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Division of Building Materials

CHLORIDE TRANSPORT AND REINFORCEMENT CORROSION IN CONCRETE EXPOSED TO SEA WATER PRESSURE

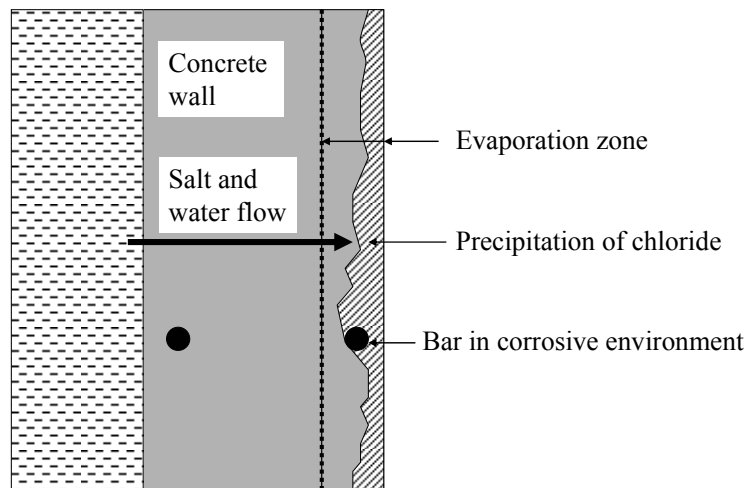
Göran Fagerlund

CONTENT	Page
1 INTRODUCTION AND SUMMARY	2
2 WATER FLOW THROUGH THE WALL	3
2.1 Water flow 1 caused by water pressure	3
2.2 Water flow 2 caused by capillary under-pressure	3
2.3 Combined water flow	6
3 CHLORIDE FLOW THROUGH THE WALL	6
3.1 Chloride flow not considering chloride binding	6
3.2 Chloride flow considering chloride binding	7
4 REINFORCEMENT CORROSION	9
4.1 The threshold concentration for initiation of corrosion	9
4.2 Reinforcement corrosion at the upstream part of concrete	11
4.3 Reinforcement corrosion at the downstream part of concrete. Life time before corrosion	11
REFERENCES	13
APPENDIX 1: APPLICATIONS OF THE THEORY	14
Structure 1. Basement exposed to moderately high water pressure	14
Example A: Moderately high salt concentration; 10 g/litre	14
Example B: High salt concentration; 19 g/litre	16
Structure 2. Submerged tunnel exposed to high water pressure	18
Example C: Moderately high salt concentration; 10 g/litre. Low permeability; 10^{-13} s	18
Example D: High salt concentration; 19 g/litre. Low permeability; 10^{-13} s	19
Example E: Moderately high salt concentration; 10 g/litre. High permeability; 10^{-12} s	21
Example F: Moderately high salt concentration; 10 g/litre High permeability: 10^{-12} s 50% higher chloride binding capacity	22
Comments to the examples	23
APPENDIX 2: CHLORIDE CONCENTRATION IN SEA WATER	25
APPENDIX 3: WATER PERMEABILITY OF CONCRETE	26

1 INTRODUCTION AND SUMMARY

Many reinforced concrete structures are exposed to outer pressure of saline water. Examples are:

- Submerged tunnels
- Foundations in saline groundwater
- Culverts in seawater or saline groundwater
- Outlet tunnels leading saline water



Due to one-sided outer water pressure, salt water will penetrate the concrete by convective transport. After certain “incubation time”, salt will reach the downstream surface. Water will evaporate and salt will precipitate within the downstream evaporation zone. After a certain time, when a threshold chloride concentration has been reached, corrosion will start on reinforcement located in the downstream part of the structure.

The report presents a method for how to calculate the amount of chloride penetrating concrete, and the time needed for corrosion to start. Equations are given by which the calculations can be easily made when the composition of the concrete, the water permeability of concrete, the outer water pressure, and the outer salt concentration are known.

In APPENDIX 1 some applications of the method are demonstrated. It is shown that the most important factors determining time to corrosion for given outer salt concentration and water pressure are:

- Water permeability of concrete
- Chloride binding capacity of concrete
- Thickness of concrete member

In APPENDIX 2 values are given for the chloride content in seawater around the Scandinavian coast.

In APPENDIX 3 the permeability of concrete to water under one-sided pressure is discussed. Data from literature are given.

2 WATER FLOW THROUGH THE WALL

Water flow depends on two simultaneously acting mechanisms:

1. Flow caused by difference in water pressure between the two sides of the wall
2. Flow caused by capillary under-pressure (suction) in the pore system

The two mechanisms are described below.

2.1 WATER FLOW 1 CAUSED BY WATER PRESSURE

At equilibrium the flow is the same in all parts of the wall, i.e. the rate of inflow on the upstream side is equal to the rate of outflow from the downstream side.

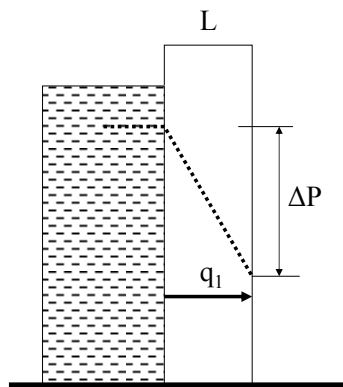


Figure 1: Flow 1 caused by water pressure

The flow is described by Darcy's law:

$$q_1 = B \cdot \frac{\Delta P}{L} \quad (1)$$

q_1 is the flow ($\text{kg}/\text{m}^2 \cdot \text{s}$)

B is the permeability coefficient ($\text{kg}/(\text{m} \cdot \text{s} \cdot \text{Pa})$) or (s)

ΔP is the pressure difference between the upstream and downstream surfaces (Pa)

L is the flow path (the wall thickness) (m)

The value of the permeability coefficient is discussed in APPENDIX 3.

2.2 WATER FLOW 2 CAUSED BY CAPILLARY UNDER-PRESSURE

At the downstream surface the concrete is in equilibrium with surrounding air. The relative humidity (RH) of air is the same as the relative humidity in concrete at the downstream surface. Since RH in air normally is lower than 100%, a capillary under-pressure arises in the downstream pore water. On the other hand, capillary pressure in the inner, saturated part of the concrete is zero (100% RH). Within a part of the wall located between the downstream surface and the inner saturated concrete there is a gradual transition from RH in air to 100%; see Figure 1. At equilibrium the transition is normally not linear but is curved upwards, as shown in the figure.

The gradient in under-pressure creates suction that draws water from the interior of concrete to the downstream surface. A water flow will occur also in cases where an outer over-pressure is lacking.

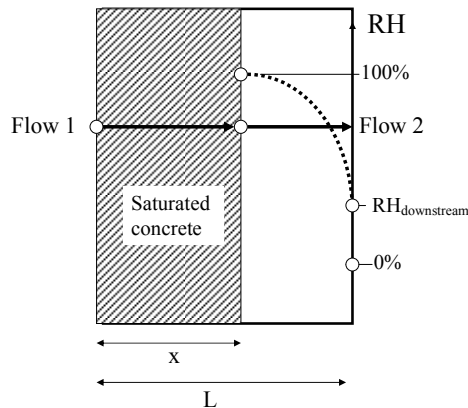


Figure 2: Flow 2 caused by capillary under-pressure

Flow 2 can be determined by placing a specimen with the bottom side in contact with water, and the upper surface exposed to air of certain constant RH obtained by a saturated salt solution. The vertical sides of the specimen are sealed. The flow upwards is determined by weighing the solution at different time. Flow 2 is found when steady state conditions are reached. RH inside the specimen shall be measured on different depths from the top surface using calibrated RH-sensors. The measurement principle is illustrated by Figure 3. The test technique was developed and used by Hedenblad (1993).

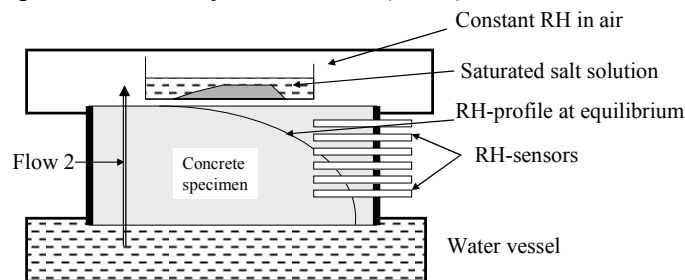


Figure 3: Method for determining a reference value of flow 2.

An example of the result of application of the test method is shown in Figure 4. It shows the RH-profile determined after 5 years (very close to equilibrium) across a 15 cm thick concrete specimen (w/c 0.50) with the upper side in air of 33% RH (saturated CaCl_2 -solution); Hedenblad (1993).

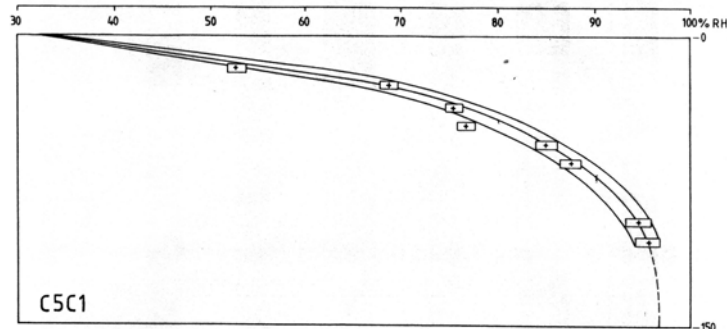


Figure 4: Equilibrium RH-profile across a 15 cm thick specimen with the bottom surface in water and the top surface at 33% RH; Hedenblad (1993).

The following equilibrium flow was determined by Hedenblad (1993) for specimens of 15 cm thickness with different w/c-ratio. The cement was of type OPC:

w/c 0.40:	$q_{2,15\text{cm}}=1.68 \cdot 10^{-8} \text{ kg/m}^2 \cdot \text{s}$
w/c 0.50:	$q_{2,15\text{cm}}=3.70 \cdot 10^{-8} \text{ kg/m}^2 \cdot \text{s}$
w/c 0.60:	$q_{2,15\text{cm}}=5.84 \cdot 10^{-8} \text{ kg/m}^2 \cdot \text{s}$
w/c 0.70:	$q_{2,15\text{cm}}=1.13 \cdot 10^{-7} \text{ kg/m}^2 \cdot \text{s}$
w/c 0.80:	$q_{2,15\text{cm}}=1.41 \cdot 10^{-7} \text{ kg/m}^2 \cdot \text{s}$

These data are plotted in Figure 5. The following relation is approximately valid:

$$q_{2,15\text{cm}}=25 \cdot 10^{-8} \cdot (w/c)^3 \quad (2)$$

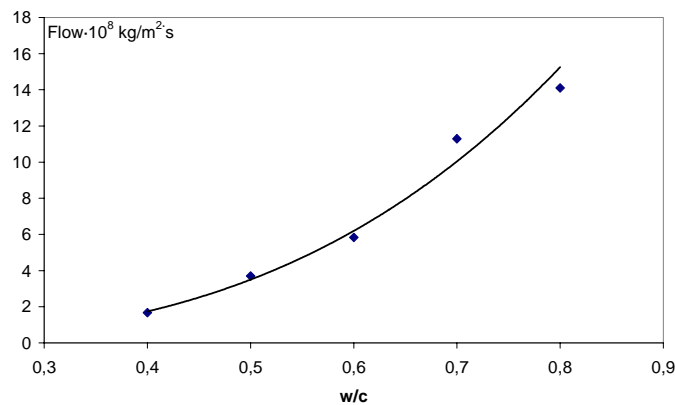


Figure 5: Observed flow of type 2 through 15 cm thick specimens as function of the water-cement ratio; Hedenblad (1993).

The measured equilibrium flow, and the corresponding RH-profile in the lab specimen, can be used for calculating the moisture flow for different boundary conditions and different thicknesses of the real member through which flow occurs. The method is illustrated by Figure 6.

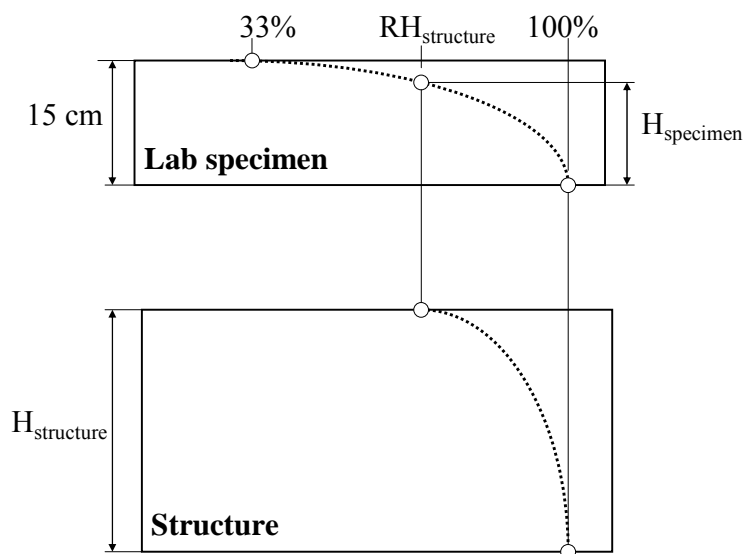


Figure 6: Principles for how to use the reference flow through a small lab specimen to calculate the real equilibrium moisture flow through a full-size structural member.

From the measured equilibrium RH-curve, valid for the lab specimen, the distance between the wet side (100% RH) and the point where RH corresponds to RH at the downstream side of the real structure is measured. This distance is called $H_{specimen}$. At equilibrium a moisture flow is always inversely proportional to the distance (thickness) between the RH-value for the upstream and downstream surfaces. The equilibrium moisture flow in the structure can therefore be calculated by:

$$q_{structure} = q_{specimen} \cdot \frac{H_{specimen}}{H_{structure}} \quad (3)$$

Thus, flow decreases linearly with increased construction thickness, and decreases with increased RH of air at the downstream surface.

2.3 COMBINED WATER FLOW

Flow 2 dominates in the non-saturated part closest to the downstream surface while flow 1 dominates in the saturated upstream part of the wall.

The water content increases gradually with increased distance from the downstream surface, which is illustrated by Figure 2. On a certain distance x from the upstream surface, flow 1 is equal to flow 2. On this depth the air pressure in the pores is equal to normal atmospheric pressure. Relative humidity is 100%. Thus, location x corresponds to the surface placed in contact with water in the lab test.

The depth x is calculated by putting flow 1 equal to flow 2; i.e.:

$$B \cdot \frac{\Delta P}{x} = q_{specimen} \cdot \frac{H_{specimen}}{H_{structure} - x} \quad (4)$$

The combined flow is calculated by:

$$q_{1+2} = B \cdot \frac{\Delta P}{x} \quad \text{or} \quad q_{1+2} = q_{specimen} \cdot \frac{H_{specimen}}{H_{structure} - x} \quad (5)$$

3 CHLORIDE FLOW THROUGH THE WALL

3.1 CHLORIDE FLOW NOT CONSIDERING CHLORIDE BINDING

The highest rate of salt transport occurs when transport is fully convective; i.e. when the water stream transports salt ions, and the salt concentration of transported water is the same as that of outer water. In order to simplify, flow 2 is also supposed to bring chloride ions convectively by the same rate as flow 1. This is probably not correct, but since in most cases flow 1 dominates over the biggest portion of the cross-section, the error is normally small.

The total convective salt transport during a period of N years is:

$$Q_{Cl,N} = q_{1+2} \cdot N \cdot c_{Cl} \quad (\text{g/m}^2) \quad (6)$$

q_{1+2} is the total water transport during one year (litre/m²·year)

c_{Cl} is the outer salt concentration in upstream water (g/litre)

Salt cannot reach the downstream surface until all pore water has been exchanged by water containing salt. This exchange process takes a certain time. It is assumed that only capillary water contains easily movable water. The capillary porosity is:

$$P_{cap} = C \cdot (w/c - 0.39 \cdot \alpha) \quad (\text{litre/m}^3) \quad (7)$$

C is the cement content (kg/m^3)
w/c is the water/cement ratio (-)
 α is the degree of hydration (-)

This formula is valid for concrete made with OPC, but approximately also for concrete containing a moderately high amount of fly ash, at which this is included in C.

The amount of capillary water in a wall with thickness L (m) is:

$$w_{cap} = P_{cap} \cdot L \quad (\text{litre/m}^2) \quad (8)$$

The following amount of chloride is required to fill the capillary pore system with salt water of the same concentration as outside water:

$$Q_{Cl, cap} = w_{cap} \cdot c_{Cl} \quad (\text{g/m}^2) \quad (9)$$

The time it takes for salt water to reach the downstream surface is:

$$N_0^{no\ binding} = \frac{Q_{Cl, cap}}{q_{1+2} \cdot c_{Cl}} \quad (\text{years}) \quad (10)$$

The effective number of years, N_{eff} , during which chloride is transported to the downstream surface, and is precipitated there, is:

$$N_{eff}^{no\ binding} = N - N_0^{no\ binding} \quad (\text{years}) \quad (11)$$

Provided no chemical or physical binding occurs, the total amount of chloride that can be transported to the downstream surface during N years is:

$$Q_{Cl, N}^{no\ binding} = Q_{Cl, N} - Q_{Cl, cap} = q_{1+2} \cdot N_{eff}^{no\ binding} \cdot c_{Cl} \quad (\text{g/m}^2) \quad (12)$$

3.2 CHLORIDE FLOW CONSIDERING CHLORIDE BINDING

Chloride ions will be bound chemically by reaction with hydration products (cement gel), and bound physically by adsorption to pore walls. Chloride binding has been studied by Tuutti (1982), Tang (1996) and others. Equilibrium will be rapidly reached between the chloride concentration of pore water and the amount of bound chloride. Chloride binding will increase with increased chloride concentration of pore water. An experimentally determined relation between free and bound chloride for paste made with a Swedish OPC is shown in Figure 7; Tang (1996). Chloride binding is different for different chemical composition of the cement. Therefore, somewhat different binding curves are valid for other types of binders.

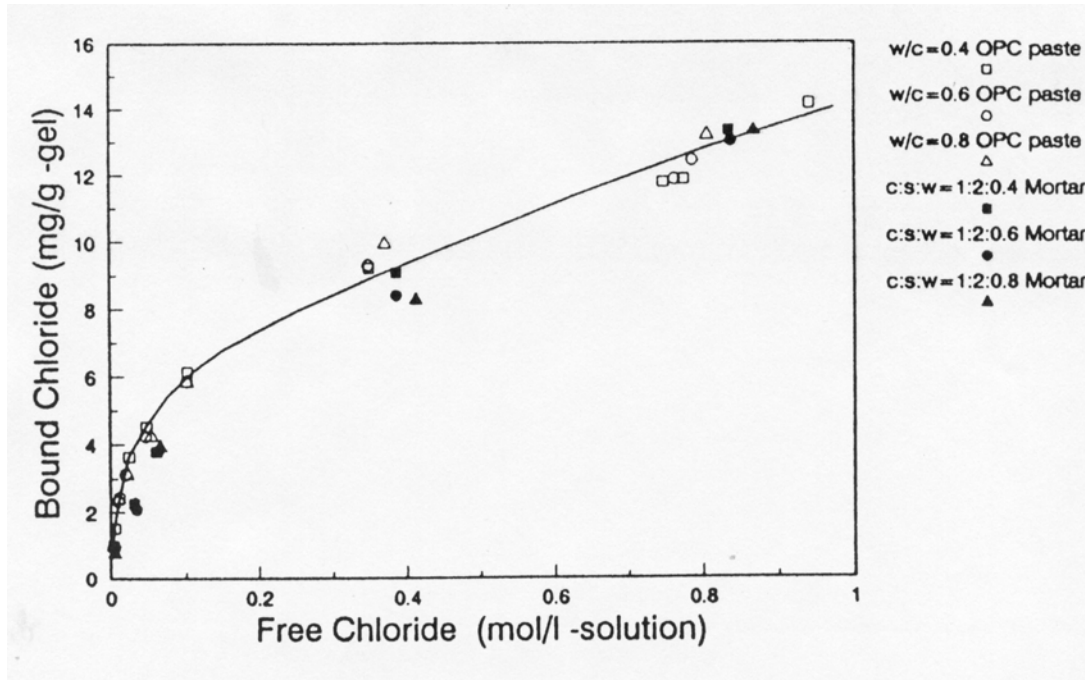


Figure 7: Example of the relation between free chloride ion concentration in pore water and bound chloride in cement gel; Tang (1996).

The weight of cement gel in 1 m² of the wall is:

$$Q_{gel} = L \cdot 1.25 \cdot \alpha \cdot C \cdot 10^3 \quad (\text{g/m}^2) \quad (13)$$

The free chloride concentration in pore water at equilibrium is supposed to be the same as in outer water; i.e. expressed in terms of mole/litre the concentration is:

$$c_{Cl,free} = \frac{c_{Cl}}{35.5} \quad (\text{mole/litre}) \quad (14)$$

Thus, when the outer chloride concentration c_{Cl} is known, the total amount of bound chloride can be found from Figure 7.

The total amount of “immobilized” chloride is the sum of chloride needed to fill the capillary pore system -equation (9)- and bound chloride.

The amount of chloride able to reach the downstream surface during N years becomes:

$$Q_{Cl,N}^{with\ binding} = Q_{Cl,N} - Q_{Cl,cap} - Q_{Cl,bound} \quad (\text{g/m}^2) \quad (15)$$

Note: It was assumed that chloride can be bound over the entire cross-section of the wall. Probably, smaller or no binding occurs in the more dry downstream part of the wall. Therefore, chloride binding using equation (13) is somewhat exaggerated. This is compensated for by the assumption made that convective flow of chloride takes place also in the dry zone where flow 2 is active; see equation (6).

Besides, in most cases the dry zone (RH<90 à 95%) is only a small portion of the entire wall thickness.

No chloride can be accumulated in the downstream part of concrete until the inflow is equal to or higher than chloride dissolved in capillary water and bound to concrete. This “incubation time” is:

$$N_0^{with\ binding} = \frac{Q_{Cl,cap} + Q_{Cl,bound}}{q_{1+2} \cdot c_{Cl}} \quad (\text{years}) \quad (16)$$

“The effective” flow time that will cause chloride accumulation is:

$$N_{Neff}^{with\ binding} = N - \frac{Q_{Cl,cap} + Q_{Cl,bound}}{q_{1+2} \cdot c_{Cl}} \quad \text{years} \quad (17)$$

4 REINFORCEMENT CORROSION

4.1 THE THRESHOLD CONCENTRATION FOR INITIATION OF CORROSION

Threshold concentration of free chloride

Reinforcement corrosion is initiated when the free chloride concentration in pore water surrounding the bar has reached a certain threshold value. This is not very well known. In this report the Hausmann criterion is used; Hausmann (1967):

$$[Cl_{free}]_{thr} = 0.6 \cdot [OH] \quad (18)$$

$[Cl_{free}]_{thr}$ is the threshold concentration of free chloride in pore water (mole/litre)

$[OH]$ is the OH-ion concentration in pore water (mole/litre)

Thus, more chloride is needed when the pore water is more alkaline. The threshold concentration should therefore be higher the higher the water soluble alkali content in cement is. The threshold also increases with lower amount of pore water in which alkali is dissolved. Therefore, it increases with decreased water/cement ratio.

The alkali content of the cement is expressed in terms of the equivalent Na_2O content:

$$(Na_2O)_{equiv} = Na_2O + 0.66 \cdot K_2O \quad (\% \text{ of the cement weight}) \quad (19)$$

Where Na_2O and K_2O are the water soluble alkali oxides expressed as weight-% of the cement.

One kg of Na_2O produces $2 \cdot M_{OH}/M_{Na_2O} = 34/62 = 0.55$ kg of OH ions corresponding to 32 mole OH-ions (M is the molar mass). The amount of OH-ions in concrete therefore is, $0.32 \cdot C \cdot (Na_2O)_{equiv}$ (mole/m³) where $(Na_2O)_{equiv}$ is expressed as weight-% of cement.

The total water content at saturation is equal to the entire porosity (not including air pores):

$$W = C \cdot (w/c - 0.19 \cdot \alpha) \quad (\text{litre/m}^3) \quad (20)$$

Thus, the OH-concentration becomes:

$$[OH] = \frac{0.32 \cdot (Na_2O)_{equiv}}{w/c - 0.19 \cdot \alpha} \quad (\text{mole/litre}) \quad (21)$$

The equation shows that the OH-concentration is independent of the cement content. It is only dependent on the alkalinity of the cement and on the w/c-ratio and degree of hydration.

The threshold concentration becomes:

$$[Cl_{free}]_{thr} = 0.6 \cdot \frac{0.32 \cdot (Na_2O)_{equiv}}{w/c - 0.19 \cdot \alpha} = \frac{0.19 \cdot (Na_2O)_{equiv}}{w/c - 0.19 \cdot \alpha} \quad (\text{mole/litre}) \quad (22)$$

Note: Gradual leaching of alkali from concrete constantly exposed to water will reduce the OH-concentration and thereby decrease the threshold concentration. The leaching from saturated concrete can be calculated by Fick's law. The OH-concentration on distance T (at the bar surface) from the concrete surface at exposure time t is calculated by:

$$\frac{[OH]_{T,t}}{[OH]_0} = \text{erf} \left\{ \frac{T}{(4 \cdot \delta_{Cl} \cdot t)^{1/2}} \right\} \quad (23)$$

[OH]₀ is the OH-concentration before leaching (mole/litre)

δ_{Cl} is the diffusivity of OH-ions (m²/s)

erf is the error function

Threshold concentration of total chloride

Often the threshold is given in terms of total chloride (bound+free). A value of the order 0.5% of the cement weight is often stated and supposed to be “on the safe side”. Theoretically, the value shall depend on the type of binder, since different binders have different ability to bind chloride chemically. It shall also depend on the OH-concentration of pore water, which is depending on the chemical composition of the binder. A Swedish working group on durability of concrete proposed the values in Table 1; Swedish Concrete Association (1998). As shown, the use of mineral by-products is supposed to lower the threshold, which depends on the lowered OH-concentration of pore water.

Table 1: Threshold concentration of total chloride (acid-soluble) in concrete, weight-% of binder weight.

Environment type	Type of binder			
	portland cement CEM I	8% silica fume	15% fly ash	15% blastfurnace slag
Cyclic moisture load	0,7 (variation 0,6-2,2)	0,4 (var 0,3-1,5)	0,5	0,5
Constantly high moisture level	1,5 (var 1,5-2,2)	0,8 (var 0,8-1,9)	1,0 (var 0,9-1,4)	1,0 (var 0,8-2,0)
Marine environment	0,8 (var 0,6-2,2)	0,5 (var 0,5-1,0)	0,6 (var 0,4-0,8)	0,6 (var 0,5-1,2)
De-icing salt environment	0,6 (var 0,4-1,0)	0,3	0,4	0,4

4.2 REINFORCEMENT IN THE UPSTREAM PART OF CONCRETE

The free chloride concentration in pore water surrounding reinforcement bars in the upstream part of concrete is constant and equal to the outer chloride concentration in water. Theoretically, corrosion can be initiated if the outer concentration is above the threshold concentration. Leaching will reduce the threshold concentration in upstream concrete.

However, since concrete is saturated, the concentration of oxygen around the reinforcement bars is so low that the corrosion rate will be negligible, provided the concrete is so dense that macro-cell corrosion cannot take place. At macro-cell corrosion, the cathode, driving corrosion, is located in non-saturated, "oxygen-rich", concrete above the water surface, rather long distance from the corrosion site (the anode), which is located in saturated concrete below the water surface. For this corrosion to take place the concrete must be very porous and the chloride content high, so that the electrical conductivity in concrete becomes very high.

4.3 REINFORCEMENT IN THE DOWNSTREAM PART OF CONCRETE LIFE TIME BEFORE CORROSION

Corrosion might occur in reinforcement in the downstream part of the concrete, provided the chloride concentration exceeds the threshold concentration, and the moisture conditions are favourable. Most corrosive conditions exist when reinforcement is located in the evaporation zone where flow of type 2 is active. In this zone RH of concrete is between 100% and RH of the space surrounding the downstream surface; see Figure 8. The most corrosive conditions exist when RH of concrete is between about 80% RH and 95% RH; Tuutti (1982).

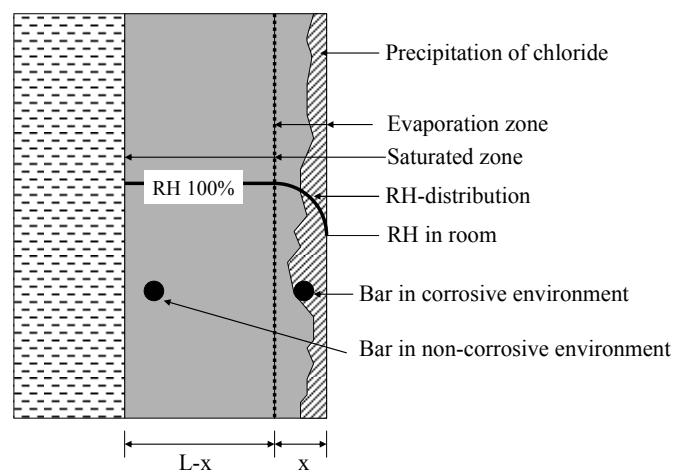


Figure 8: Cross-section of a wall with corrosive and non-corrosive zones.

Life time based on the threshold of free chloride

Evaporation of water transported through the concrete will occur within a zone with thickness $L-x$ from the downstream surface. L and x are defined in Figure 2. On depth $L-x$ from the downstream surface the saturated flow 1 equals the non-saturated flow 2. Often the reinforcement bars are located within the evaporation zone.

Evaporation causes salt to be gradually precipitated increasing the chloride concentration in the evaporation zone.

The amount of pore water in the evaporation zone able to dissolve chloride is supposed to correspond to all pore water (capillary water+gel water). This amount of water is:

$$W_{evaporation\ zone} = C \cdot (w/c - 0.19 \cdot \alpha) \cdot (L - x) \quad (\text{litres/m}^2) \quad (24)$$

Note: It is possible that only capillary water can dissolve chloride. In that case the amount of water becomes:

$$W_{evaporation\ zone} = C \cdot (w/c - 0.39 \cdot \alpha) \cdot (L - x) \quad (\text{litres/m}^2) \quad (24')$$

Assuming salt dissolved in pore water being equally distributed within the evaporation zone the concentration of chloride in pore water in this zone becomes:

$$[Cl]_{free} \downarrow_N = \frac{Q_{Cl,N}^{with\ binding}}{35.5 \cdot W_{evaporation\ zone}} \quad (\text{mole/litre}) \quad (25)$$

Corrosion is initiated when the actual chloride concentration is equal to, or bigger than the threshold concentration. The time until start of corrosion can therefore be found by the following expression:

$$[Cl]_{free} \downarrow_N = [Cl]_{thr} \quad (26)$$

Inserting the equation for $Q_{Cl,N}^{with\ binding}$ -equation (15)- in equation (25) and (26) gives the following expression for the exposure time in years when corrosion starts (the life time):

$$N_{life} = \frac{[Cl]_{thr} \cdot 35.5 \cdot W_{evaporation\ zone} + Q_{Cl,cap} + Q_{Cl,bound}}{q_{1+2} \cdot c_{Cl}} \quad (\text{years}) \quad (27)$$

or

$$N_{life} = \frac{[Cl]_{thr} \cdot 35.5 \cdot W_{evaporation\ zone}}{q_{1+2} \cdot c_{Cl}} + \frac{Q_{Cl,cap}}{q_{1+2} \cdot c_{Cl}} + \frac{Q_{Cl,bound}}{q_{1+2} \cdot c_{Cl}} \quad (\text{years}) \quad (27')$$

Where $Q_{Cl,bound}$ is given by the binding isotherm; Figure 7. According to equation (27), life time depends on the permeability to water (q_{1+2}), the outer chloride concentration (c_{Cl}), and the composition of the concrete (cement content C , alkali content of cement $[Cl]_{thr}$ and water/cement ratio w/c).

The first term on the right in equation (27') gives the evaporation time needed for pore water in the evaporation zone to reach the threshold concentration, the second term gives the time needed to make capillary water saline, and the third term gives the time needed to bind chloride chemically in hydration products and physically to pore walls.

Life time based on the threshold of total chloride

Another possibility is to use a threshold value for the total chloride, $[Cl_{tot}]_{thr}$.

The amount of total chloride brought to the evaporation zone is:

$$Q_{Cl,N,tot} = \frac{Q_{Cl}^{with\ binding}}{L-x} \quad (\text{g/m}^3) \quad (28)$$

The amount of total chloride in the evaporation zone related to the cement weight becomes:

$$[Cl_{tot}]_N = \frac{Q_{Cl}^{with\ binding}}{C \cdot (L-x)} \quad (\text{g/kg cement}) \quad (29a)$$

or

$$[Cl_{tot}]_N = \frac{0.1 \cdot Q_{Cl}^{with\ binding}}{C \cdot (L-x)} \quad (\text{weight-\% of cement}) \quad (29b)$$

Corrosion starts when the total amount of chloride equals the threshold value. Values of this might be obtained from Table 1.

Inserting equations for $Q_{Cl}^{no\ binding}$ -equation (15)- in equation (29b) gives the following relation for the time until corrosion starts:

$$N_{life} = \frac{[Cl_{tot}]_{thr} \cdot C \cdot (L-x) + 0.1 \cdot [Q_{Cl,cap} + Q_{Cl,bound}]}{0.1 \cdot q_{1+2} \cdot c_{Cl}} \quad (30)$$

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APPENDIX 1: APPLICATION OF THE THEORY

STRUCTURE 1. BASEMENT EXPOSED TO MODERATELY HIGH WATER PRESSURE

Outer chloride concentration: Example A: 10 g/litre (Kattegat)

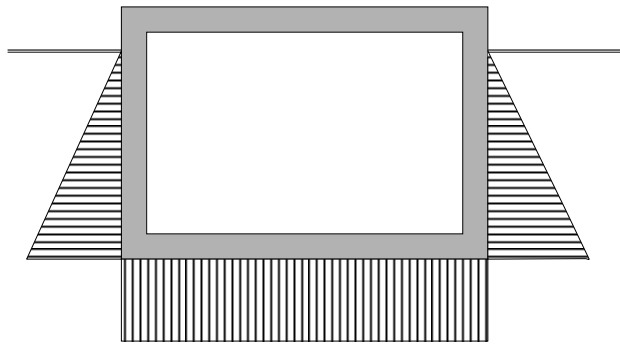
Example B: 19 g/litre (North Sea)

Wall and bottom thickness 40 cm

Maximum 4 m water head (water pressure $0.4 \cdot 10^5$ Pa)

Inner RH: 60%

Concrete cover 4 cm



Concrete

w/c, 0.45

CEM I. $(\text{Na}_2\text{O})_{\text{equiv}}$ 0.6%

Cement content C, 350 kg/m^3

Water permeability, $5 \cdot 10^{-13}$ s

Average degree of hydration: 0.80

EXAMPLE A: MODERATELY HIGH SALT CONCENTRATION; 10 G/LITRE

1. Water flow

Flow 1

$$\text{Eq (1) gives: } q_1 = 5 \cdot 10^{-13} \frac{0.4 \cdot 10^5}{0.4} = 5 \cdot 10^{-8} \text{ kg}/\text{m}^2 \cdot \text{s} \text{ or } 1.58 \text{ kg}/\text{m}^2 \cdot \text{year}$$

Flow 2

The equilibrium flow for the lab specimen is $q_{2,15\text{cm}} = 2.3 \cdot 10^{-8} \text{ kg}/\text{m}^2 \cdot \text{s}$ (Equation (2)).

The distance between 100% RH and 60% RH in the lab specimen is 13 cm; see Figure 4. (Note: the figure is valid for w/c 0.50. The curve is, however, almost the same for w/c 0.45).

$$\text{Eq (3) gives: } q_2 = 2.3 \cdot 10^{-8} \cdot \frac{0.13}{0.40} = 0.75 \cdot 10^{-8} \text{ kg}/\text{m}^2 \cdot \text{s} \text{ or } 0.24 \text{ kg}/\text{m}^2 \cdot \text{year}$$

Combined flow 1 and 2

$$\text{Equation (4) gives: } 5 \cdot 10^{-13} \cdot \frac{0.4 \cdot 10^5}{x} = 2.3 \cdot 10^{-8} \cdot \frac{0.13}{0.40 - x}$$

This gives $x = 0.35 \text{ m} = 35 \text{ cm}$. “The evaporation zone”, where saturated flow 1 stops and goes over to non-saturated flow 2, is located on a distance 5 cm from the downstream surface

$$\text{Equation (5) gives combined flow: } q_{1+2} = 5 \cdot 10^{-13} \cdot \frac{0.4 \cdot 10^5}{0.35} = 5.7 \cdot 10^{-8} \text{ kg}/\text{m}^2 \cdot \text{s}$$

or $1.80 \text{ kg}/\text{m}^2 \cdot \text{year}$

2. Chloride flow without binding

Eq (6) gives the total salt transport during N years: $Q_{Cl,N} = 1.80 \cdot N \cdot 10 = 18 \cdot N \text{ g/m}^2$

Eq (7): $P_{cap} = 350 \cdot (0.45 - 0.39 \cdot 0.8) = 48 \text{ litres/m}^3$

Eq (8): $w_{cap} = 48 \cdot 0.4 = 19.2 \text{ litre/m}^2$

Eq (9): $Q_{Cl, cap} = 19.2 \cdot 10 = 192 \text{ g/m}^2$

Eq (10): $N_0^{no \text{ binding}} = \frac{192}{18} = 11 \text{ years}$

(it takes 11 years for any chloride to reach the downstream surface)

Chloride flow, Eq (11): $Q_{Cl}^{no \text{ binding}} = 18 \cdot N - 192 \text{ g/m}^2$

3. Chloride flow with binding

Eq (14): $c_{Cl, free} = \frac{10}{35.5} = 0.28 \text{ mole/litre}$

Eq (13): $Q_{gel} = 0.4 \cdot 1.25 \cdot 0.8 \cdot 350 \cdot 10^3 = 1.4 \cdot 10^5 \text{ g/m}^2$

Fig 7: Bound chloride, $8 \cdot 10^{-3} \text{ g/g gel}$

$Q_{Cl, bound} = 8 \cdot 10^{-3} \cdot 1.4 \cdot 10^5 = 1120 \text{ g/m}^2$

Time not leading to salt accumulation, Eq (16): $N_0^{with \text{ binding}} = \frac{192 + 1120}{1.8 \cdot 10} = 73 \text{ years}$

Chloride flow, Eq (15): $Q_{Cl}^{with \text{ binding}} = 18 \cdot N - 192 - 1120 = 18 \cdot N - 1312 \text{ g/m}^2$

4. Life time before corrosion, based on threshold of free chloride

The evaporation zone is 5 cm wide. The reinforcement is located in the evaporation zone. Therefore, corrosion can take place.

The threshold concentration, Eq (22): $[Cl]_{thr} = \frac{0.19 \cdot 0.6}{0.45 - 0.19 \cdot 0.8} = 0.38 \text{ mole/liter}$

Amount of pore water, Eq (24): $W_{evaporation \text{ zone}} = 350 \cdot (0.45 - 0.19 \cdot 0.8) \cdot (0.40 - 0.35) = 5.2 \text{ litres/m}^2$

Life time before corrosion, Eq (27):

$N_{life} = \frac{0.38 \cdot 35.5 \cdot 5.2 + 1312}{1.8 \cdot 10} = 77 \text{ years}$

This means that accumulation has only occurred during $77 - 73 = 4$ years. The other 73 years were needed to bind chloride in water and reaction products.

Note: If only capillary water is assumed to dissolve chloride -equation (24')- the amount of water is: $W_{evaporation \text{ zone}} = 350 \cdot (0.45 - 0.39 \cdot 0.8) \cdot (0.40 - 0.35) = 2.4 \text{ litres/m}^2$.

$$\text{Life time becomes: } N_{life} = \frac{0.38 \cdot 35.5 \cdot 2.4 + 1312}{1.8 \cdot 10} = 75 \text{ years}$$

5. Life time before corrosion, based on total chloride

Table 2. The threshold chloride content is 0.8 weight-% of cement weight (marine environment).

Life time before corrosion, Eq (30):

$$N_{life} = \frac{0.8 \cdot 350 \cdot (0.40 - 0.35) + 0.1 \cdot 1312}{0.1 \cdot 1.8 \cdot 10} = 81 \text{ years}$$

EXAMPLE B: HIGH SALT CONCENTRATION; 19 G/LITRE

1. Water flow

Unchanged, 1.8 kg/m²·year

Thickness of evaporation zone unchanged: 5 cm

2. Chloride flow without binding

Eq (6), total salt transport during N years: $Q_{Cl,N} = 1.80 \cdot N \cdot 19 = 34.2 \cdot N \text{ g/m}^2$

Eq (8): w_{cap} , unchanged, 19.2 litres/m²

Eq (9): $Q_{Cl,cap} = 19.2 \cdot 19 = 365 \text{ g/m}^2$

Chloride flow, Eq (12): $Q_{Cl}^{no \text{ binding}} = 34.2 \cdot N - 365 \text{ g/m}^2$

3. Chloride flow with binding

Eq (14): $c_{Cl,free} = \frac{19}{35.5} = 0.54 \text{ mole/litre}$

Eq (13): Q_{gel} , unchanged, $1.4 \cdot 10^5 \text{ g/m}^2$

Fig 7: Bound chloride, Figure 7, $10.5 \cdot 10^{-3} \text{ g/g gel}$

$$Q_{Cl,bound} = 10.5 \cdot 10^{-3} \cdot 1.4 \cdot 10^5 = 1470 \text{ g/m}^2$$

The time not leading to salt accumulation, Eq (16): $N_0^{with \text{ binding}} = \frac{365 + 1470}{1.8 \cdot 19} = 54 \text{ years}$

(the “incubation time” is reduced from 88 years to 54 years depending on the higher chloride concentration)

Chloride flow, Eq (15): $Q_{Cl}^{with \text{ binding}} = 34.2 \cdot N - 365 - 1470 = 34.2 \cdot N - 1835 \text{ g/m}^2$

4. Life time before corrosion, based on threshold of free chloride

The evaporation zone is 5 cm wide. The reinforcement is located in the evaporation zone. Therefore, corrosion can take place.

The threshold concentration, Eq (22), unchanged, $[Cl]_{thr} = 0.38 \text{ mole/liter}$

Amount of pore water, Eq (24), unchanged, $W_{\text{evaporation zone}} = 5.2 \text{ litres/m}^2$

Life time before corrosion, Eq (27):

$$N_{\text{life}} = \frac{0.38 \cdot 35.5 \cdot 5.2 + 1835}{1.8 \cdot 19} = \mathbf{56 \text{ years}}$$

5. Life time before corrosion, based on total chloride

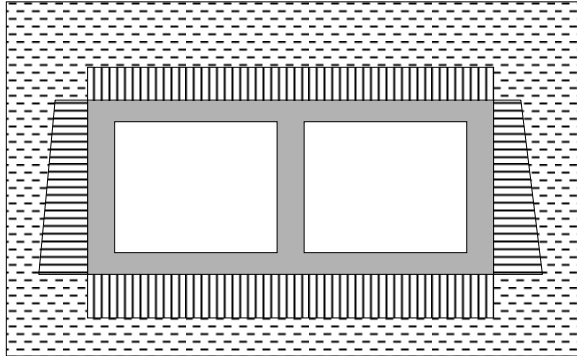
Table 2: The threshold chloride content is 0.8 weight-% of cement weight (marine environment).

Life time before corrosion, Eq (30):

$$N_{\text{life}} = \frac{0.8 \cdot 350 \cdot (0.40 - 0.35) + 0.1 \cdot 1835}{0.1 \cdot 1.8 \cdot 19} = \mathbf{58 \text{ years}}$$

STRUCTURE 2. SUBMERGED TUNNEL EXPOSED TO HIGH WATER PRESSURE

Outer chloride concentration: Example C, E, F: 10 g/litre (Kattegat)
 Example D: 19 g/litre (the North Sea)
 Wall and bottom thickness 1 m
 30 m water head (water pressure $3 \cdot 10^5$ Pa)
 Inner RH: 60%
 Concrete cover 5 cm



Concrete

w/c, 0.40

CEM I. $(\text{Na}_2\text{O})_{\text{equiv}}$ 0.6%

Cement content C, 380 kg/m³

Water permeability, Example C and D: 10^{-13} s

Example E and F: 10^{-12} s

Average degree of hydration: 0.75

Chloride binding:

Binding capacity as Fig 7: Example C, D, E

Chloride binding 50% higher: Example F

EXAMPLE C: MODERATELY HIGH SALT CONCENTRATION; 10 G/LITRE. LOW PERMEABILITY; 10^{-13} S

1. Water flow

Flow 1

$$\text{Eq (1) gives: } q_1 = 10^{-13} \cdot \frac{3 \cdot 10^5}{1} = 3 \cdot 10^{-8} \text{ kg/m}^2 \cdot \text{s} \text{ or } 0.95 \text{ kg/m}^2 \cdot \text{year}$$

Flow 2

The equilibrium flow for the lab specimen is $q_{2,15\text{cm}} = 1.68 \cdot 10^{-8} \text{ kg/m}^2 \cdot \text{s}$ (Figure 5).

The distance between 100% RH and 60% RH in the lab specimen is 13 cm.

$$\text{Eq (3) gives: } q_2 = 1.68 \cdot 10^{-8} \cdot \frac{0.13}{1} = 2.2 \cdot 10^{-9} \text{ kg/m}^2 \cdot \text{s} \text{ or } 0.07 \text{ kg/m}^2 \cdot \text{year}$$

Combined flow 1 and 2

$$\text{Equation (4) gives: } 10^{-13} \cdot \frac{3 \cdot 10^5}{x} = 1.68 \cdot 10^{-8} \cdot \frac{0.13}{1-x}$$

This gives $x=0.93$. “The evaporation zone”, where saturated flow 1 stops and goes over to non-saturated flow 2, is located on a distance 7 cm from the downstream surface

$$\text{Equation (5) gives combined flow: } q_{1+2} = 10^{-13} \cdot \frac{3 \cdot 10^5}{0.93} = 3.3 \cdot 10^{-8} \text{ kg/m}^2 \cdot \text{s}$$

or 1.04 kg/m²·year

2. Chloride flow without binding

Eq (6) gives the total salt transport during N years: $Q_{Cl,N} = 1.04 \cdot N \cdot 10 = 10.4 \cdot N \text{ g/m}^2$

Eq (7): $P_{cap} = 380 \cdot (0.40 - 0.39 \cdot 0.75) = 41 \text{ litres/m}^3$

Eq (8): $w_{cap} = 41 \cdot 1 = 41 \text{ litres/m}^2$

Eq (9): $Q_{Cl, cap} = 41 \cdot 10 = 410 \text{ g/m}^2$

Eq (10): $N_0^{no \text{ binding}} = \frac{410}{10.4} = 39 \text{ years}$

Chloride flow, Eq (12): $Q_{Cl}^{no \text{ binding}} = 10.4 \cdot N - 410 \text{ g/m}^2$

3. Chloride flow with binding

Eq (14): $c_{Cl, free} = \frac{10}{35.5} = 0.28 \text{ mole/litre}$

Eq (13): $Q_{gel} = 1 \cdot 1.25 \cdot 0.75 \cdot 380 \cdot 10^3 = 3.56 \cdot 10^5 \text{ g/m}^2$

Fig 7: Bound chloride, $8 \cdot 10^{-3} \text{ g/g gel}$

$Q_{Cl, bound} = 8 \cdot 10^{-3} \cdot 3.56 \cdot 10^5 = 2848 \text{ g/m}^2$

Time not leading to salt accumulation, Eq (16): $N_0^{with \text{ binding}} = \frac{410 + 2848}{1.04 \cdot 10} = 313 \text{ years}$

Chloride flow, Eq (15): $Q_{Cl}^{with \text{ binding}} = 10.4 \cdot N - 410 - 2848 = 10.4 \cdot N - 3258 \text{ g/m}^2$

4. Life time before corrosion, based on threshold of free chloride

The evaporation zone is about 7 cm wide. The reinforcement is located inside the evaporation zone and can therefore corrode rapidly.

The threshold concentration, Eq (22): $[Cl]_{thr} = \frac{0.19 \cdot 0.6}{0.40 - 0.19 \cdot 0.75} = 0.44 \text{ mole/litre}$

Amount of pore water, Eq (24): $W_{evaporation \text{ zone}} = 380 \cdot (0.40 - 0.19 \cdot 0.75) \cdot (1.00 - 0.93) = 6.8 \text{ litres/m}^2$

Life time before corrosion, Eq (27): $N_{life} = \frac{0.38 \cdot 35.5 \cdot 6.8 + 3258}{1.04 \cdot 10} = 322 \text{ years}$

EXAMPLE D: HIGH SALT CONCENTRATION; 19 G/LITRE. LOW PERMEABILITY; 10^{-13} S

1. Water flow

Flow 1

Unchanged $q = 3 \cdot 10^{-8} \text{ kg/m}^2 \cdot \text{s}$ or $0.95 \text{ kg/m}^2 \cdot \text{year}$

Flow 2

Unchanged, $q_1 = 2.2 \cdot 10^{-9} \text{ kg/m}^2 \cdot \text{s}$ or $0.07 \text{ kg/m}^2 \cdot \text{year}$

Combined flow 1 and 2

Unchanged: $q_{1+2} = 3.3 \cdot 10^{-8}$ kg/m²·s or 1.04 kg/m²·year

Thickness of evaporation zone unchanged, 7 cm

2. Chloride flow without binding

Eq (6) gives the total salt transport during N years: $Q_{Cl,N} = 1.04 \cdot N \cdot 19 = 19.8 \cdot N$ g/m²

Eq (7): $P_{cap} = 41$ litres/m³

Eq (8): $w_{cap} = 41$ litres/m²

Eq (9): $Q_{Cl, cap} = 41 \cdot 19 = 779$ g/m²

Eq (10): $N_0^{no\ binding} = \frac{779}{19.8} = 39$ years

Chloride flow, Eq (12): $Q_{Cl}^{no\ binding} = 19.8 \cdot N - 779$ g/m²

3. Chloride flow with binding

Eq (14): $c_{Cl, free} = \frac{19}{35.5} = 0.54$ mole/litre

Eq (13): $Q_{gel} = 1 \cdot 1.25 \cdot 0.75 \cdot 380 \cdot 10^3 = 3.56 \cdot 10^5$ g/m²

Fig 7: Bound chloride, $10.5 \cdot 10^{-3}$ g/g gel

$Q_{Cl, bound} = 10.5 \cdot 10^{-3} \cdot 3.56 \cdot 10^5 = 3738$ g/m²

Time not leading to salt accumulation, Eq (16): $N_0^{with\ binding} = \frac{779 + 3738}{1.04 \cdot 19} = 229$ years

Chloride flow, Eq (15): $Q_{Cl}^{with\ binding} = 19.8 \cdot N - 779 - 3738 = 19.8 \cdot N - 4517$ g/m²

4. Life time before corrosion, based on threshold of free chloride

The evaporation zone is about 9 cm wide. The reinforcement is located inside the evaporation zone.

The threshold concentration, Eq (22): $[Cl]_{thr} = \frac{0.19 \cdot 0.6}{0.40 - 0.19 \cdot 0.75} = 0.44$ mole/liter

Amount of pore water, Eq (24): $W_{evaporation\ zone} = 380 \cdot (0.40 - 0.19 \cdot 0.75) \cdot (1.00 - 0.93) = 6.8$ litres/m²

Life time before corrosion, Eq (27):

$N_{life} = \frac{0.38 \cdot 35.5 \cdot 6.8 + 4517}{1.04 \cdot 19} = 233$ years

**EXAMPLE E: MODERATELY HIGH SALT CONCENTRATION; 10 G/LITRE.
HIGH PERMEABILITY; 10^{-12} S**

1. Water flow

Flow 1

Eq (1) gives: $q_1 = 10^{-12} \frac{3 \cdot 10^5}{1} = 3 \cdot 10^{-7} \text{ kg/m}^2 \cdot \text{s}$ or $9.46 \text{ kg/m}^2 \cdot \text{year}$

Flow 2

Unchanged, $q_1 = 2.2 \cdot 10^{-9} \text{ kg/m}^2 \cdot \text{s}$ or $0.07 \text{ kg/m}^2 \cdot \text{year}$

Combined flow 1 and 2

Equation (4) gives: $10^{-12} \cdot \frac{3 \cdot 10^5}{x} = 1.68 \cdot 10^{-8} \cdot \frac{0.13}{1-x}$

This gives $x=0.99$ $m=99$ cm. “The evaporation zone”, where saturated flow 1 stops and goes over to non-saturated flow 2, is located on a distance 1 cm from the downstream surface

Equation (5) gives combined flow: $q_{1+2} = 10^{-12} \cdot \frac{3 \cdot 10^5}{0.99} = 3 \cdot 10^{-7} \text{ kg/m}^2 \cdot \text{s}$
or $9.46 \text{ kg/m}^2 \cdot \text{year}$

2. Chloride flow without binding

Eq (6) gives the total salt transport during N years: $Q_{Cl,N} = 9.46 \cdot N \cdot 10 = 94.6 \cdot N \text{ g/m}^2$

Eq (7): $P_{cap} = 41 \text{ litres/m}^3$

Eq (8): $w_{cap} = 41 \text{ litres/m}^2$

Eq (9): $Q_{Cl,cap} = 41 \cdot 10 = 410 \text{ g/m}^2$

Eq (10): $N_0^{no \text{ binding}} = \frac{410}{94.6} = 4 \text{ years}$

Chloride flow, Eq (12): $Q_{Cl}^{no \text{ binding}} = 94.6 \cdot N - 410 \text{ g/m}^2$

3. Chloride flow with binding

Eq (14): $c_{Cl,free} = \frac{10}{35.5} = 0.28 \text{ mole/litre}$

Eq (13): $Q_{gel} = 3.56 \cdot 10^5 \text{ g/m}^2$

Fig 7: Bound chloride, $8 \cdot 10^{-3} \text{ g/g gel}$

$Q_{Cl,bound} = 8 \cdot 10^{-3} \cdot 3.56 \cdot 10^5 = 2848 \text{ g/m}^2$

Time not leading to salt accumulation, Eq (16): $N_0^{with \text{ binding}} = \frac{410 + 2848}{9.46 \cdot 10} = 34 \text{ years}$

Chloride flow, Eq (15): $Q_{Cl}^{with \text{ binding}} = 94.6 \cdot N - 410 - 2848 = 94.6 \cdot N - 3258 \text{ g/m}^2$

4. Life time before corrosion, based on threshold of free chloride

The evaporation zone is 1 cm wide. The reinforcement is located outside the evaporation zone. However, due to the high salt transport, and for safety reasons, it is assumed that corrosion can take place.

The threshold concentration, Eq (22): $[Cl]_{thr} = \frac{0.19 \cdot 0.6}{0.45 - 0.19 \cdot 0.8} = 0.38$ mole/liter

Amount of pore water, Eq (24): $W_{evaporation\ zone} = 380 \cdot (0.40 - 0.19 \cdot 0.75) \cdot (1 - 0.99) = 1$ litre/m²

Life time before corrosion, Eq (27):

$$N_{life} = \frac{0.38 \cdot 35.5 \cdot 1 + 3258}{9.46 \cdot 10} = 35 \text{ years}$$

This means that accumulation has only occurred during about 1 year.

EXAMPLE F: MODERATELY HIGH SALT CONCENTRATION; 10 G/LITRE. HIGH PERMEABILITY; 10^{-12} S. 50% HIGER CHLORIDE BINDING CAPACITY

1. Water flow

Flow 1

As example E: 9.46 kg/m²·year

Combined flow 1 and 2

As example E: 9.46 kg/m²·year

Thickness of evaporation zone as example E: 1 cm

2. Chloride flow without binding (same as example E)

Total salt transport during N years: $Q_{Cl,N} = 9.46 \cdot N \cdot 10 = 94.6 \cdot N$ g/m²

$$P_{cap} = 41 \text{ litres/m}^3$$

$$w_{cap} = 41 \text{ litres/m}^2$$

$$Q_{Cl,cap} = 41 \cdot 10 = 410 \text{ g/m}^2$$

$$N_0^{no\ binding} = \frac{410}{94.6} = 4 \text{ years}$$

Chloride flow during N years: $Q_{Cl}^{no\ binding} = 94.6 \cdot N - 410$ g/m²

3. Chloride flow with binding

$$\text{Eq (14): } c_{Cl,free} = \frac{10}{35.5} = 0.28 \text{ mole/litre}$$

$$\text{Eq (13): } Q_{gel} = 3.56 \cdot 10^5 \text{ g/m}^2$$

Fig 7: Bound chloride, $1.5 \cdot 8 \cdot 10^{-3} = 1.2 \cdot 10^{-2}$ g/g gel (50% higher than example E)

$$Q_{Cl, bound} = 10 \cdot 1.2 \cdot 10^{-2} \cdot 3.56 \cdot 10^5 = 4272 \text{ g/m}^2$$

$$\text{Time not leading to salt accumulation, Eq (16): } N_0^{with binding} = \frac{410 + 4272}{9.46 \cdot 10} = 49 \text{ years}$$

$$\text{Chloride flow, Eq (15): } Q_{Cl}^{with binding} = 94.6 \cdot N - 410 - 4272 = 94.6 \cdot N - 4682 \text{ g/m}^2$$

4. Life time before corrosion, based on threshold of free chloride

The evaporation zone is 1 cm wide. Reinforcement is located outside the evaporation zone, but corrosion is supposed to be possible.

$$\text{The threshold concentration, Eq (22): } [Cl]_{thr} = \frac{0.19 \cdot 0.6}{0.45 - 0.19 \cdot 0.8} = 0.38 \text{ mole/liter}$$

$$\text{Amount of pore water, Eq (24): } W_{evaporation zone} = 380 \cdot (0.40 - 0.19 \cdot 0.75) \cdot (1 - 0.99) = 1 \text{ litre/m}^2$$

Life time before corrosion, Eq (27):

$$N_{life} = \frac{0.38 \cdot 35.5 \cdot 1 + 4682}{9.46 \cdot 10} = \mathbf{50 \text{ years}}$$

Thus, increased chloride binding by 50% increases life time by 43%.

COMMENTS TO THE EXAMPLES

1. The difference between the two ways of defining the threshold concentration (free or total) is small (see examples A and B).

Threshold value based on free chloride is based entirely on properties of the concrete. The service life predicted therefore obtains one single, theoretically calculated value.

On the other hand, different selected values of the threshold concentration of total chloride will predict different calculated service life, which is shown by the following example.

From example A: Selection of 1.5 weight-% instead of 0.8% gives 87 years service life instead of 81 years.

From example B: Selection of 1.5 weight-% instead of 0.8% gives 61 years service life instead of 56 years.

2. The small difference between the ways of defining threshold concentration demonstrated by examples A and B depends on the fact that, for dense concrete, *service life is almost entirely dependent on the time it takes for chloride to reach the evaporation zone*; i.e. time it takes to make capillary water saline and to bind chloride to concrete. Once chloride is able to accumulate in the evaporation zone, only a few more years (2 to 5) are necessary for corrosion to start.

3. For constant permeability the ability of concrete to bind chloride is the most important factor for service life. According to Example D with a total service life of 232 years, 189 years depend on chloride binding, 39 years depend on making capillary water saline, and 4 years depend on the threshold concentration. Comparison of example E with example F shows that 50% increased chloride binding increases life time by 43%.

Different types of cement have different chloride binding ability. Curves of type Figure 7 should therefore be determined for different cement types.

4. The permeability is of very big importance, which is seen by comparing examples C and E. Increasing permeability from 10^{-13} s to 10^{-12} s decreases the service life from 320 years to 35 years. Therefore, the maximum allowable permeability of concrete should be specified in specifications of concrete for structures that will be exposed to sea water pressure.
5. The thickness of the structure has big importance, since increased thickness reduces the water flow and increases the amount of chloride that has to be bound before chloride can reach the downstream surface.

APPENDIX 2: CHLORIDE CONCENTRATION IN SEA WATER

The normal concentration of Cl in seawater is 55% of the total salinity. The salinity depends on the location of the structure. The following concentrations are valid for sea water around the Scandinavian coast.

Location	Salinity ‰ or g/litre	Content of chloride ions	
		‰ (g/litre)	mole/litre
North Gulf of Bothnia	2.5-4.5	1.4-2.5	0.04-0.07
South Gulf of Bothnia	4.5-6.0	2.5-3.3	0.07-0.09
Åland Sea	6.0	3.3	0.09
The Gulf of Finland	3.0-5.5	1.7-3.0	0.05-0.08
North Baltic Sea	6.0-7.0	3.3-3.9	0.09-0.11
Central Baltic Sea	7.0-7.5	3.9-4.1	0.11-0.12
South Baltic Sea	7.0-8.0	3.9-4.4	0.11-0.13
Strait of Öresund	10-15	5.5-8.3	0.15-0.23
Danish Belt Sea	10-17	5.5-9.4	0.15-0.26
South Kattegat	13-18	7.2-10	0.20-0.28
North Kattegat	18-24	10-13	0.28-0.37
Skagerak. Swedish west coast	20-26	11-14	0.31-0.39
Norwegian south coast	24-31	13-17	0.37-0.48
Norwegian west and north coast	31-35	17-19	0.48-0.53
Danish west coast	26-32	14-18	0.39-0.51

APPENDIX 3: WATER PERMEABILITY OF CONCRETE

In the analysis above the permeability coefficient is based on equation (A1) according to which pressure is expressed in Pascal, and flow in kg.

$$q(\text{kg} / \text{m}^2 \cdot \text{s}) = B(\text{s}) \cdot \frac{\Delta P(\text{Pa})}{L(\text{m})} \quad (\text{A1})$$

Often pressure is expressed as m water head and flow as m^3 .

$$w(\text{m}^3 / \text{m}^2 \cdot \text{s}) = K(\text{m} / \text{s}) \cdot \frac{\Delta P(\text{m water head})}{L(\text{m})} \quad (\text{A2})$$

The relation between the two definitions of coefficient of permeability is.

$$B=1 (\text{s}) \text{ corresponds to } K=10 (\text{m/s}) \quad (\text{A3})$$

Permeability data from literature are listed in Table A1. In most cases the data are valid for Portland cement.

Table A1: Permeability coefficient from different literature references.

Reference	Material	w/c-ratio	Permeability; B(s)
Powers et al (1954/55)	Cement paste	0,5	$6 \cdot 10^{-15}$
		0,6	$25 \cdot 10^{-15}$
		0,7	$110 \cdot 10^{-15}$
Hearn (1992) Literature review	Concrete	0,4	$2 \cdot 10^{-15}$ à $5 \cdot 10^{-12}$
		0,45	$1 \cdot 10^{-14}$ à $5 \cdot 10^{-12}$
		0,5	$5 \cdot 10^{-14}$ à $5 \cdot 10^{-11}$
		0,6	$1 \cdot 10^{-13}$ à $5 \cdot 10^{-11}$
Bamforth (1991)	Concrete	0,46	$5 \cdot 10^{-12}$
		0,43	$1 \cdot 10^{-12}$
		0,46+40%FA	$3 \cdot 10^{-12}$
Nyame&Illston (1980)	Concrete	0,47, 28 dygn	$1 \cdot 10^{-14}$
		0,47, 7 dygn	$5 \cdot 10^{-13}$
Young (1988)	Cement paste	0,5	$5 \cdot 10^{-15}$
		0,6	$4 \cdot 10^{-14}$
	Concrete	0,5	$5 \cdot 10^{-13}$
		0,6	$1 \cdot 10^{-12}$
Reinhardt&Jooss (1998)	Concrete	0,45	$7 \cdot 10^{-14}$ after 1 hour test $4,5 \cdot 10^{-15}$ after 24 hour test
Lawrence (1982)	Concrete	0,7	$0,8 \cdot 10^{-14}$ à $2,9 \cdot 10^{-14}$
Ruettgers, Vidal, Wing (1935)	Concrete 38 mm stone	0,45	$2 \cdot 10^{-13}$ (extrapolated value)
		0,5	$7 \cdot 10^{-13}$
		0,6	$5 \cdot 10^{-12}$
	Concrete 75 mm stone	0,5	$1 \cdot 10^{-12}$
		0,6	$9 \cdot 10^{-12}$
	Cement mortar 4 mm sand	0,45	$3 \cdot 10^{-14}$ (extrapolated value)
		0,5	$1 \cdot 10^{-13}$
0,6		$6 \cdot 10^{-13}$	

Comments

In most cases, start of measurements seems to have been made only a few days or weeks after application of the pressure. Furthermore, the measurement time has often been fairly short. In many cases measurements have probably been made before equilibrium has been reached; i.e. before the flow out from the specimen has been the same as the flow into this. Measurements by Ruettgers et al. are the only where measurements were made both of outflow rate and inflow rate, and the permeability coefficient was not determined until the two flows were equal. It took often more than 400 hours to obtain steady state flow.

A probable degree of hydration of concrete during the measurements probably was of the order 70 to 80%. Since the expected service life of structures often is 100 years or more the degree of hydration during the major part of the real exposure time ought to be higher; maybe of the order 85 to 90%. This means that permeability gradually diminishes during exposure. Measurements by Powers et al (1954/55) on cement paste show a considerable dependency of the capillary porosity on permeability. The measurements are shown in Figure A1. The figure shows that the influence of capillary porosity can be expressed by:

$$P_{cap} = 2.43 \cdot 10^{-11} \cdot P_{cap}^{5.9} \text{ s} \quad (\text{A4})$$

where P_{cap} is defined:

$$P_{cap} = \frac{w/c - 0.34 \cdot \alpha}{w/c + 0.32} \quad (\text{A5})$$

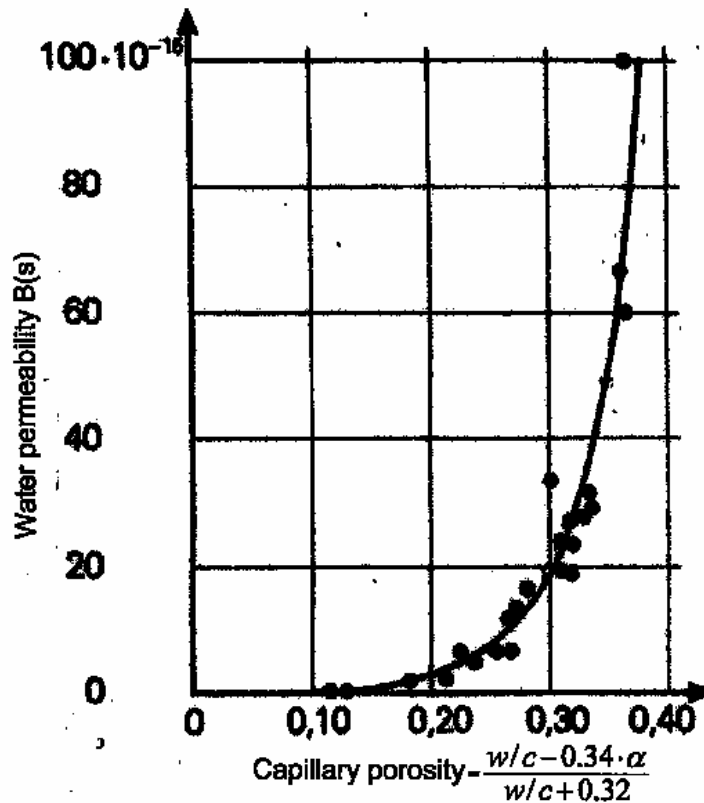


Figure A1: Permeability of cement paste as function of capillary porosity; Powers et al. (1954/55).

Example 1: Effect of w/c-ratio. Constant concrete age

w/c=0.40: Degree of hydration 0.75. $P_{cap}=0.20$. $B=1.8 \cdot 10^{-15}$ s
 w/c=0.45: Degree of hydration 0.80. $P_{cap}=0.23$. $B=4.2 \cdot 10^{-15}$ s
 w/c=0.50: Degree of hydration 0.85. $P_{cap}=0.26$. $B=8.6 \cdot 10^{-15}$ s

Example 2: Effect of concrete age. w/c=0.45

$\alpha=0,70$: $P_{cap}=0,31$ $B=24,2 \cdot 10^{-15}$ s
 $\alpha=0,75$: $P_{cap}=0,25$ $B= 6,8 \cdot 10^{-15}$ s
 $\alpha=0,80$: $P_{cap}=0,23$ $B= 4,2 \cdot 10^{-15}$ s
 $\alpha=0,85$: $P_{cap}=0,21$ $B= 2,4 \cdot 10^{-15}$ s
 $\alpha=0,90$: $P_{cap}=0,19$ $B= 1,3 \cdot 10^{-15}$ s

Permeability data presented in Table A1 are valid for water of room temperature. Sea water is normally colder. Permeability is directly proportional to the viscosity of water. It increases by 50% when temperature is lowered from +20°C to +5°C, and by 30% when it is lowered to +10°C.

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