface of the structure is proportional to the relative increase of free chloride content as a result of carbonation the following relationship can be written:

$$\frac{Cl_{lib}^-}{Cl_{free}^- + Cl_{lib}^-} = \frac{C'_s - C_s}{C'_s} = \alpha \quad (105)$$

where Cl_{lib}^- is liberated free chloride content as a result of carbonation, g/m^3 ,
 Cl_{free}^- original free chloride content in non-carbonated concrete g/m^3 ,
 C'_s apparent total chloride content at the surface of the structure as a result of carbonation, g/m^3 ,
 C_s Original total chloride content at the surface of the structure (without the effect of carbonation), g/m^3 ,
 α constant.

From Equation 105 the following equation is obtained for C'_s :

$$C'_s = \frac{C_s}{1 - \alpha} \quad (106)$$

Assuming that all liberated chloride ions remain in the porosity of concrete the effect of carbonation on the chloride penetration could be evaluated by substituting C_s by C'_s in the previous analyses of chloride penetration. However, as the free chloride content after carbonation may be greater than the free chloride

content outside concrete there will be a chloride flow also out of concrete. This outward flow reduces the apparent surface content from that presented in Eq. 106 and the Eq. 107 should be used instead.

$$C'_s = \frac{\beta \cdot C_s}{1 - \alpha} \quad (107)$$

where β is a parameter which takes into account the outward flow of free chloride ions ($\beta \leq 1$).

The total depth of chloride penetration, H , is not assumed to increase because of carbonation as in essence H it is not dependent on the surface content (Eq. 18). However, the depth of critical chloride content is expected to increase and the initiation time of corrosion is expected to decrease when the chloride content at the surface (according to Eq. 107) is increased. The Interaction factor is of the following type:

$$I_{cl;ca} = \frac{\left(1 - \sqrt{\frac{c_{crit}}{c'_s}}\right)^2}{\left(1 - \sqrt{\frac{c_{crit}}{c_s}}\right)^2} \quad (108)$$

where c'_s is determined from Eq. 107.

13 The Effect of Chloride Penetration on Carbonation

The effect of chloride penetration on the rate of carbonation is complex too [12]. The effects of chlorides may be direct or indirect. There may be a direct effect as a result of the chemical changes caused by chemically bound chlorides in the cement paste. However, the free chlorides can also have an effect indirectly. The free chlorides are hygroscopic absorbing moisture into concrete blocking the porosity of concrete from CO_2 and retarding the related carbonation reactions.

As the carbonation proceeds through the already carbonated concrete the properties of concrete after carbonation are more essential than those before carbonation. The physical properties may be significantly changed as a result of carbonation and these changes are much dependent on cement quality. In portland cement concrete the permeability of concrete may be reduced as a result of carbonation while in slag cement concrete the permeability may be increased. Another change which takes place in carbonation is the liberation of bound chlorides. As a result of this phenomenon the amount of free chlorides in carbonated concrete is increased. The liberation of chlorides entails increasing of the moisture content in carbonated concrete which again affects the permeability properties of concrete. The exact amount of free chlorides in the carbonated concrete is difficult to evaluate as there may be a slow flow of chlorides to both directions, towards the non-carbonated concrete and out of concrete (see discussion above).

In chloride environments the problems of carbonation are considered less important than the chloride penetration. That is why the effects of chlorides to carbonation have not been studied intensively. For a mathematical treatment of

the problem there is not enough research data to base on. The shortest way for determination of interaction factors is direct testing. Based on simple carbonation tests in which the rate of carbonation is studied in chloride contaminated concretes (made of several binding agents and several chloride contents) would give as a result k_{ca} -coefficients from which the interaction factors could be determined as follows:

$$I_{ca;cl} = \frac{k_{ca;cl}^2}{k_{ca;0}^2} \quad (109)$$

where $I_{ca;cl}$ is interaction factor of service life (chlorides to carbonation).
 $k_{ca;cl}$ coefficient of carbonation in chloride contaminated concrete, $\text{mm/a}^{0.5}$
 $k_{ca;0}$ coefficient of carbonation in concrete without chlorides, $\text{mm/a}^{0.5}$.

14 Discussion

One of the objectives of this research has been to present reasonably correct solutions for the material, structural and environmental factors for the service life models based on the “factor approach”. In the factor approach the service life of a structure is evaluated from the following equation [8]:

$$t_L = t_{L,ref} \cdot A \cdot B \cdot C \cdot D \cdot E \cdot F \cdot G \cdot H \cdot I \quad (110)$$

where t_L is service life a structure, years,
 $t_{L,ref}$ reference service life, years,
 A...I factors, which take into account different influences.

The factors are organised to take into account the following influences

- A Materials
- B Structural features
- C Work execution and workmanship
- D Indoor environment
- E Outdoor environment
- F In-use conditions
- G Inspection and cure
- H Maintenance and repair
- I Interaction between degradation mechanisms.

In case it is impossible to present all influences of the same category by only one character, several characters may be given which are differentiated by a lower index (1, 2, 3 etc.). Accordingly there may be several material factors, (A_1, A_2, A_3 etc.), several structural factors, (B_1, B_2, B_3 etc.) and several environmental factors, (E_1, E_2, E_3 etc.). Also, there may be several interaction parameters depending on the number of the other degradation mechanisms occurring simultaneously (I_1, I_2, I_3 etc.).

In some cases the process of degradation consists of two subsequent degradation mechanisms so that the first mechanism is a pre-condition for the second one to start. The two phases of degradation can be called the “initiation time” and the “propagation time”. An example of such a 2-phase degradation process is corrosion of reinforcement which can only happen if some chemical changes occur first in concrete. Both periods of time are determined separately by the factor approach and the service life is determined as the sum of these two. The factors of the propagation time are provided with a comma to separate them from the factors of the initiation time.

$$\begin{aligned}
 t_L &= t_0 + t_1 & (111) \\
 t_0 &= t_{0,ref} \cdot A \cdots I \\
 t_1 &= t_{1,ref} \cdot A' \cdots I'
 \end{aligned}$$

where t_0 is initiation time of corrosion, years,
 t_1 propagation time of corrosion, years.

In the case of corrosion of reinforcement the initiation time of corrosion is determined based on either carbonation or chloride penetration in concrete. Both carbonation and chloride penetration are able to initiate corrosion in reinforcement as they are able to destroy the passive film which normally protects reinforcement in concrete.

The actual objective of this report has been to present a theoretical basis for determination of the initiation time of corrosion with respect to carbonation and chloride penetration. The differential equations have been solved analytically whenever possible. In some cases only a numerical solution is possible.

The basic idea of the factor approach has been to classify and separate the different effects of degradation using different factors A, B, C ... etc. This makes the calculation easy and systematic. However, for the developer of models such simplification is challenging as the separation of factors is not always theoretically possible. Especially when time dependent material parameters are used in the analyses the separation of factors is practically impossible.

Usually the error-function model which fulfils the Fick's 2nd law of diffusion has been applied for the solution of chloride content in concrete. The error-function can, however, be replaced by the parabola function, which fulfils the Fick's 1st law, without practical difference in the results. The parabola-model was selected consciously as it is applicable to more complicated problems of structural design. For the same reason a fairly simple “moving boundary” model was chosen for the basic solution for of carbonation.

From these starting points the following degradation problems have been solved systematically:

- Carbonation and chloride penetration on normal (sound) concrete surface
- Carbonation and chloride penetration at cracks of concrete
- Carbonation and chloride on a coated concrete surface
- The effects of internal frost attack and frost scaling on carbonation and chloride penetration.

One of the special aims in the DuraInt project has been modelling of interaction between two degradation mechanisms. An arithmetic solution for interaction factors of service life models is not always possible. However, numerical solutions based on theoretically “correct” differential equations can usually be derived. In this report interaction factors of frost attack on carbonation and frost attack on chloride penetration have been determined numerically.

Carbonation and chloride penetration have also mutual interaction. Although allusions of these influences have been observed experimentally the modelling of these phenomena is still too early. So, the interaction factors of carbonation on chloride penetration and vice versa are only discussed and a route signing for a solution for them is tentatively given.

15 Summary

The objective of this research was to lay a theoretical, systematic and practical basis for treating the problems of carbonation and chloride penetration in concrete. For that purpose theoretical/analytic models were first derived for carbonation and chloride penetration on a normal concrete surface. Then these solutions were extended to more challenging cases, such as cracks in concrete, coated concrete surfaces, aging of concrete and concrete affected by other degradation mechanisms. The other degradation mechanisms which were assumed to occur simultaneously with carbonation and chloride penetration were internal frost attack and frost scaling. The mutual effects of carbonation and carbonation were discussed.

The theoretical solutions for carbonation and chloride penetration problems were derived with the final purpose of developing service life models based on the ‘factor approach’. In several cases a theoretically sound solution which would allow separation of material, structural and environmental parameters could be obtained. In some other cases, however, an analytical solution could not be derived but a numerical solution was given instead. Thus, the ‘interaction factors’ for the effects of simultaneous internal frost attack and frost-salt scaling could be numerically determined.

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