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Content

The residual service life of concrete exposed to the combined effect of frost attack and reinforcement corrosion

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Synopsis. Frost damage increases the rate of penetration of the carbonation front and the rate of diffusion of chlorides through the concrete cover. It also might influence the corrosion rate. Thus, if the previous and future frost attack is not considered, a large over-estimation of the residual service life can be made. In the report, equations are given for the interactive effects of frost attack and corrosion. These equations can be used for a more safe estimation of the residual service life with regard to reinforcement corrosion. Salt scaling as well as internal frost attack are considered.

1. Frost damage as a pure surface attack (e.g. salt scaling)

Frost attack due to the combined effect of salt, moisture and freezing temperatures is normally a pure surface attack or erosive attack. The surface is scaled but the remaining concrete, beneath the scaling, is often almost intact. Therefore, the concrete cover is gradually reduced which increases the rate of carbonation or the rate of penetration of the threshold chloride concentration. This combined effect can be treated theoretically by a simple theory which will be described below.

1.1 The time before start of corrosion

1.1.1 Frost scaling

The frost scaling is often linear with time; i.e every frost cycle of a certain "severeness" (a certain lowest temperature and duration of the lowest temperature) gives about the same amount of scaling. When the surface layer of the concrete is of a lower quality than the deeper part, for instance due to separation of the fresh concrete, the first frost cycles give more damage than the cycles to follow. After a few cycles, however, the scaling rate can be regarded constant. In some types of concrete an accelerating rate of damage can be seen in a continuous laboratory experiment where the concrete has no time to dry between the cycles. This behaviour is however hardly observed in practice. Hence, the erosion rate depends on the scaling during each cycle and on the spectrum and total number of freezing cycles per year. If the outer climate as regards temperature, wetness and salinity is constant there should theoretically be a constant erosion rate.

$$(dx/dt)_e = C_e \qquad\qquad (1)$$

Where $(dx/dt)_e$ is the rate of frost erosion and C_e is a constant which depends on the concrete quality and the actual freeze/thaw spectrum, salinity and wetness.

1.1.2 Carbonation

The carbonation depth after an initial period with higher carbonation rate can often be described by:

$$x_c = C'_c \cdot \sqrt{t} \qquad (2)$$

Derivating this gives:

$$(dx/dt)_c = C_c/\sqrt{t} \qquad (3)$$

Where x_c is the depth of the carbonation front, $(dx/dt)_c$ is the rate of penetration of the carbonation front and $C_c = C'_c/2$ is a rate determining constant determined by the diffusivity of carbon dioxide, the amount of lime which can carbonate and the outer concentration of carbon dioxide.

1.1.3 Chloride penetration

The depth of a certain constant chloride concentration, for example the threshold concentration initiating reinforcement corrosion, can often be described by:

$$x_{cl} = C'_{cl} \cdot \sqrt{t} \qquad (4)$$

Derivation gives:

$$(dx/dt)_{cl} = C_{cl}/\sqrt{t} \qquad (5)$$

Where x_{cl} is the depth of the actual chloride concentration regarded, $(dx/dt)_{cl}$ is the rate of penetration of this constant concentration level and $C_{cl} = C'_{cl}/2$ is a rate determining constant determined by the outer chloride concentration and the effective chloride diffusivity of the concrete. The significance of eq (5) is illustrated in Fig 1.
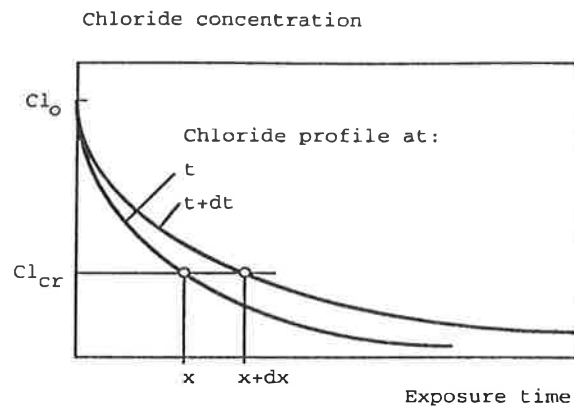
Fig 1: The chloride profile after the time t and t+dt. The rate of penetration depth of a certain constant concentration -e.g. the threshold concentration Cl_{cr} can often be described by a square-root relationship; eq (4) and (5).

1.1.4 Synergistic effects of erosion and penetration- an approximative solution

After a certain time, t^*, counted from the "birth" of the structure the rate of erosion equals the rate of penetration of the carbonation front or the rate of penetration of the threshold chloride concentration. After this time, the carbonation rate or the rate of penetration of the threshold chloride concentration is constant and no longer proportional to the square-root of time; Fig2(a).

The limiting time t^* can be found by putting eq (1) equal to eq (3) or (5):

$$(t^*)_c = \{C_c/C_e\}^2 \tag{6}$$

$$(t^*)_{cl} = \{C_{cl}/C_e\}^2 \tag{7}$$

After these times, corresponding to the penetration depth x*, the penetration rate is determined by the constant C_e under condition that the corrosion does not start due to the normal "non-synergistic effect" before the limiting time t* has been reached:

$(dx/dt)_c = C_e$ for t>t*   (8a)

$(dx/dt)_{cl} = C_e$ for t>t*   (8b)

Example 1(Erosion and carbonation):

The coefficients C_e and C_c are supposed to be $5 \cdot 10^{-4}$m/year and $1,7 \cdot 10^{-3}$m√year respectively. Then it is valid:

$(t^*)_c = \{1,7 \cdot 10^{-3}/5 \cdot 10^{-4}\}^2 = 12$ years corresponding to a carbonation depth of $1,7 \cdot 10^{-3} \cdot \sqrt{12} = 1,2 \cdot 10^{-2}$ m = 12 mm.

Let us assume that the concrete cover is 25 mm. Then, the following total service lives t until onset of corrosion are valid:

No frost erosion: $t = \{25 \cdot 10^{-3}/3,4 \cdot 10^{-3}\}^2$ = **54 years**

With frost erosion: $t = 12 + (25-12) \cdot 10^{-3}/5 \cdot 10^{-4} = $ **38 years**

Example 2 (Erosion and chloride penetration):

The coefficients C_e and C_{cl} are supposed to be $5 \cdot 10^{-4}$m/year and $3,4 \cdot 10^{-3}$m√year respectively. Then it is valid:

$(t^*)_{cl} = \{3,4 \cdot 10^{-3}/5 \cdot 10^{-4}\}^2 = 46$ years corresponding to a penetration depth x* of $6,7 \cdot 10^{-3} \cdot \sqrt{46} = 4,5 \cdot 10^{-2}$ m = 45 mm.

Let us assume that the concrete cover is 40 mm. Then the following total service lives until onset of corrosion are valid:

No frost erosion: $t = \{40 \cdot 10^{-3}/6,7 \cdot 10^{-3}\}^2 = $ **36 years**   (<t^*)

Thus, in this case, frost erosion will have a limited effect since the penetration rate of the chlorides will always be larger than the frost erosion rate. With a larger concrete cover or a larger erosion rate the effect of frost on the service life should have been more significant. With the same concrete as above but with a concrete cover of 60 mm the result is:

No frost erosion: $t = \{60 \cdot 10^{-3}/6,7 \cdot 10^{-3}\}^2$ = **80 years**

With frost erosion: $t = 46 + (60-45) \cdot 10^{-3}/5 \cdot 10^{-4} = $ **76 years**

Note: In reality the penetration rates are seldom governed by a simple square-root relationship but by some other time function of type $x = C \cdot t^k$ where k<0,5. The principal reasoning concerning the interactive effects performed in this report is however not changed. Only the equations must be altered by introducing the exponents k instead of 0,5 and 1/k instead of 2.

1.1.5 Possible errors in the extrapolation of the residual time until start of corrosion

The erosive effect by frost causes the carbonation-time curve or the chloride penetration-time curve to change its shape at the point where t=t* and x=x*; see Fig 2(a). The curve can also be plotted with the depth and time in log-scale. As long as there is no erosion (or minor erosion) the line has a slope close to 1/2:1. As soon as the erosion rate equals the rate of penetration there is a change in the slope to 1:1 (assuming a new scale on the vertical axis).
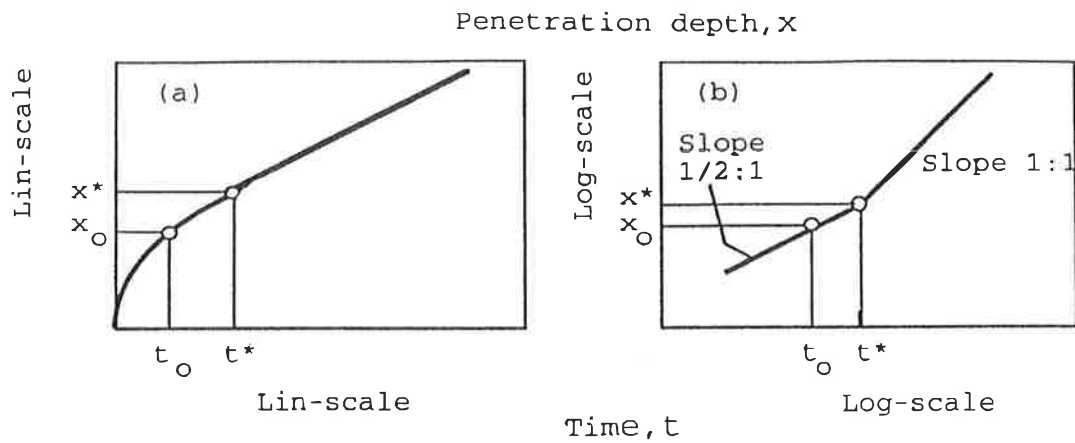
Penetration depth, x

Fig 2: Penetration-time curve with erosive attack on the surface.
(a) lin-lin scale. (b) log-log scale.

In reality, there is a gradual transition from one slope to the other and not the abrupt change shown in Fig 2; c.f. chapter 1.1.7 below. If this change in the penetration-time curve is not considered an over-estimation of the calculated residual service life is made. The errors are of two types depending on where the actual measured penetration-time point is situated on the curve.

Error of type 1 (Fig 3):

The actual penetration-time point obtained at the measurement lies on the square-root curve; i.e. erosion is not yet determining the erosion rate. The measured penetration at time t_0 is x_0.
When the concrete structure is old and there is no erosion the continuing penetration rate can be assumed to be proportional to the square-root of time. The concrete cover is D. Then, the extrapolated residual service life until onset of corrosion is:

$$t_{r,1} = t_1 - t_0 \qquad (9)$$

Where t_1 is the time where the square-root curve intersects the line x=D.

In reality, at time t^*, there is a transition to a linear penetration-time relation. Therefore, the real residual service life until start of corrosion is:

$$t_{r,2} = t_2 - t_0 \qquad (10)$$

Where t_2 is the time where the line with the slope C_e intersects the line x=D.
The real residual service life might be considerably shorter than that calculated by a simple extrapolation of a square-root curve.
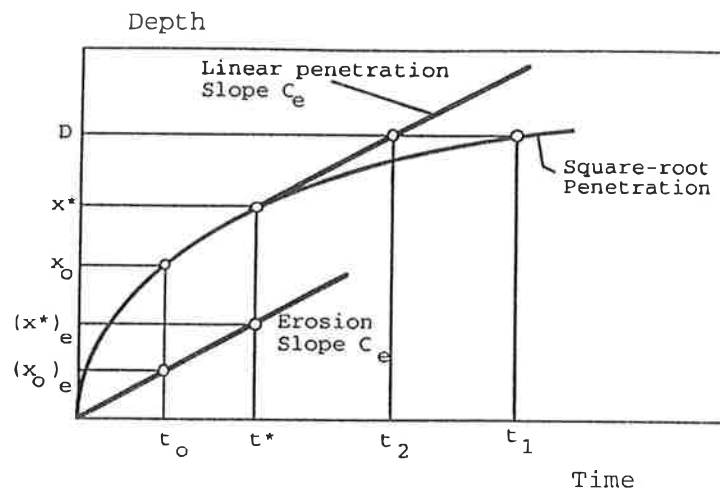

Fig 3: Extrapolation for determination of the residual service life. Error of type 1; $t^* > t_0$.

Error of type 2 (Fig 4):

The actual penetration-time point obtained at the measurement is situated on the linear portion of the penetration-time curve; i.e. $t^* < t_0$. If this is not observed by the investigator he will extrapolate along a square-root curve running through the measured point. The extrapolated service life will be too long since the real extrapolation should be along the line with the slope C_e.
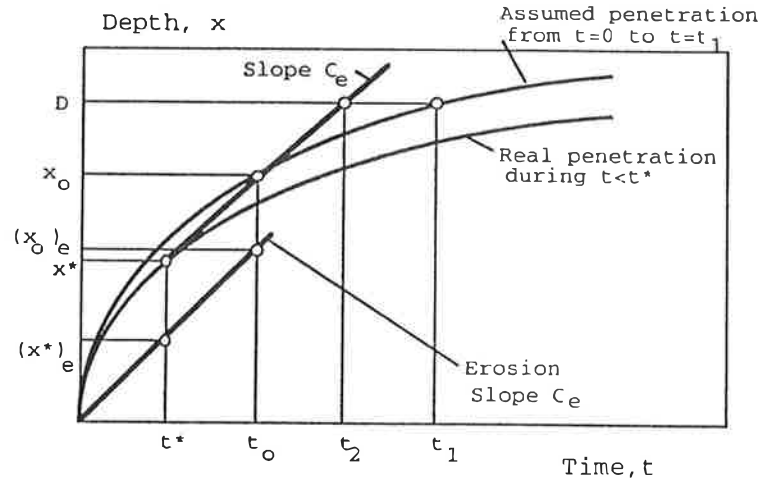

Fig 4: Extrapolation for determination of the residual service life. Error of type 2; $t^* < t_0$.

1.1.6 A method of calculating the residual service life until start of reinforcement corrosion

(a) Constant diffusion (penetration) coefficients C´ (see Fig 5)

In the practical case, a certain erosion of the surface has occurred during the previous years. This must be estimated before a correct service life prediction can be made. The actual total erosion at time t_0 is $(x_0)_e$. This means that the coefficient C_e determining the rate of erosion is:

$$C_e = (x_0)_e / t_0 \qquad (13)$$

The value $(x_0)_e$ must be estimated for example by comparing the level of the eroded surface with the level of such parts of the surface of the structure that are not eroded.

The actual penetration depth x_0 is:

$$x_0 = (x_0)_e + x_0´ \qquad (14)$$

Where $x_0´$ is the measured peneration depth from the actual, eroded surface.

At first one must estimate if the penetration follows the linear penetration curve or if it follows the square-root curve; i.e. whether the time t* at which the erosion rate and the penetration rate are equal is shorter or longer than the actual time t_0. In the latter case one must also estimate if the erosion rate will ever become rate-determining before corrosion starts or if the penetration rate will continue to diminish according to the square-root relation all the time until onset of corrosion.

The coefficient C´ assuming a square-root relation until the actual time t_0 is:

$$C´ = x_0 / \sqrt{t_0} \qquad (15)$$

Or, using eq (14):

$$C´ = [(x_0)_e + x_0´] / \sqrt{t_0} \qquad (16)$$

If erosion is the rate-determining factor, the constant C' according to eq (16) will be a fictive constant since erosion is neglected. The value of C' is however only used for calculating an approximative value of t^*.

Thus, according to eq (6) and (7) the time t^* is:

$$t^* \approx \{C'/2 \cdot C_e\}^2 \tag{17}$$

Or after inserting eq (13) and (16):

$$t^* = \{1 + x_0'/(x_0)_e\}^2 \cdot \{t_0/4\} \tag{18}$$

t^* is compared with the actual time t_0 and with the predicted time t_1 assuming the continuing penetration follows a square-root relationship until onset of corrosion.

One can distinguish three cases.

Case 1; $t^* < t_0$ (Fig 5a):

Then, erosion is already the rate-determining factor. The residual service life $t_{r,2a}$ is:

$$t_{r,2a} = t_2 - t_0 = [D_0 - x_0]/C_e \tag{19}$$

Where D_0 is the initial concrete cover. The remaining concrete cover D i

$$D = D_0 - (x_0)_e \tag{20}$$

After inserting this expression and eq (13), eq (20) can be written:

$$t_{r,2a} = t_0 \cdot \{D - x_0'\}/(x_0)_e \tag{21}$$

Case 2; $t_0 < t^* < t_1$ (Fig 5b)

The erosion rate will determine the penetration rate after the time t^*. The residual service life $t_{r,2b}$ is:

$$t_{r,2b} = t^* - t_0 + \{D_0 - x^*\}/C_e \tag{22}$$

Where x^* is:

$$x^* = C' \cdot \sqrt{t^*} = \sqrt{t^*/t_0} \cdot x_0 \tag{23}$$

Inserting eq (18) and (14) gives:

$$x^* = \{(x_0)_e + x_0'\}^2 / 2 \cdot (x_0)_e \tag{24}$$

Both $(x_0)_e$ and x_0' are measured at the inspection at time t_0.
Inserting Eq (17) and (24) in (22) gives:

$$t_{r,2b} = \{D/(x_0)_e - [(x_0)_e + x_0']^2/[2 \cdot (x_0)_e]^2\} \cdot t_0 \tag{25}$$

Case 3; $t^* > t_1$ (Fig 5c)

In this case the square-root relation is valid until corrosion starts at time t_1. This is:

$$t_1 = \{D_0/C'\}^2 = \{D_0/x_0\}^2 \cdot t_0 \tag{26}$$

The residual service life $t_{r,1}$ until start of corrosion is:

$$t_{r,1} = t_1 - t_0 = t_0 \cdot \{(D_0/x_0)^2 - 1\} \tag{27}$$

It is more easy to use the actually measured values D and x_0'. The relations $D_0 = D + (x_0)_e$ and $x_0 = (x_0)_e + x_0'$ are inserted in eq (27):

$$t_{r,1} = t_0 \cdot \left\{ [D + (x_0)_e]^2 / [(x_0)_e + x_0']^2 - 1 \right\} \tag{28}$$

Thus, the residual service life can be estimated by eq (21), (25) or (28) provided the actual erosion $(x_0)_e$ and the actual penetration x_0' are known. The shortest of the times tr,1 and tr,2a or tr,2b define the residual service life until onset of corrosion.

Note: If frost erosion occurring both before and after the actual point of time when the measurement is made is neglected, the predicted service life before start of corrosion is very much over-estimated.
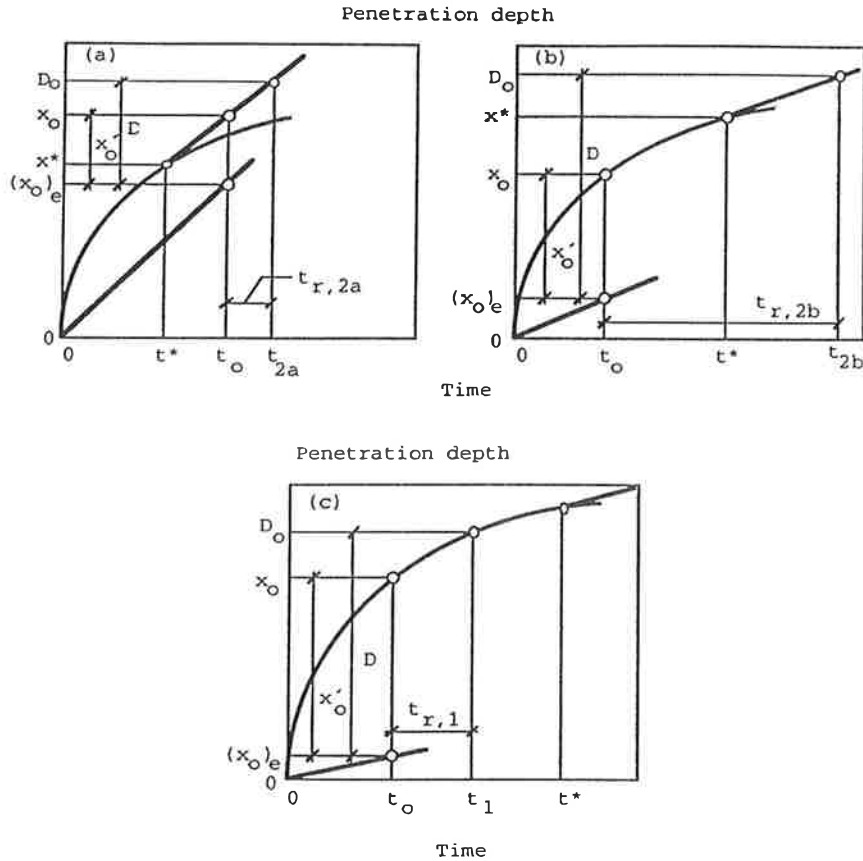
Fig 5: Data needed for an estimation of the residual service life until start of corrosion. Three different cases.

(b) Variable diffusion (penetration) coefficients C' (see Fig 6)

In the formulas presented above it is assumed that the coefficient C' determining the rate of penetration of the carbonation front or the chloride threshold concentration is constant from t=0 and x=0 until the structure fails. In reality, a certain initial penetration can be assumed to

take place much more rapidly, i.e. with higher, and also time-variable, values of the coefficients C´ than the more constant coefficients C´ determining the penetration rate of the mature concrete. The calculations shown in 1.6(a) will therefore under-estimate the real residual service life.

This can be regarded by introducing a new origin in the penetration depth-time curve; see Fig 6. Hence, in all formulas and examples shown above in 1.6(a) the time t*, the corresponding penetration depth x* and the residual service life $t_{r,1}$ and $t_{r,2b}$ are supposed to be counted

from a certain initial penetration depth Δ x obtained at an initial time Δt counted from the

"birth" of the structure until it has become "stabilized". The time Δ t can be of the order of size 1 month to 1/2 year. The corresponding depth Δ x can be of the order of size 1 to 5 mm. The following changed relations are valid:

$$t^* \approx \{1 + (x_0{´} - \Delta x)/(x_0)_e\}^2 \cdot \{t_0/4\} \tag{29}$$

$$x^* = \{(x_0)_e + x_0{´} - \Delta x\}^2 / 2 \cdot (x_0)_e \tag{30}$$

$$t_{r,2a} = t_0 \cdot \{D - x_0{´}\}/(x_0)_e \quad \text{(unchanged)} \tag{21}$$

$$t_{r,2b} \approx \{D/(x_0)_e - [(x_0)_e + x_0{´} - \Delta x]^2 / [2 \cdot (x_0)_e]^2\} \cdot t_0 \tag{31}$$

$$t_{r,1} \approx (t_0 - \Delta t) \cdot \{[D + (x_0)_e - \Delta x]^2 / [(x_0)_e + x_0{´} - \Delta x]^2 - 1\} \tag{32}$$

An extrapolation,based on the assumption that the diffusivity has been the same during the whole time is very much on the safe side.
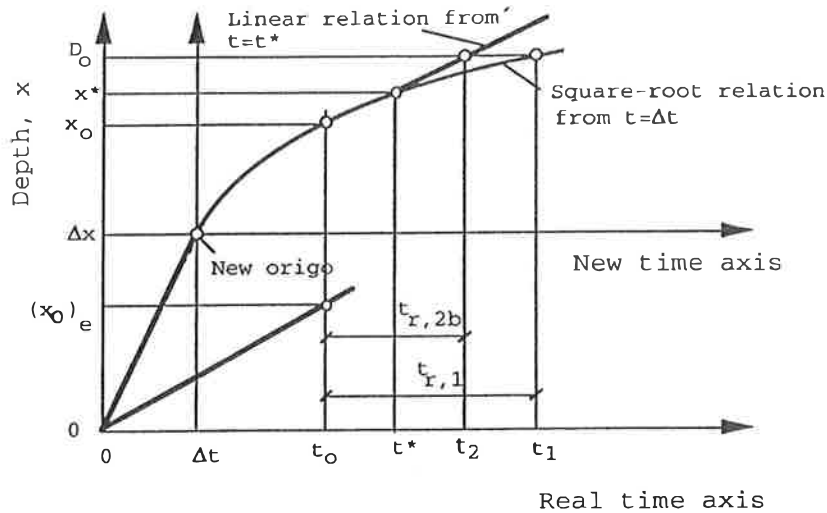
Fig 6: Method of considering an initial more rapid penetration of either the carbonation front or the chloride threshold concentration; principles only.

1.1.7. A theoretically more stringent relation for the residual service life before start of corrosion

In a more stringent derivation of the synergistic effects consideration should be taken to the fact that the concrete surface is gradually eroded already before the approximative limiting

times t^* calculated by eq (6) or (7) are reached. Therefore, the carbonation rate and the chloride penetration rate is a bit more rapid than those described by eq (3) and (5).

With no erosion the differential equation describing the penetration of a constant concentration level is:

$$x \cdot dx/dt = K \tag{33}$$

Which, when solved, gives eq (2) or (4).

$$x = C' \cdot \sqrt{t} \tag{2), (4}$$

Identification of coefficients gives a relation between K and C'.

$$C' = \sqrt{2} \cdot K \tag{34}$$

With erosion eq (33) is changed to

$$(x - x^*) \cdot dx/dt = K \tag{35}$$

Where x^* is the actual erosion depth. This is described by eq (1).

$$x^* = C_e \cdot t \tag{36}$$

The differential equation describing the combined erosion and diffusion therefore is

$$(x - C_e \cdot t) \cdot dx/dt = K \tag{37}$$

Or

$$(x - C_e \cdot t) \cdot dx/dt = (C')^2/2 \tag{38}$$

This can be easily solved numerically when the rate determining coefficients C_e and C' (C'_c or C'_{cl}) are known.

Example 3:
The following coefficients are valid for a certain concrete:

$C' = 3 \cdot 10^{-3}$ m/$\sqrt{\text{year}}$

$C_e = 5 \cdot 10^{-4}$ m/year

This means that the limiting time t* is:

$$t^* = \{C'/2 \cdot C_e\}^2 = 3 \cdot 10^{-3}/2 \cdot 5 \cdot 10^{-4}\}^2 = 9 \text{ years}$$

Then, the differential equation (38) can be written:

$$\Delta x = \left[\{3 \cdot 10^{-3}\}^2/2 \cdot \{\Sigma \Delta x - 5 \cdot 10^{-4} \cdot \Sigma \Delta t\}\right] \cdot \Delta t = \left[4,5 \cdot 10^{-6}/\{\Sigma \Delta x - 5 \cdot 10^{-4} \cdot \Sigma \Delta t\}\right] \cdot \Delta t$$

This equation is plotted in lin-lin scale in Fig 7a and in log-log scale in Fig 7b.

It is quite clear that the exact solution gives a higher penetration than the approximative. At t*=9 years the approximative penetration x* is:

$$x^*_{approx} = 3 \cdot 10^{-3} \cdot \sqrt{9} = 9 \cdot 10^{-3} \text{ m} = 9 \text{ mm}$$

The exact solution gives:

$$x^*_{exact} \approx 11 \text{ mm}$$

The exact solution approaches a constant penetration rate equal to $C_e = 5 \cdot 10^{-4}$. It is quite clear however that there is not an abrupt transition from a square-root relation to a linear relation as shown in Fig 2b but a gradual transition.

The concrete cover is assumed to be 30 mm. The approximative solution gives the following total service life :

$$t_{approx} = t^* + (D - x^*)/C_e = 9+(30-9)\cdot 10^{-3}/5\cdot 10^{-4} = \mathbf{51\ years}$$

The exact solution gives:

$$t_{exact} = \mathbf{43\ years}$$

Note: The service life neglecting erosion is:

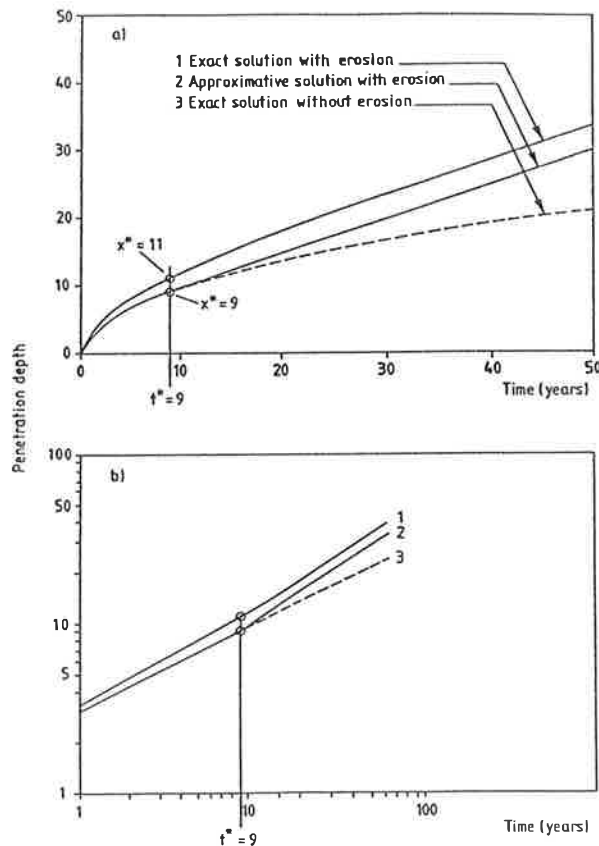$$t = \{D/C'\}^2 = \{30\cdot 10^{-3}/3\cdot 10^{-3}\}^2 = \mathbf{100\ years}$$

Fig 7: Solution of example 3.
     (a) lin-lin scale. (b) log-log scale.

1.2. The corrosion time

In the following the corrosion is assumed to be **diffusion controlled**; i.e. the corrosion rate is assumed to be governed by the rate by which oxygen can diffuse through the concrete cover. This leads to an increase in the corrosion rate when the cover is gradually eroded. In reality, however, there is normally oxygen enough around the corroding bar. Hence, the corrosion rate is often almost independent of the erosion degree. It might even be that a reduced cover is favourable, slowing down the corrosion rate, simply because the reinforcement bar will, during certain periods, be surrounded by a more dry concrete than what is the case when the cover is thicker and therefore more continuously moist at the level of the bar; the effect of the concrete cover on the moisture variations due to outer moisture variations are calculated in (ref 1).

1.2.1 Corrosion has not yet started when the estimation is made (see Fig 8)

The time until start of corrosion is given by one of the equations (21), (25) or (28), or eventually by one of the equations (31) or (32). In order to obtain the total service life a corrosion period must be added. This is called t_{corr}. Thus the total residual service life t_r is:

$$t_r = t_{r,1} + t_{corr} \tag{39a}$$

or

$$t_r = t_{r,2} + t_{corr} \tag{39b}$$

Where $t_{r,1}$ and $t_{r,2}$ are the residual times until start of corrosion. They are calculated by the equations mentioned above.

The corrosion rate is described by:
$$dz/dt = C_{corr}/D(t) \tag{40}$$
where z is the degree of corrosion expressed in meter of corrosion depth and C_{corr} is a constant in m^2/year. C_{corr} is determined by the electrical resistivity and the diffusivity of oxygen through the concrete cover. $D(t)$ is the concrete cover which is, due to the frost erosion, a function of time:
$$D(t) = D^* - C_e \cdot t_{corr} \tag{41}$$

Where D^* is the remaining thickness when corrosion starts. D^* can be described by:
$$D^* = D_0 - (\Delta D)_{corr} = D_0 - C_e \cdot [t_{r,1} + t_0] \tag{42}$$
Or
$$D^* = D_0 - (\Delta D)_{corr} = D_0 - C_e \cdot [t_{r,2} + t_0] \tag{43}$$

Where D_0 is the initial concrete cover and $(\Delta D)_{corr}$ is the eroded cover when corrosion starts. The parameter $t_{r,1}$ is defined by eq (28) or (32). The parameter $t_{r,2}$ is defined by eq (21), (25) or (31).

The largest value of D^* should be used in eq (41).
Inserting eq (41) in (40) and integrating gives:
$$z = \ln\left\{ 1/[1 - C_e \cdot t_{corr}/D^*] \right\} \cdot C_{corr}/C_e \tag{44}$$

The maximum allowable corrosion is z_{cr}. Then, the maximum allowable residual corrosion time is:

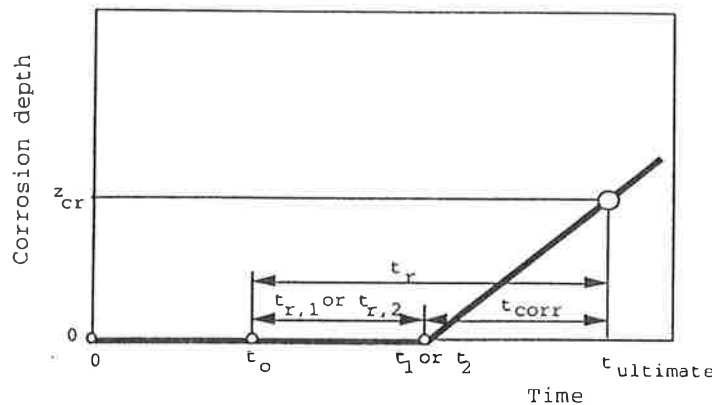$$\mathbf{t_{corr} = \{1 - 1/exp[z_{cr} \cdot C_e/C_{corr}]\} \cdot D^*/C_e} \tag{45}$$

Fig 8: Definition of the total residual service life. Corrosion is not initiated when the inspection is made.

1.2.2 Corrosion has started when the estimation is made (see Fig 9)

In some cases the corrosion is already going on when the estimation of the residual service life is made. Then, there is no "incubation time" before onset of corrosion. The residual service life is given by:

$$t_r = t_{corr} \tag{46}$$

The rate of corrosion is described by eq (40) with the concrete cover $D(t)$ described by:

$$D(t) = D^{**} - C_e \cdot t_{corr} \tag{47}$$

Where D^{**} is the residual concrete cover at the time of inspection. The coefficient C_e is as described above estimated from the amount of erosion occurring before the inspection takes place:

$$C_e = (D_0 - D^{**})/t_0 \tag{48}$$

Where D_0 and D^{**} are the initial and the actual concrete covers and t_0 is the age of the concrete at the inspection.

Inserting eq (47) in (46) and integrating gives:

$$z = z_0 + \ln\left\{ 1/(1 - C_e \cdot t_{corr}/D^{**}) \right\} \cdot C_{corr}/C_e \tag{49}$$

Where z_0 is the corrosion depth when the inspection is made.

The residual service life, $t_r = t_{corr}$, is given by the condition $z = z_{cr}$:

$$t_{corr} = \{1 - 1/\exp[(z_{cr} - z_0) \cdot C_e/C_{corr}]\} \cdot D^{**}/C_e \tag{50}$$

The coefficient C_{corr} determining the corrosion rate can be estimated from the estimated time when corrosion started (t_1 or t_2). This is found by measuring the actual penetration depth of the threshold concentration or carbonation front. The following relation for t_1 can be used if erosion is neglected:

$$t_1 \approx t_0 \cdot \{D^{**}/x_0\}^2 \tag{51}$$

Where t_1 is the concrete age when corrosion started, t_0 is the age at inspection, D^{**} is the actual remaining concrete cover and x_0 is the actual depth of the penetration of carbonation or threshold chloride concentration counted from the actual eroded surface.

Then, C_{corr} is estimated by (c.f eq (40)):

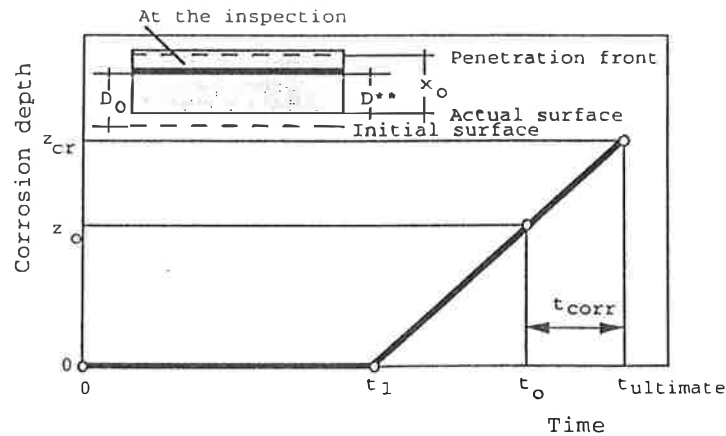$$C_{corr} \approx D^{**} \cdot z_0/(t_0 - t_1) \tag{52}$$

Fig 9: Definition of the total residual service life. Corrosion is already initiated when the inspection is made

2. Frost damage as an internal attack

When freezing occurs in pure water or in concrete with very low W/C-ratio damage is normally concentrated to the interior of the concrete. Every frost cycle of a sufficiently high severity gives its contribution to the damage. Normally, however, the first few cycles give the most severe damage. Repeated frost cycles of the same severeness in terms of internal moisture content in the concrete and in terms of the lowest temperature reached do normally not add much to the damage caused by the first cycles. Therefore, already during the first years (giving 50 or more frost cycles) the structure is normally damaged to a degree which is then kept almost constant. Besides, after frost damage has occurred, a certain self-healing might take place keeping the structure in about the same, although somewhat damaged, condition.

2.1 Time before start of corrosion

There is, as mentioned above, no surface scaling. Therefore, the extrapolation of the future penetration depth based on the penetration measured on an "old" structure can be made according to the square-root relation; see Fig 10. Extrapolation from data for a young structure might however give an overestimation of the residual service life simply because the damage level has not yet been stabilized. This means that the rate determining coefficients C' are smaller than what can be expected for an older, more damaged structure. This is visualized in Fig 10 where the "square-root lines" lies on different levels at different age of the structure. They approach a common line when the concrete is old.

The service life until start of corrosion can be calculated by eq (25) or (28). The service life will however in this case be over-estimated since the more slow diffusion during the very first time, before frost damage has ocurred, is influencing the mean, "historic" value of the diffusivity which is implicated in the equations. Another and better possibility is to use eq (31) or (32) in which the constants Δt and Δx express the time and the penetration depth when the more rapid frost destruction is terminated and the concrete diffusivity is "stabilized" on a rather constant level.
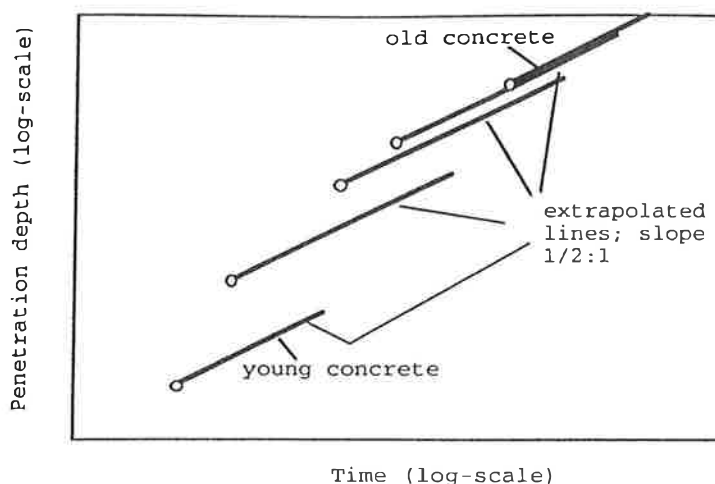

Fig 10: Extrapolation of penetration-time curves for structures with different degrees of internal frost damage (different coefficients C'). After some time the degree of damage stabilizes on a certain level.

2.2 The corrosion time

As said above, the concrete is assumed to be in a more or less constant degree of damage. Therefore, the corrosion rate can be assumed to be constant and determined by a coefficient C_{corr} defined by eq (40). C_{corr} can only be determined by a practical test of the damaged concrete or estimated on basis of experience.

The maximum acceptable corrosion time is obtained by eq (40) with constant concrete cover, $D(t) = D$:

$$t_{corr} = D \cdot z_{cr}/C_{corr} \qquad (53)$$

Where D is the thickness of the concrete cover and z_{cr} is the maximum corrosion depth.

3. Summary

Frost damage increases the rate of penetration of the carbonation front and the rate of diffusion of chlorides through the concrete cover. Two different cases must be considered:

* Salt scaling of the concrete surface. The process is often linear with time. In some cases scaling is a bit more rapid during the first years after which the rate of scaling becomes more or less constant.

* Internal damage causing an increase in porosity and permeability (diffusivity) and a decrease in strength. The process is often more rapid during the first years after which the future change in concrete properties is marginal. Thus, after a few years, the concrete becomes "fixed" in its damaged state.

The effect of frost attack on the penetration of the carbonation front and the penetration of the threshold chloride concentration is treated in the report. The main emphasis is put on the effect of salt scaling. Formulas for calculating the residual service life until onset of corrosion or until the corrosion has reached an unacceptable level are derived. The formulas are mainly based upon three properties which are determined at an inspection of the structure:

* The residual concrete cover; D
* The scaling (erosion) depth; Δx
* The penetration depth (of carbonation or of the threshold chloride concentration) from the eroded surface; x_0'

An exact method for calculating the combined effect of erosion and penetration is given by eq (38) which can be solved numerically. An example is shown in Fig 7 showing the very large effect of salt scaling on the service life.

An approximative method for calculating the residual time until onset of corrosion, based upon the assumption that the erosion has no effect on the penetration of carbonation or chlorides until the rate of penetration due to diffusion equals the rate of erosion, are given by equations (21), (25) and (28) assuming constant diffusion constants and by equations (21), (31) and (32) assuming higher diffusion coefficients when the structure was young.

A method for considering also the corrosion period, thus providing the total residual service life, is given by equations (45) and (50) which are however based on the assumption that corrosion is diffusion controlled, a somewhat dubious assumption on the safe side.

References

(1) Fagerlund, G and Hedenblad, G: Calculation of the moisture-time fields in concrete. Div. of Building Materials, Lund Institute of Technology, Report TVBM-3052, Lund 1993.