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Content

Preface

This report is produced within the BRITE/EURAM project BREU-CT92-0591 "The Residual Service Life of Concrete Structures".

Six partners are involved in the project:

1: British Cement Association (The coordinator)
2: Instituto Eduardo Torroja, Spain
3: Geocisa, Spain
4: Swedish Cement and Concrete Research Institute
5: Cementa AB, Sweden
6: Div. of Building Materials, Lund Inst. of Technol.

Three deterioration mechanisms are treated in the project:

1: Corrosion of reinforcement
2: Freeze-thaw effects
3: Alkali-silica reaction

This report refers to Task 4 of the work, "Assessment of deterioration rates" and treats the synergistic effects of two deterioration mechanisms acting simultaneously; reinforcement corosion and freeze-thaw effects.

Lund June 28, 1993

Göran Fagerlund

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:

I: 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.

II: 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_o'

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).

The different equations for calculating the residual service life are applied to a number of practical examples. They show that large errors in the estimation the residual service life can be made if salt scaling is neglected.

I: Frost damage as a pure surface attack

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.

I:1. Time before start of corrosion

I: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.

$$\mathbf{(dx/dt)_e = C_e} \tag{1}$$

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.

Example 1:

A typical scaling during a severe freeze/thaw experiment of a concrete with fair but not excellent frost resistance is $10 \cdot 10^{-6}$ m/cycle. Assuming the total number of such cycles is 50 each year the constant C_e will be $50 \cdot 10 \cdot 10^{-6} = 5 \cdot 10^{-4}$ m/year or 0,5 mm/year. The erosion depth after 20 years is 10 mm, an erosion which is often found in practice.

I:1.2 Carbonation

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

$$x_c = C'_c \cdot \sqrt{t} \tag{2}$$

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.

Example 2:

The carbonation in a certain concrete after 20 years is $15 \cdot 10^{-3}$ m = 15 mm. Then, the coefficient C'_c is $3,4 \cdot 10^{-3}$ m/$\sqrt{\text{year}}$ and the coefficient C_c is $1,7 \cdot 10^{-3}$ m/$\sqrt{\text{year}}$.

I: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.

Example 3:

The threshold concentration in a certain concrete has penetrated to the depth $30 \cdot 10^{-3}$ m = 30 mm after 20 years. Then, the coefficient C'_{cl} is $6,7 \cdot 10^{-3}$ m/$\sqrt{\text{year}}$ and the coefficient C_{cl} is $3,4 \cdot 10^{-3}$ m/$\sqrt{\text{year}}$.

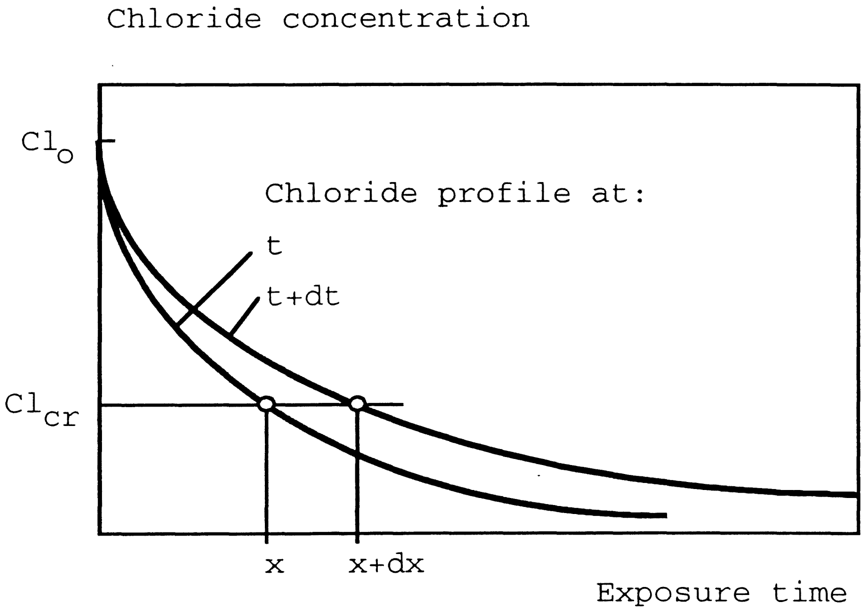

Fig 1: The chloride profile after the time t and t+dt. The rate of penetration depth of a certain constant concentration -e.g. the threshold concentration Cl_{cr} is described by a square-root relationship; eq (4) and (5).

I: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; see Fig 2(a).

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

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

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

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:

$$(dx/dt)_c = C_e \quad \text{for } t>t^* \qquad (8a)$$

$$(dx/dt)_{cl} = C_e \quad \text{for } t>t^* \qquad (8b)$$

Example 4 (Erosion and carbonation):

The coefficients C_e and C_c given by the examples 1 and 2 above are supposed to be valid for the actual concrete. Then it is valid:

$(t^*)_c = \{1,7 \cdot 10^{-3}/5 \cdot 10^{-4}\}^2 = 12$ years corresponding to a carbonation depth of $3,4 \cdot 10^{-3} \cdot \sqrt{12} = 1,2 \cdot 10^{-2}$ 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 5 (Erosion and chloride penetration):

The coefficients C_e and C_{cl} given by the examples 1 and 3 above are supposed to be valid for the actual concrete. 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**

I: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).

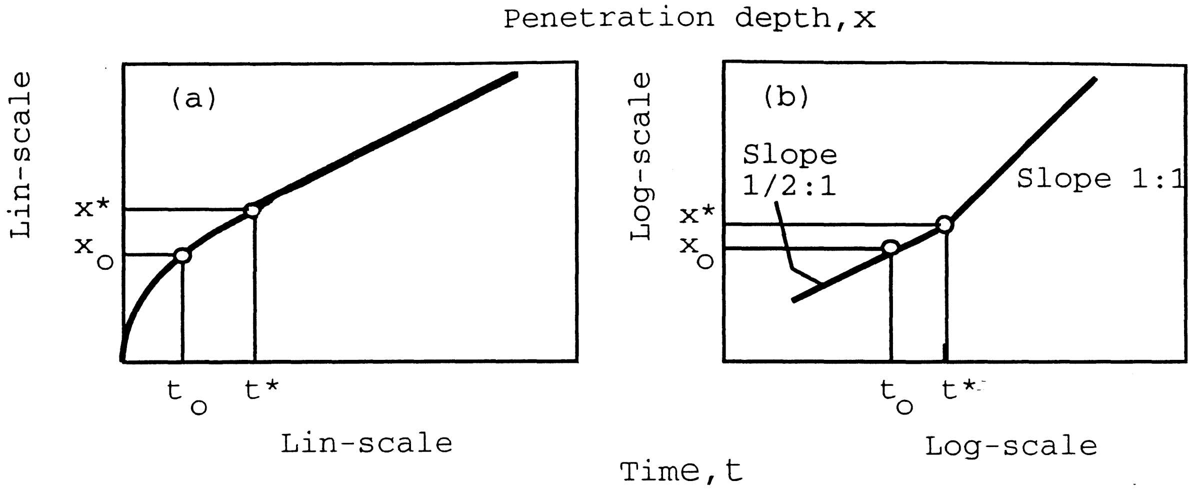

Fig 2: Penetration-time curve with erosive attack on the surface. (a) lin-lin scale. (b) log-log scale.

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 I: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_o is x_o. 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:

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

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:

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

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. This can be shown by an example.

Example 6:

At 20 years the penetration depth in a certain concrete is 15 mm counted from the initial surface. The initial concrete cover is 25 mm.

Then, $C' = 15 \cdot 10^{-3}/\sqrt{20} = 3{,}35 \cdot 10^{-3}$ and $C = C'/2 = 1{,}68 \cdot 10^{-3}$.

The erosion rate of the actual concrete is assumed to be governed by $C_e = 3{,}5 \cdot 10^{-4}$.

Then, $t^* = \{1{,}68 \cdot 10^{-3}/3{,}5 \cdot 10^{-4}\}^2 = 23$ years

This time is a bit longer than the age of the structure when it is investigated. The corresponding erosion depth is:

$(x^*)_e = 23 \cdot 3{,}5 \cdot 10^{-4} = 8$ mm

The erosion depth at the time of the measurement is:

$(x_o)_e = 20 \cdot 3{,}5 \cdot 10^{-4} = 7$ mm

Such a marginal erosion might be a bit difficult to observe and therefore easy to ignore.

The extrapolated time t_1 assuming no erosion is:

$t_1 = \{25 \cdot 10^{-3}/3{,}35 \cdot 10^{-3}\}^2 = 56$ years

The erroneously extrapolated residual service life until onset of corrosion therefore is

$t_{r,1} = 56 - 20 =$ **36 years**

The real residual service life until corrosion starts is:

$$t_{r,2} = t^* - t_o + \frac{D - x^*}{C_e} \qquad (11)$$

$x^* = C' \cdot \sqrt{t^*} = 3{,}35 \cdot 10^{-3} \cdot \sqrt{23} = 0{,}016$ m $= 16$ mm.

Therefore,

$t_{r,2} = 23 - 20 + (25-16) \cdot 10^{-3}/3{,}5 \cdot 10^{-4} =$ **29 years.**

The erroneous extrapolation where no consideration is taken to erosion therefore overestimates the residual service life by 7 years or 24 %.

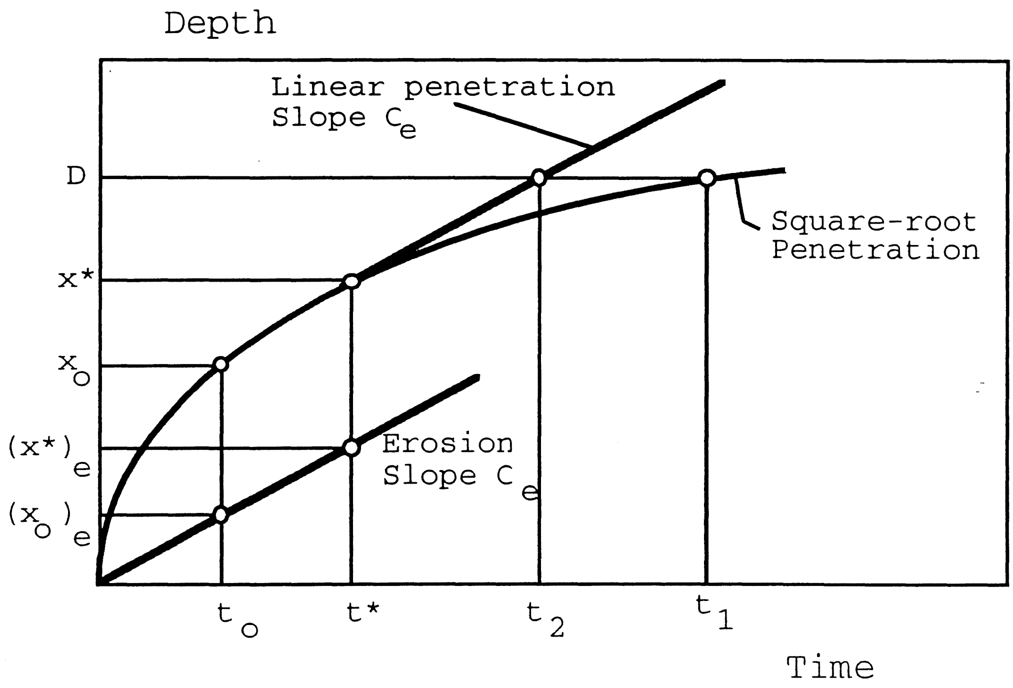

Fig 3: Extrapolation for determination of the residual service life. Error of type 1; $t^* > t_o$.

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. $t^* < t_o$. 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. The effect can be shown by an example:

<u>Example 7</u>:

At 11 years the penetration depth in a certain concrete is 10 mm counted from the initial surface. The initial concrete cover is 25 mm.

Then, the coefficient $(C')_{fictive}$ assuming that penetration is determined by a square-root relation all the time from t=0 to $t=t_1$ is:

$(C')_{fictive} = 10 \cdot 10^{-3}/\sqrt{11} = 3 \cdot 10^{-3}$

and

$C_{fictive} = (C')_{fictive}/2 = 1{,}5 \cdot 10^{-3}$

The extrapolated time t_1 therefore is:

$t_1 = \{D/x_o\}^2 \cdot t_o = \{D/(C')_{fictive}\}^2 = \{25 \cdot 10^{-3}/3 \cdot 10^{-3}\}^2 = 69$ years

The erroneously extrapolated residual service life until onset of corrosion therefore is:

$t_{r,1}$ = 69-11 = **58 years**

The erosion rate is assumed to be governed by $C_e = 5\cdot10^{-4}$.

The erosion depth at the measurement is:

$(x_o)_e = 11\cdot5\cdot10^{-4} = 5{,}5$ mm

The real residual service life $t_{r,2}$ is:

$$t_{r,2} = \frac{D - x_o}{C_e} \tag{12}$$

Or

$t_{r,2} = (25-10)\cdot10^{-3}/5\cdot10^{-4} =$ **30 years**

The erroneous extrapolation does therefore overestimate the residual service life by 28 years or 50 %.

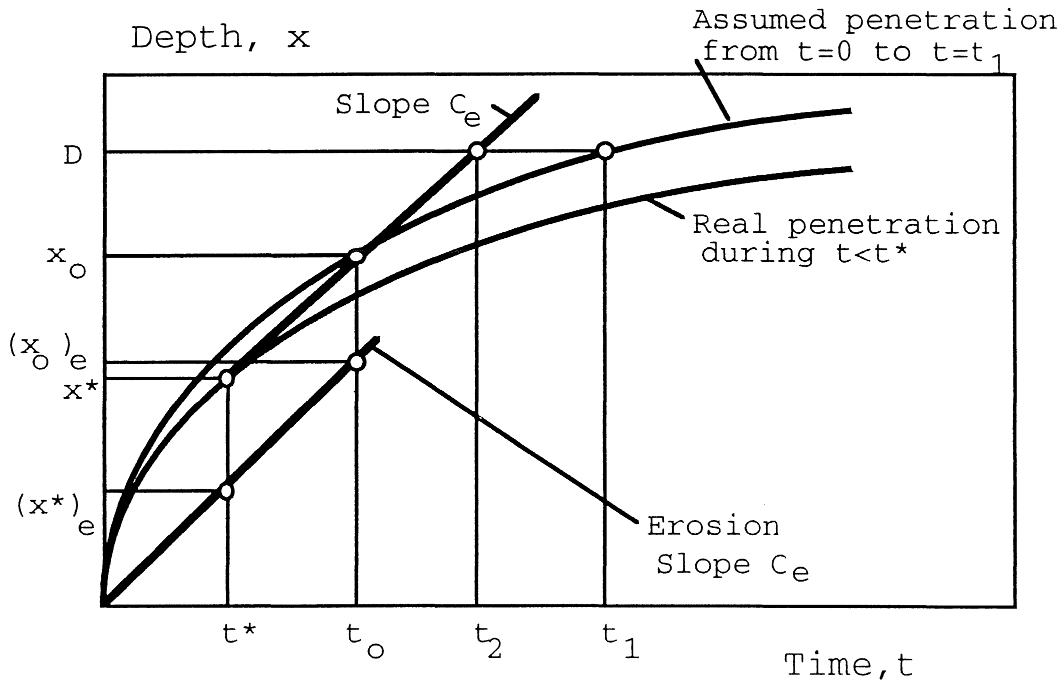

Fig 4: Extrapolation for determination of the residual service life. Error of type 2; $t^* < t_o$.

I: 1.6 A method of calculating the residual service life until start of reinforcement corrosion

I:1.6.1 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_o is $(x_o)_e$. This means that the coefficient C_e determining the rate of erosion is:

$$C_e = (x_o)_e/t_o \qquad (13)$$

The value $(x_o)_e$ 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_o is:

$$x_o = (x_o)_e + x_o' \qquad (14)$$

Where x_o' 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_o. 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_o is:

$$C' = x_o/\sqrt{t_o} \qquad (15)$$

Or, using eq (14):

$$\mathbf{C' = [(x_o)_e + x_o']/\sqrt{t_o}} \qquad (16)$$

If erosion is the rate-determing 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:

$$t^* \approx \{C'/2 \cdot C_e\}^2 \qquad (17)$$

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

$$\mathbf{t^* = \{1 + x_o'/(x_o)_e\}^2 \cdot \{t_o/4\}} \qquad (18)$$

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

One must differentiate between three cases.

Case 1; $t^* < t_o$ (Fig 5a):
Then, erosion is already the rate-determining factor. The residual service life $t_{r,2a}$ is:

$$t_{r,2a} = t_2 - t_o = [D_o - x_o]/C_e \qquad (19)$$

Where D_o is the initial concrete cover. The remaining concrete cover D is:

$$D = D_o - (x_o)_e \qquad (20)$$

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

$$\mathbf{t_{r,2a} = t_o \cdot \{D - x_o'\}/(x_o)_e} \qquad (21)$$

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

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

$$t_{r,2b} = t^* - t_o + \frac{D_o - x^*}{C_e} \qquad (22)$$

Where x^* is:

$$x^* = C' \cdot \sqrt{t^*} = \sqrt{t^*/t_o} \cdot x_o \qquad (23)$$

Inserting eq (18) and (14) gives:

$$\mathbf{x^* = \frac{\{(x_o)_e + x_o'\}^2}{2 \cdot (x_o)_e}} \qquad (24)$$

Both $(x_o)_e$ and x_o' are measured at the inspection at time t_o.

Inserting Eq (17) and (24) in (22) gives:

$$t_{r,2b} = \{D/(x_o)_e - [(x_o)_e + x_o']^2/[2\cdot(x_o)_e]^2\}\cdot t_o \quad (25)$$

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:

$$t_1 = \{D_o/C'\}^2 = \{D_o/x_o\}^2\cdot t_o \quad (26)$$

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

$$t_{r,1} = t_1 - t_o = t_o\cdot\{(D_o/x_o)^2 - 1\} \quad (27)$$

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

$$t_{r,1} = t_o\cdot\{\frac{[D + (x_o)_e]^2}{[(x_o)_e + x_o']^2} - 1\} \quad (28)$$

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

Example 8:

The erosion depth in a certain concrete is estimated to be 14 mm after 22 years. The carbonation depth at the same time is 15 mm counted from the eroded surface and the remaining concrete cover is 25 mm. Thus the following parameters are valid:

D	= 25 mm
$D_o = D+(x_o)_e = 25+14$	= 39 mm
$(x_o)_e$	= 14 mm
x_o'	= 15 mm
$x_o = x_o'+(x_o)_e = 15+14$	= 29 mm
t_o	= 22 years

The time t^* is:

$$t^* = \{1 + 15/14\}^2\cdot 22/4 = 24 \text{ years}$$

The time t_1 is:

$$t_1 = \{39/29\}^2 \cdot 22 = 40 \text{ years}$$

Thus, $t_o < t^* < t_1$; Case 2 is valid.

$$t_{r,2b} = \{25/14 - [14+15]^2/[2 \cdot 14]^2\} \cdot 22 = 15{,}7 \approx \mathbf{16\ years}$$

The service lives $t_{r,1}$ and $t_{r,2a}$ are:

$$t_{r,1} = \{\frac{(25+14)^2}{(15+14)^2} - 1\} \cdot 22 = 17{,}8 \approx 18 \text{ years}$$

$$t_{r,2a} = 22 \cdot (25-15)/14 = 15{,}7 \approx 16 \text{ years}$$

Thus, in this example, the difference between the service lives $t_{r,1}$ assuming a continuing square-root relation or $t_{r,2a}$ assuming a linear penetration rate and the real value is small.

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 overestimated. The residual service life is then simply calculated by eq (2) or (4) which gives $t_r = (25/15)^2 \cdot 22 = 61$ years which is 45 years more than the real service life.

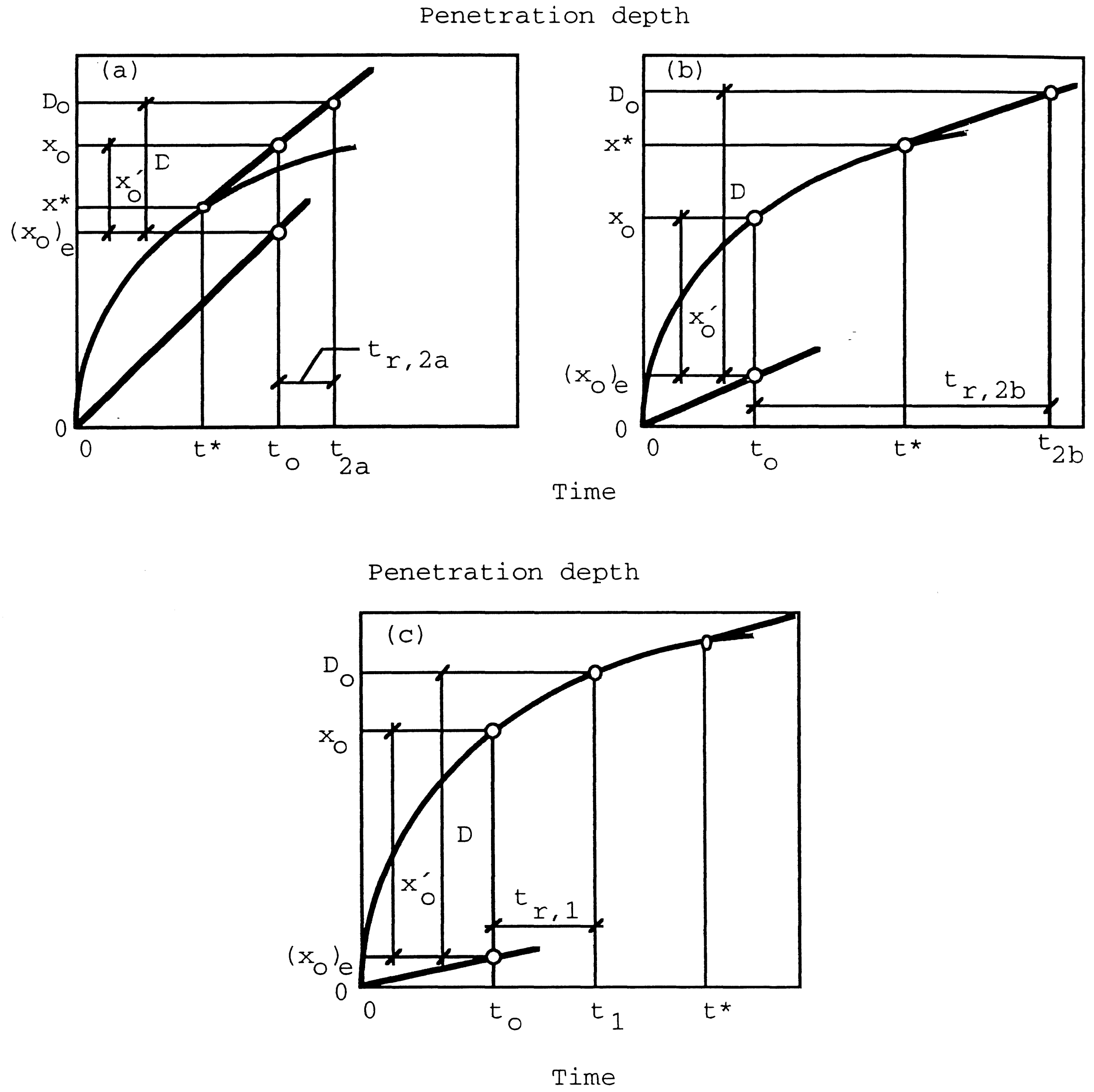

Fig 5: Data needed for an estimation of the residual service life until start of corrosion. Three different cases.

I:1.6.2 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 I:1.6.1 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 section I:1.6.1 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 Δx 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 Δx can be of the order of size 1 to 5 mm.

The following changed relations are valid:

$$t^* \approx \{1 + (x_o{}' - \Delta x)/(x_o)_e\}^2 \cdot \{t_o/4\} \qquad (29)$$

$$x^* = \frac{\{(x_o)_e + x_o{}' - \Delta x\}^2}{2 \cdot (x_o)_e} \qquad (30)$$

$$t_{r,2a} = t_o \cdot \{D - x_o{}'\}/(x_o)_e \qquad \text{(unchanged)} \qquad (21)$$

$$t_{r,2b} \approx \{D/(x_o)_e - [(x_o)_e + x_o{}' - \Delta x]^2/[2 \cdot (x_o)_e]^2\} \cdot t_o \qquad (31)$$

$$t_{r,1} \approx (t_o - \Delta t) \cdot \left\{ \frac{[D + (x_o)_e - \Delta x]^2}{[(x_o)_e + x_o{}' - \Delta x]^2} - 1 \right\} \qquad (32)$$

<u>Example 9</u>:

The same as example 8 but the first penetration occurs with a higher rate; 5 mm of the penetration is supposed to have taken place after 6 months. Thus, Δx=5 mm and Δt=0,5 years.

The time t* is:

$$t^* = \{1+(15-5)/14\}^2 \cdot \{22/4\}=16 \text{ years}$$

Thus, the penetration is linear already when the measurement is made; i.e. the penetration is determined by the erosion rate. The residual service life $t_{r,2a}$ is:

$$t_{r,2a} = 22 \cdot (25-15)/14 = \mathbf{16\ years}$$

The service life is not changed in this case in comparison to example 8 but the rate-determining mechanism is changed from a square-root relation to a linear relation.

The residual service life $t_{r,2b}$ according to eq (31) has no meaning since the time t* is shorter than the time of measurement t_o.

The residual service life $t_{r,1}$ assuming erosion being negligible is:

$$t_{r,1} = (22-0,5) \cdot \left\{ \frac{[25+14-5]^2}{[14+15-5]^2} - 1 \right\} = 22 \text{ years}$$

This value is 4 years longer than in example 8.

Example 10:

The fact that the diffusivity is larger during the first year will also effect the predicted future service life even if there was no erosion This is shown by the following example:

A concrete has a concrete cover of 30 mm. The penetration depth after 25 years is 22 mm. The initial penetration, Δx, during the first year, Δt, was 10 mm.

According to eq (32), the real residual service life is:

$$t_{r,1} = (25-1) \cdot \{(30-10)^2/(22-10)^2 -1\} = 43 \text{ years}$$

If no consideration is taken to the initial more rapid penetration the service life will be:

$$t_r = 25 \cdot \{30^2/22^2 -1\} = 21 \text{ years.}$$

Thus, an extrapolation, based on the assumption that the diffusivity has been the same during the whole time, is very much on the safe side.

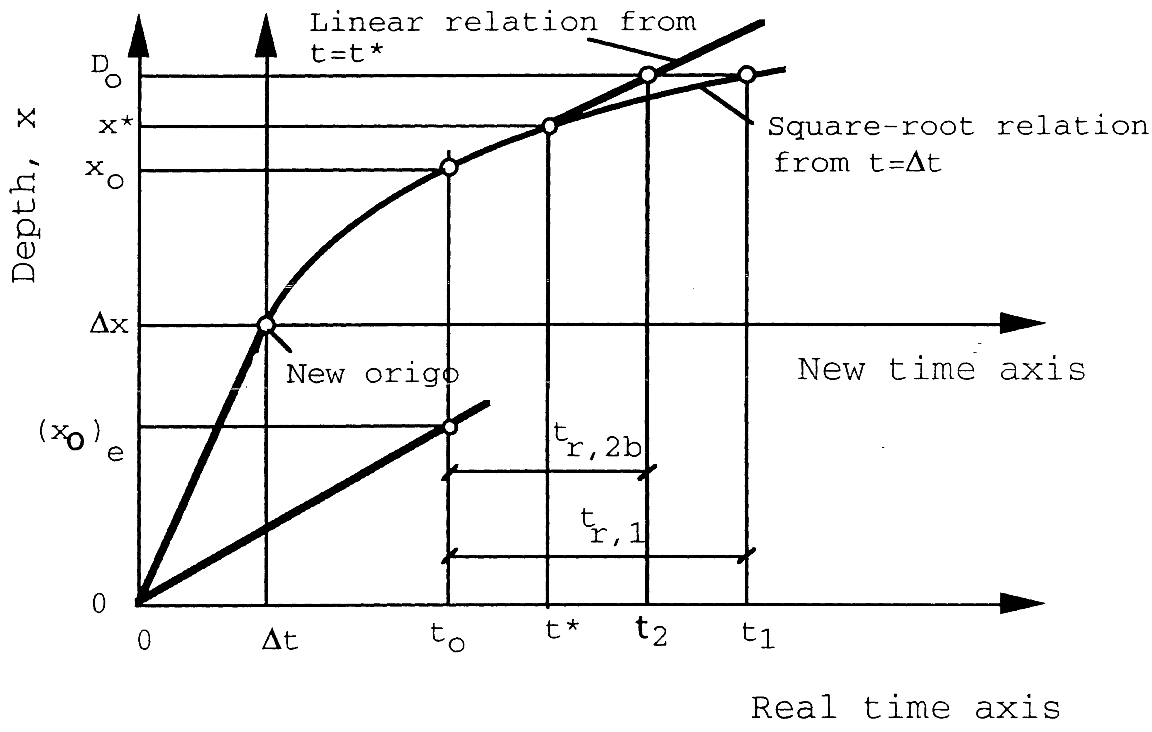

Fig 6: Method of considering an initial more rapid penetration of either the carbonation front or the chloride threshold concentration; principles only.

I: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:

$$x \cdot dx/dt = K \qquad (33)$$

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

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

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

$$C' = \sqrt{2 \cdot K} \qquad (34)$$

With erosion eq (33) is changed to

$$(x - x^*)\cdot dx/dt = K \qquad (35)$$

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

$$x^* = C_e\cdot t \qquad (36)$$

The differential equation describing the combined erosion and diffusion therefore is

$$(x - C_e\cdot t)\cdot dx/dt = K \qquad (37)$$

Or

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

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

<u>Example 11</u>:

The following coefficients are valid for a certain concrete:

$C' = 3\cdot 10^{-3}$
$C_e = 5\cdot 10^{-4}$

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:

$$\Delta x = \frac{\{3\cdot 10^{-3}\}^2}{2\cdot\{\Sigma\Delta x - 5\cdot 10^{-4}\cdot\Sigma\Delta t\}}\cdot\Delta t = \frac{4{,}5\cdot 10^{-6}}{\Sigma\Delta x - 5\cdot 10^{-4}\cdot\Sigma\Delta t}\cdot\Delta t$$

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 :

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

The exact solution gives:

$t_{exact} =$ **43 years**

<u>Note</u>: The service life neglecting erosion is:

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

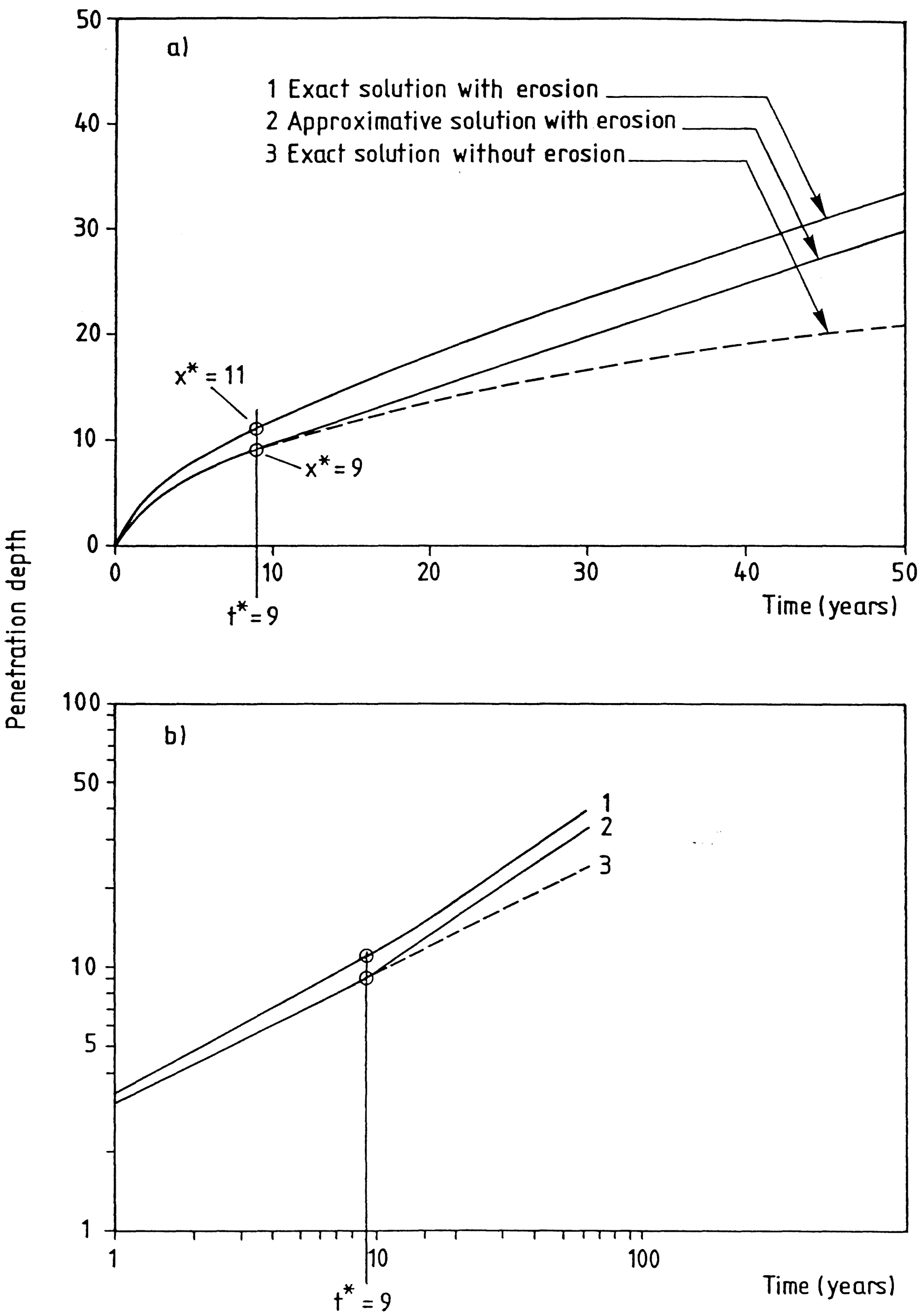

Fig 7: Solution of example 11.
(a) lin-lin scale. (b) log-log scale.

I:2. Corrosion time

I: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 in m 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:

$$D^* = D_o - (\Delta D)_{corr} = D_o - C_e \cdot [t_{r,1} + t_o] \tag{42}$$

Or

$$D^* = D_o - (\Delta D)_{corr} = D_o - C_e \cdot [t_{r,2} + t_o] \tag{43}$$

Where D_o 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:

$$z = \ln\{1/[1 - C_e \cdot t_{corr}/D^*]\} \cdot C_{corr}/C_e \tag{44}$$

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

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

<u>Example 12</u>:

The same as example 8.

The corrosion rate is supposed to be 10 μm per year when the cover is 25 mm. Thus, the coefficient $C_{corr}=10 \cdot 10^{-6} \cdot 25 \cdot 10^{-3}/1= 2,5 \cdot 10^{-7}\ m^2/year$.

The critical corrosion depth is supposed to be 100 μm = $100 \cdot 10^{-6}$ m.

The coefficient $C_e=0,014/22=6,4 \cdot 10^{-4}$ m/year.

The time $t_{r,2b}$ is determining the onset of corrosion. $t_{r,2b}$ = 16 years according to the calculations in example 8.

Thus, $D^* = 39 \cdot 10^{-3} - 6,4 \cdot 10^{-4} \cdot [16 + 22] \approx 15 \cdot 10^{-3}$ m = 15 mm.

The corrosion time t_{corr} is:

$$t_{corr} = \{1-1/exp[100 \cdot 10^{-6} \cdot 6,4 \cdot 10^{-4}/2,5 \cdot 10^{-7}]\} \cdot 15 \cdot 10^{-3}/6,4 \cdot 10^{-4} = \\ = 5,3 \text{ years} \approx 5 \text{ years.}$$

The total residual service life is:

t_r = 16 + 5 = 21 years

Note: if the gradual reduction of the concrete cover is neglected the corrosion time will be:

$$t_{corr} = D^* \cdot z_{cr}/C_{corr} = 15 \cdot 10^{-3} \cdot 100 \cdot 10^{-6}/2,5 \cdot 10^{-7} = \\ = 6 \text{ years.}$$

Therefore, the effect of the eroding cover is rather small in this case. This depends on the slow erosion rate assumed.

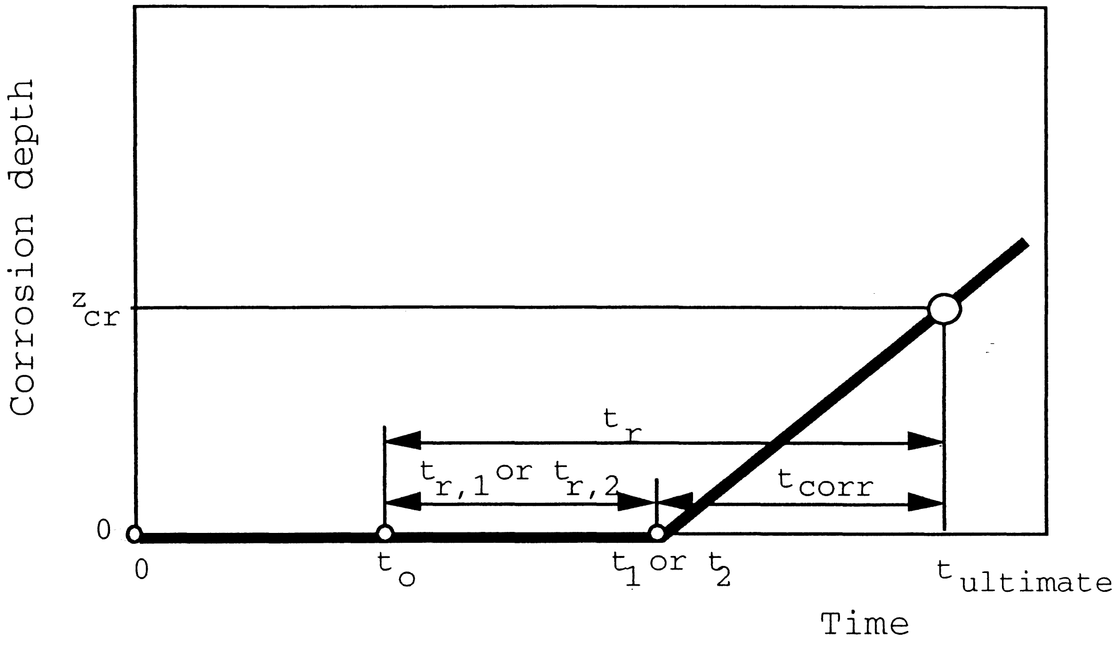

Fig 8: Definition of the total residual service life. Corrosion is not initiated when the inspection is made.

I: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:

$$C_e = (D_o - D^{**})/t_o \tag{48}$$

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

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

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

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

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

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

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:

$$t_1 \approx t_o\cdot\{D^{**}/x_o\}^2 \quad (51)$$

Where t_1 is the concrete age when corrosion started, t_o is the age at inspection, D^{**} is the actual remaining concrete cover and x_o 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)):

$$C_{corr} \approx D^{**}\cdot z_o/(t_o-t_1) \quad (52)$$

<u>Example 13</u>:

The reinforcement in a concrete structure which is 25 years old has a corrosion depth z_o of 50 µm. The residual concrete cover D^{**} is 23 mm and the threshold chloride concentration is located at a depth x_o of 31 mm from the eroded surface. The initial concrete cover D_o is estimated to be 40 mm.
The critical corrosion depth z_{cr} is 150 µm.

$C_e \approx (40-23)\cdot 10^{-3}/25=6,8\cdot 10^{-4}$ m/year.

$t_1 \approx 25\cdot\{23/31\}^2=14$ years

(i.e. corrosion has been going on for 11 years)

$C_{corr} \approx 23\cdot 10^{-3}\cdot 50\cdot 10^{-6}/(25-14)=1,3\cdot 10^{-7} m^2/year$

$t_{corr}=\{1-1/exp[(150-50)10^{-6}\cdot 6,8\cdot 10^{-4}/1,3\cdot 10^{-7}]\}\cdot 23\cdot 10^{-3}/6,8\cdot 10^{-4}=$

$= 13,8$ years ≈ 14 years.

Note: if the erosion is neglected the residual service life will be:

$$t_{corr}=(z_{cr}-z_o)\cdot D^{**}/C_{corr}= (150-50)10^{-6}\cdot 23\cdot 10^{-3}/1,3\cdot 10^{-7}= =18 \text{ years}.$$

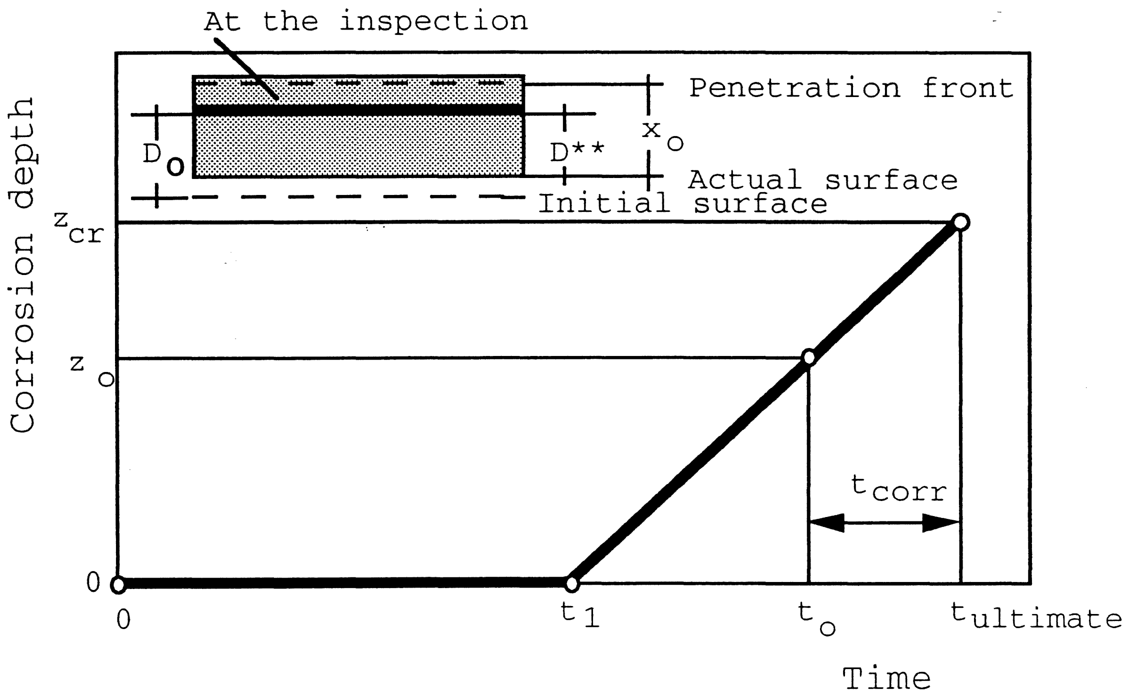

Fig 9: Definition of the total residual service life. Corrosion is already initiated when the inspection is made.

II: 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.

II: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 overestimated 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.

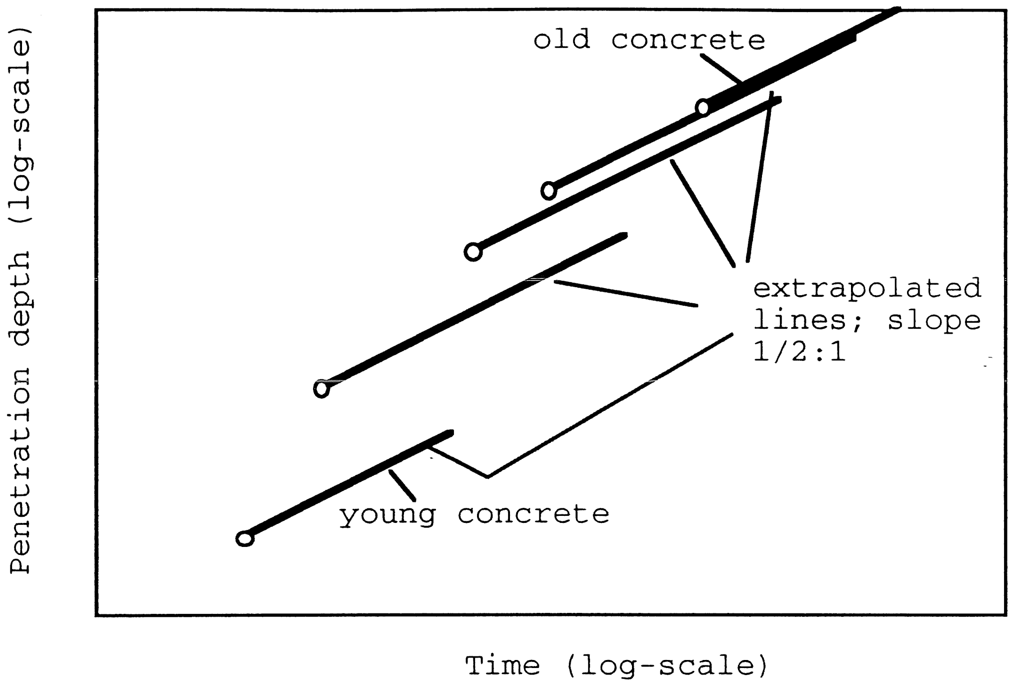

Fig 10: Extrapolation of penetration-time curves for structures with different degrees of internal frost damage (different coefficients C´). After some time the degree of damage stabilizes on a certain level.

II:2 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:

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

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