13 Expectation values for typical chloride environments

Expectation values for some typical chloride environments can be extracted from the data presented in Chater 10, 11 and 12. The aim of this Chapter is to provide the reader with some easy to handle expectation values for analysis based on the experiences presented earlier.

This Chapter compiles the data of Chapters 10, 11 and 12 into easy-to-handle expectation values to be used for service life analysis in several different environments.

The findings of this Chapter are "objective" with respect to the basic data. Future developments of scientifically models (like those presented in Chapter 4 and 7) and more data from already established test series from natural exposure (like the Swedish marine exposure station in Träslövsläge and the Swedish exposure station at the highway between Gothenburg and Borås) will ensure a basis for revising the findings to more "correct" ones within a couple of years or so. This is expressed mainly to the long time development. The findings may also be regarded as hypotheses that may be withdrawn or changed due to the constant gain of knowledge in this field.

13.1 Estimation of the future development of chloride profiles

In Chapters 11 and 12 the collected data showed that some time-dependence of the chloride ingress must be expected. At the moment no one can tell the depth of the chloride ingress (or rather the chloride profile) after 100 years of exposure of a modern concrete. After one year of exposure in a marine environment one will learn a lot about the concrete's response to the environment. A few more years of natural exposure and systematically collection of data may give enough data to make a prediction of the future development.

The field exposure must be regarded as one of the most direct ways of gaining experiences as discussed in Section 12.1. The use of relatively short term results has the advantage of being easy-to-use now, but the disadvantage of not being proved correct for a prolonged period of time.

13.2 Interpretation of observations from marine exposure

Even if it might be far too early to make any conclusion about the change of the achieved diffusion coefficient D_a and the chloride concentration C_{sa} of the concrete surface versus time it is tried to carry out an interpretation of the observations and the determined parameters from the Träslövsläge marine exposure station presented in Chapter 12. At the moment the major amount of the concrete types is described by chloride profiles achieved at two periods of exposure time and a minor part by three chloride profiles. However, during the spring of 1997 most of the concrete types will be analysed again.

When the parameters are estimated from just two chloride profiles the estimates are extremely sensitive even for small changes and variations of the observations. Especially at the early years of chloride ingress into the concrete small variations are expected e.g. due to skin effects. It is believed that after a period of time where about 4 to 5 chloride profiles have been achieved the effect of such deviations may be of minor importance.

13.2.1 Achieved surface concentration

The values of C_1 given (together with C_{100}) in Table 12.2.2:4 were taken from the data sheets in the Appendix. The disadvantage in the use of these values is the unacceptable disagreement with the C_{sa} values from the chloride profiles. In more than 25% of the data sheets. Therefore the C_1 values have been recalculated and determined by interpolation acc. to (3.2.2:3) so that the needed agreement is achieved.

The C_1 and C_{100} values (recalculated into the unit "% mass binder" in order to compensate for the large deviations in the binder content of the different concretes) are given in Table 13.2.1:1. Those values must be regarded as "the best estimates possible" to make from the present data sets at the moment.

Table 13.2.1:1. The derived parameters C_1 and C_{100} of some of the concretes from the Träslövsläge marine exposure station. Further details are found in Table 12.2.2:1.

ID Number	Marine submerged [% of binder]		Marine splash [% of binder]		Marine atmosphere [% of binder]	
	C_1	C_{100}	C_1	C_{100}	C_1	C_{100}
3-75	3.6	3.9				
1-50	2.4	4.2	2.1	2.0	0.7	5.6
2-50	2.0	10.9				
3-50	2.6	5.4				
Ö	3.0	3.9	1.8	10.6	1.3	3.3
2-40	1.7	6.1	0.6	10.6	0.6	9.8
3-40	2.8	4.2	1.5	10.5	0.9	2.8
H4	3.2	3.8	2.1	2.1	1.1	1.2
10-40	2.5	2.9	1.8	5.7	0.8	10.0
12-35	1.8	3.1	1.2	7.9	0.9	0.9
H3	1.9	2.3	0.6	10.0	0.8	0.8
H1	2.2	6.3	1.5	1.4	0.6	7.6
H2	1.4	9.8	1.0	9.8	1.1	1.1
H8	1.8	1.6	1.2	1.1	0.8	2.6
H5	0.9	9.1	1.0	6.7	0.6	3.2

The tendencies of Table 13.2.1:1 are not clear at all. Therefore, in order to obtain *some* kind of a conclusion from the data, it is tried to carry out a regression analysis of the "empirical model" suggested by the data. In order to do so a rough knowledge of the decisive parameters is needed. A summary of the relevant parameters are given below.

The effect of the w/c ratio

From Frederiksen et al. [1996] it is known that an almost straight line dependence between the *w/c* ratio and the parameter C_{sp} was found experimentally. That was supported by the theory (as used by *ClinConc* presented in Chapter 4) as it was possible to very accurately model the experimentally found C_{sp} values.

In fact a straight line dependency is found when recalculating the values of Frederiksen et al. [1996] into the unit "% mass cement". The result of this is shown in Figure 13.2.1:1.

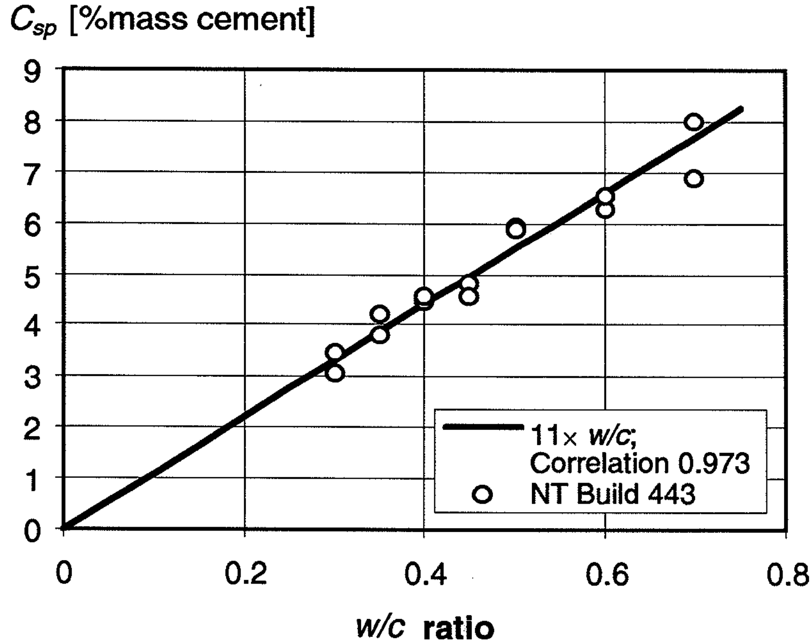


Figure 13.2.1:1. The effect of the w/c ratio on the C_{sp} values according to NT Build 443. Data from Frederiksen et al. [1996]. The very simple dependence of the w/c ratio on the C_{sp} value: $C_{sp} = 11 \times w/c$ is seen to be a good estimate.

The effect of the type of binder

It is known that the type and composition of the binder affects the value of the surface concentration, cf. Nilsson et al. [1996]. There is some correlation between the binding properties of the cement and the achieved surface concentration in a particular environment. The understanding of this phenomena is however still not sufficient to enable precise modelling. *ClinConc* and the convection model presented in Chapter 7 are believed to represent the first steps to understand the role of the binding properties in getting an "achieved surface concentration".

Some types of cement like e.g. blast furnace slag cement normally have a high degree of binding and therefore high "achieved surface concentrations" in chloride profiles. The opposite is the case of SRPCs. Addition of silica fume and/or fly ash tends to increase the binding.

In the Träslövsläge concretes two types of Portland cement were used. Some effect can be found but the overall impression is that other factors dominates and makes the effect less evident. Only few of the concretes presented in Table 12.2.2:1 contains fly ash (10-40, 12-35 and H8), while silica fume is well represented in the test programme.

As a first empirical approach it is suggested to introduce some efficiency factors. The benefits of fly ash (or micro silica) can be expressed as the efficiency factor, b. The efficiency factor related to a property of concrete is defined as the mass of cement that can be replaced by one unit mass of pozzolana while maintaining the property. The equivalent cement content is then calculated as $C + b \times P$. E.g. the more silica fume in the binder the higher the surface concentration (if the effect is found to be positive) and the more fly ash in the binder the higher the surface concentration (if the effect is found to be positive).

The effect of exposure period

The overall impression of the data in the Appendix is that the surface concentration increase with time. This is reflected in the values C_1 and C_{100} in Table 13.2.1:1 because it is often the case that $C_{100} > C_1$. The increase is however different for the different environments. A simple linearity is assumed here as well.

The effect of the environment

The overall impression of the data in the Appendix is that the surface concentration strongly depends on the local environment. To some extend this is reflected in the values C_1 and C_{100} in Table 13.2.1:1 even though the trends are not clear. The C_1 values seem to be relatively higher in the submerged exposure than in the splash and atmosphere zones. Almost consistently the atmosphere zone has lowest surface concentrations.

13.2.2 Suggested models for C_1 and C_{100}

The previous Section provides some qualitative information that is used here to form an expression that can serve as the empirical model for generating expectation values of C_1 and C_{100} for the Träslövsläge data. The proposed types of functions are:

$$C_1 = A \times \text{eqv}\,(w/c)_b \times k_{b,\,env} \;\text{[\% mass binder]} \qquad (13.2.2:1)$$

$$C_{100} = C_1 \times k_{time}\,|_{env} \;\text{[\% mass binder]} \qquad (13.2.2:2)$$

A multiple regression analysis was performed on the data in Table 13.2.1:1. Based on that analysis (13.2.2:1) is changed into (13.2.2:1') as follows:

$$C_1 = 3.667 \times \text{eqv}\,(w/c)_b \times k_{b,\,env} \;\text{[\% mass binder]} \qquad (13.2.2:1')$$

The other constants of (13.2.2:1') and (13.2.2:2) are given in Table 13.2.2:1 and 13.2.2:2.

Table 13.2.2:1. The constants of (13.2.2:1') and (13.2.2:2).

Environment: / Constant:	Marine Submerged	Marine Splash zone	Marine atmosphere
$k_{b,\ env}$	1.4	1	0.6
$k_{time\|env}$	1.5	4.5	7

Table 13.2.2:2. The efficiency factors for binding to be used when calculating the eqv $(w/c)_b$ ratio in 13.2.2:1').

Efficiency factor	Silica fume	Fly ash
b	-1.5	0.75

The quality of the suggested "model" can be visualised graphically by plotting the values of Table 13.2.1:1 versus the values obtained by calculations according to the model. Such a plot is shown in Figure 13.2.2:1.

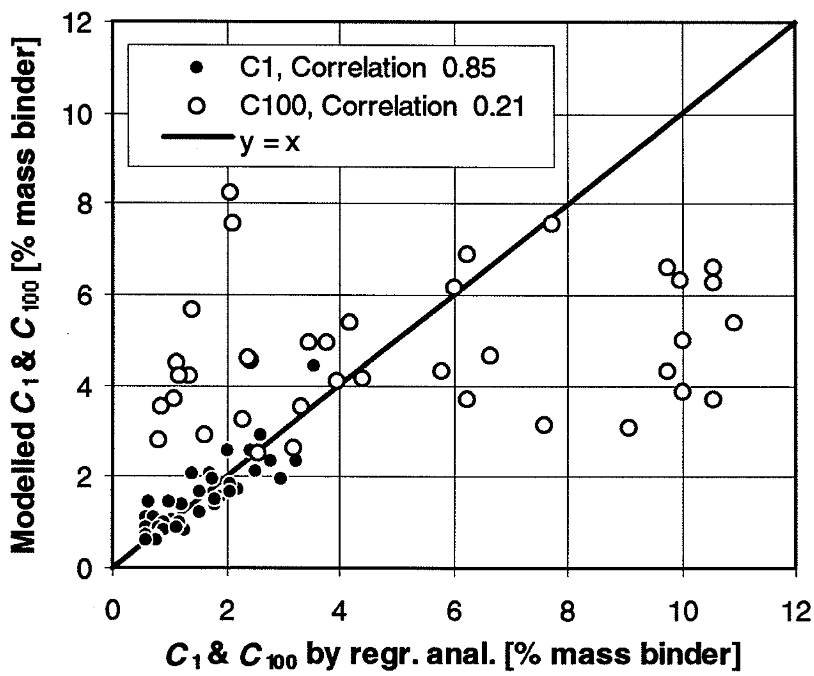


Figure 13.2.2:1. Plot of the values of Table 13.2.1:1 versus the values obtained by calculations according to the empirical models, i.e. (13.2.2:1') and (13.2.2:2). The correlation of each of the data sets are given on the graph. The estimates of C_1 are much more in agreement with the original data (Table 13.2.1:1) than those of C_{100}.

Conclusive remarks

The possibility of suggesting a model for estimating the achieved surface chloride concentrations after 1 year and 100 years of exposure respectively was attempted. The comments to the model are as follows:

- Partial replacement of cement with micro silica results in a somewhat lower binding capacity (the factor is -1.5) compared to no replacement. This is explained as a "porosity effect" as the micro silica is considered to be "filling in" space between cement particles and thus reducing the "available space".

- Partial replacement of cement with fly ash results in a somewhat lower binding capacity (the factor is 0.75) compared to no replacement. This is explained as a "filler effect" as the fly ash in this investigation is considered to be a "rather inert" binder.
- The effect of the *w/b* ratio agrees well with laboratory experiments, cf. Frederiksen et al. [1996]. In fact it seems that a simple relation exist between C_{sp} and C_1 when excluding the environmental factor. The relation is simply $C_1 = C_{sp}/3$!
- The effect of the environmental exposure was as expected.
- The effect of the exposure time was also dependent of the environment as expected.

The proposed "empirical model" can predict both the C_1 and the C_{100} but a rather large deviation must be expected especially on the C_{100} value. This is of course due the fact that the C_{100} "data" values are extrapolated from the chloride profiles after exposure of up to about only 2 years!

13.2.3 Achieved diffusion coefficients

Most chloride profiles from natural exposures can be fitted well by the error-function solution cf. (3.2.1:3). The achieved transport parameters D_a and C_{sa} in (3.2.1:3) are derived from the chloride profiles measured on the specimens in Träslövsläge. The results of each of the chloride profiles are given in the Appendix and in Table 12.2.2:2 the D_a values for each inspection time are given. Nor the tendencies of Table 12.2.2:2 neither Table 12.2.2:3 are clear. In order to reduce and simplify the data sets the D_1 values are calculated by interpolation using the expression (3.2.1:2).

Unfortunately the tendencies are still not clear. Therefore, in order to obtain *some* kind of a conclusion from the data, a regression analysis using an "empirical model" suggested by the data is carried out. In order to do so a rough knowledge of the decisive parameters is needed. A summary of the relevant parameters are given below.

The effect of the type of binder

It is known that the type and composition of the binder affects the value of the diffusion coefficient, cf. Nilsson et al. [1996]. The most convenient way of expressing this effect is to introduce efficiency factors (as defined in Section 13.2.1) of the pozzolans in question. The equivalent cement content is then calculated as $C + k \times P$.

The effect of the equivalent w/c ratio

From Frederiksen et al. [1996] it is known that a clear effect of the *w/c* ratio on the potential diffusion coefficient D_{pex} was found experimentally, cf. (3.2.1:1). A similar effect is expected in the field.

Table 13.2.3:1. Values of D_1 and α based on the original values given in Table 12.2.2:2.

	D_1 determined by interpolation			α used in the interpolation		
ID Number	Subm.	Splash	Atm.	Subm.	Splash	Atm.
3-75	366			0.46		
1-50	249	177	140	0.20	0.71	0.39
2-50	231			-0.26		
3-50	192			0.17		
Ö	105	89	64	0.14	0.13	0.93
2-40	129	16	16	0.36	-1.41	-0.94
3-40	101	43	41	1.02	0.54	1.14
H4	46	26	35	0.75	0.04	0.01
10-40	40	11	24	0.48	0.28	0.04
12-35	49	30	33	0.74	-0.10	0.65
H3	82	30	49	-0.29	-0.43	0.82
H1	30	8	15	0.25	0.32	1.36
H2	13	9	12	-0.06	-0.23	0.43
H8	64	37	21	0.62	0.77	0.12
H5	17	6	18	0.05	0.12	1.48

The effect of exposure time

The overall impression of the data in Table 12.2.2:2 is that the achieved diffusion coefficient decrease with time. This is reflected in the values D_1 and D_{100} in Table 12.2.2:3, because it is often the case that $D_{100} < D_1$. The decrease is however different for the different environments. This effect is counted for in the expression for the parameter α.

The effect of the environment

The overall impression of the data in Table 12.2.2:2 and 12.2.2:3 is that the achieved diffusion coefficient strongly depends on the local environment. This is reflected in the values D_1 and D_{100} in Table 12.2.2:3 even though the trends are not clear at all. The D_1 values seem to be relatively higher in the submerged exposure than in the splash and atmospheric zones.

13.2.4 Suggested models for D_1 and α

The previous Section provides some qualitative information that is used here to form an expression that can serve as the empirical model for generating expectation values of D_1 and α for the Träslövsläge data. The proposed types of functions are:

$$D_1 = A \times \exp\left(-\sqrt{\frac{B}{\text{eqv}\left({}^{w}\!/\!_{c} \right)_D}} \right) \times k_{D,env} \quad [\text{mm}^2/\text{yr}] \qquad (13.2.4:1)$$

$$\alpha = (U \times \text{eqv}\ (w/c)_D + V) \times k_{\alpha,\ env} \qquad (13.2.4:2)$$

A multiple regression analysis was performed on the data in Table 13.2.3:1 simultaneously. Based on that analysis (13.2.4:1) are changed into (13.2.4:1') as follows:

$$D_1 = 25{,}000 \times \exp\left(-\sqrt{\frac{10}{\text{eqv}\left(w/c\right)_D}}\right) \times k_{D,env} \quad [\text{mm}^2/\text{yr}] \qquad (13.2.4:1')$$

and (13.2.4:2) are changed into (13.2.4:2') as follows:

$$\alpha = (1 - 1.5 \times \text{eqv}\ (w/c)_D) \times k_{\alpha,\ env} \qquad (13.2.4:2')$$

The constants of (13.2.4:1') and (13.2.4:2') are given in Table 13.2.4:1 and (13.2.4:2').

Table 13.2.4:1. The constants of (13.2.4:1') and (13.2.4:2').

Environment: / Constant:	Marine Submerged	Marine Splash zone	Marine atmosphere
$k_{D,\ env}$	1	0.6	0.4
$k_{\alpha,\ env}$	0.6	0.1	1

Table 13.2.4:2. The efficiency factors for diffusivity to be used when calculating the eqv $(w/c)_D$ ratio in (13.2.4:1') and (13.2.4:2').

Efficiency factor	Silica fume	Fly ash
k	7	1

The quality of the suggested "models" for D_1 and α can be visualised graphically by plotting the values of Tables 13.2.1:1 and 13.2.1:2 versus the values obtained by calculations according to (13.2.4:1') and (13.2.4:2') respectively. Such plots are shown in Figures 13.2.4:1 and 13.2.4:2.

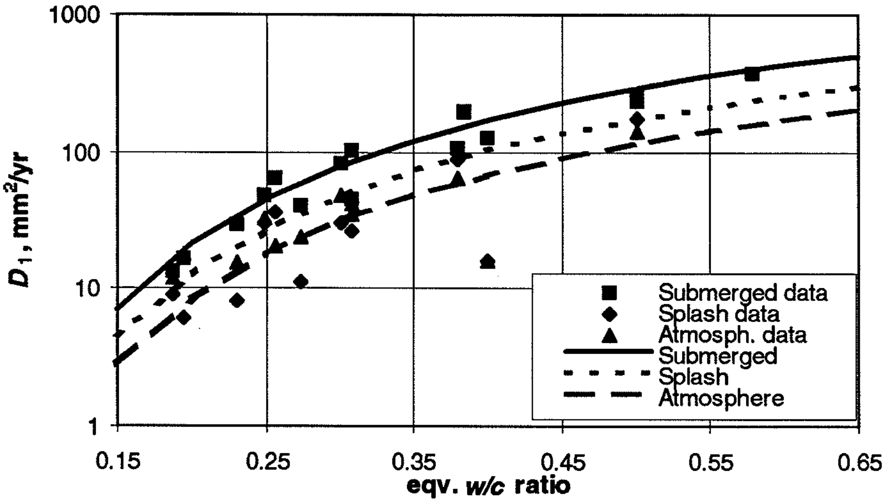


Figure 13.2.4:1. Plot of the interpolated D_1 values of Table 13.2.3:1 together with the model for D_1, i.e. (13.2.4:1') versus the eqv. $(w/c)_D$ ratio. The estimates of D_1 are in fairly good agreement with the values calculated by interpolation between the measured values of D_a.

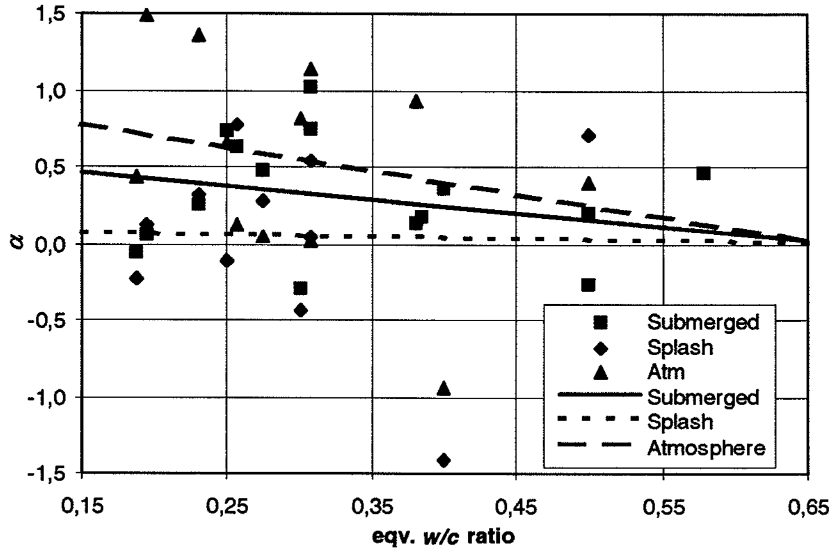


Figure 13.2.4:2. Plot of the α values of Table 13.2.3:2 used in the interpolation to determine the D_1 values of Table 13.2.3:1 and the models for α, i.e. (13.2.4:2') versus the eqv $(w/c)_D$ ratio.

By combining the models (13.2.4:1') and (13.2.4:2') with (3.2.1:2) D_a values for each exposure time corresponding to those of Table 12.2.2:2 can be found. In Figure 13.2.4:3 the correlation between those data sets is shown.

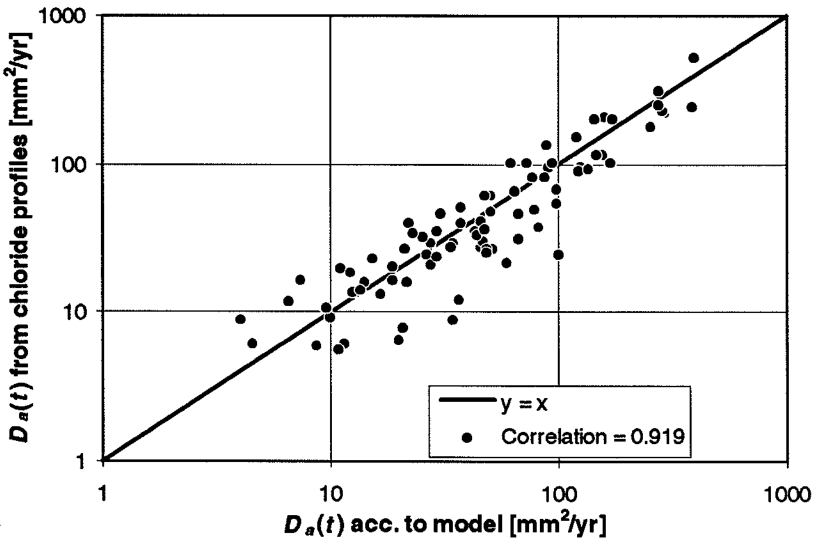


Figure 13.2.4:3. The correlation between the D_a (t) values of Table 12.2.2:2 and the models (13.2.4:1') and (13.2.4:2') combined with (3.2.1:2). The agreement is regarded as satisfactory.

Conclusive remarks

The possibility of suggesting a model for estimating the achieved chloride diffusion coefficient after 1 year and the "decrease parameter" α was attempted. The resulting model agree well with the data, but some parts of the model disagrees with experiences. The comments to the model are as follows:

- Partial replacement of cement with micro silica results in a much lower chloride diffusivity (the efficiency factor is 7) compared to no replacement. This is explained as a "porosity effect" as the micro silica is considered to be "filling in" space between cement particles and thus lowering the porosity and making the diffusion way more "narrow".
- Partial replacement of cement with fly ash results in an unchanged chloride diffusivity (the factor is 1).
- The effect of the eqv *w/c* ratio agrees well with laboratory experiments, cf. Frederiksen et al. [1996]. In fact a simple relation between D_{pex} and D_1 seems to exist when excluding the environmental factor. The relation is simply $D_1 = D_{pex}/2$!
- The effect of the environmental exposure was as expected.
- The effect of the exposure time was also dependent of the environment as expected.

The proposed "empirical model" can be used to predict both the D_1 and the D_{100} but a rather large deviation must be expected especially on the D_{100} value.

13.2.5 Conclusion

Some simple models for estimating essential parameters to be used in the Mejlbro-Poulsen model have been created. In addition the almost direct applicability of the test results of NT Build 443 (as used in Frederiksen et al. [1996]) have been documented for the data sets of the concretes tested in the Träslövsläge marine exposure station. The model's ability to make good estimates for the field data after 1 year of exposure have been shown. The need for more data after longer exposure periods is still obvious in order to improve the ability of the model to predict the future development.

13.3 Interpretation of observations from the road environment

Chapter 11 gave some indications of what was to be expected about the chloride ingress in the road environment. However the results of systematically investigations is still very few and not at all comparable to the quality of the data from the marine exposure station in Träslövsläge. The Swedish BTB project on the durability of concrete road structures exposed to de-icing salts, cf. Utgenannt et al. [1996] will hopefully provide data of a quality compared to those of the BMB project.

Some tendencies can be found in the available data and observations. A summary is listed below. The road environment must be divided into two separate groups: a "dry" and a "wet" road environment.

For the "dry" environment the following statements are given:

- C_{sa} can reach 0.5 % mass concrete at exposure periods up till approx. 40 years, cf. Chapter 11.
- C_{sa} will increase with time.
- C_{sa} will decrease linearly with the height above the road level.
- C_{sa} will decrease logarithmically with the distance from the road.
- C_{sa} will have a maximum on the leeward face.
- $D_a \times t$ will decrease and become a constant (i.e. $\alpha = 1$).

Correspondingly for the "wet" environment the following statements are given:

- The magnitude of C_{sa} is not known very well but values up to 2 % mass concrete have been reported, cf. Chapter 11.
- C_{sa} will decrease linearly with the height above the road level.
- C_{sa} will decrease logarithmically with the distance from the road.
- $D_a \times t$ will not become a constant (i.e. $\alpha < 1$).

From this it is seen that the road environment may be more complicated to model than the marine environment. Therefore no safe conclusions can be drawn at this stage. For the time being it is recommended to adopt the results from the marine environment to the extend possible.

It might be possible to compile the information of Chapter 7 with the above given statements, but it might be wasted because of the more direct way to "the goal" that is expected soon from the data of the Swedish BTB project.

13.4 A formula for calculating threshold values

The concept used to derive formulas for the decisive parameters C_1, C_{100}, D_1 and D_{100} above was applied to the estimated data given in Table 10.2.6:1. The proposed type of function for this simple model is of the type:

$$C_{\mathrm{cr}} = k_{\mathrm{cr},\,env} \times \left(K - \mathrm{eqv}\left({}^{w}\!/_{c} \right)_{\mathrm{cr}} \right) \tag{13.4:1}$$

A multiple regression analysis was performed on the data in Table 10.2.6:1. Based on that analysis (13.4:1) is changed into (13.4:1') as follows:

$$C_{cr} = k_{cr,\,env} \times \left(1.2 - \mathrm{eqv}\left({}^{w}\!/_{c}\right)_{cr}\right) \text{ [\% mass binder]} \qquad (13.4{:}1')$$

The other constants of (13.4:1') are given in Table 13.4:1 and 13.4:2.

Table 13.4:1. The constant in (13.4:1').

Environment: Constant:	Marine Submerged	Marine splash/atmosphere	De-icing splash
$k_{cr,\,env}$	2	0.75	0.5

Table 13.4:2. The efficiency factors for corrosion initiation to be used when calculating the eqv $(w/c)_{cr}$ ratio in 13.4:1').

Efficiency factor	Silica fume	Fly ash
e	-3.5	-1

The quality of the suggested "model" can be visualised graphically by plotting the values of Table 10.2.6:1 versus the values obtained by calculations according to the model. Such plots are shown in Figure 13.4:1.

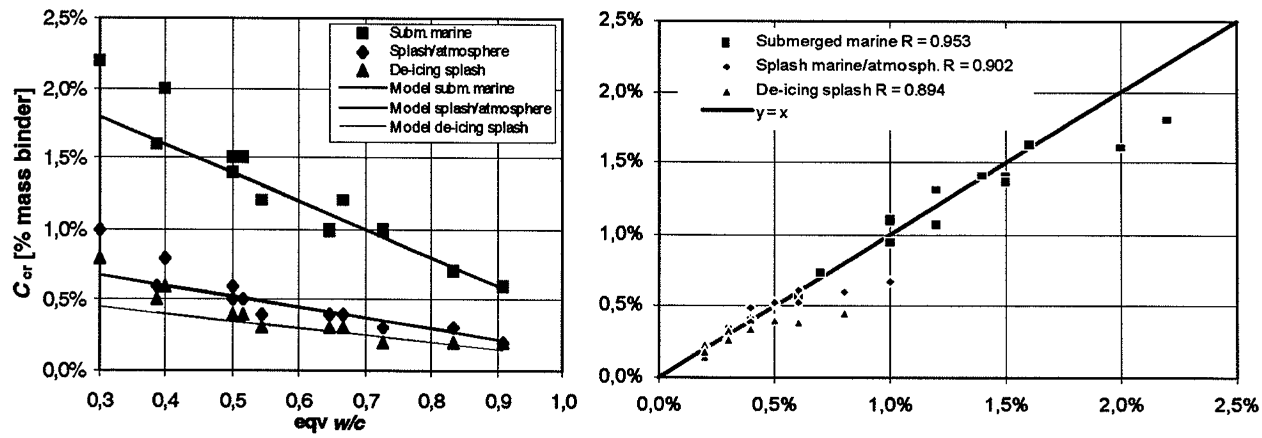


*Figure 13.4:1. **Left:** Plot of the values of Table 10.2.6:1 and the "model", i.e. (13.4:1') versus the eqv $(w/c)_{cr}$ ratio. **Right:** Plot of the same values of Table 10.2.6:1 versus the values obtained by calculations according to the "model". The correlation of each of the data sets (environmental zones) are given on the right graph. The estimates of C_{cr} are in a fairly good agreement with the original data (Table 10.2.6:1, that are estimates too).*

14 Use of the *ClinConc* model for estimating the initiation period

This Chapter presents a prediction of the chloride ingress into a submerged part of a concrete structure by use of the scientifically based numerical model presented in Chapter 4.

In this Chapter, the *ClinConc* model was used for prediction of chloride penetration into concrete by taking into account a variable chloride diffusivity, non-linear chloride binding and other practical parameters such as changes in surface concentration and temperature, degree of hydration, pore content, binder content in concrete, etc. The counter diffusion of hydroxide ions was also considered in the model. A number of specimens from the field were tested and compared with the predicted chloride profiles. The results correspond fairly well.

The Chapter is based on a paper presented at the 7th International Symposium on Durability of Building Materials and Components by Tang & Nilsson [1996].

14.1 Introduction

From the point of view of structural design, the service life is often defined as the time at which the corrosion of reinforcement in a concrete structure is initiated. After the corrosion initiation, the structure should be carefully monitored for propagation of corrosion. Therefore, the service life prediction for concrete structures in sea water is to a great extent the prediction of chloride penetration, i.e. prediction of the initiation period.

It should be noted that the exposure conditions in the splash zone are expected to be more severe and the transport mechanisms are much more complicated than the "submerged conditions". This Chapter is limited to the "submerged conditions".

14.2 Prediction of chloride penetration

The prediction results from the preliminary tests showed that the predicted chloride profiles correspond fairly well with the measured data, in spite of different exposure conditions and duration, Tang [1995].

As an example, the mix design and properties of a concrete supposed to be used in Öresund are listed in Table 14.2:1. The exposure conditions are listed in Table 14.2:2. Some parameters used in the calculation are listed in Table 14.2:3.

Table 14.2:1. Mix design and properties of concrete.

Mix No.	Cement type	Cement content kg/m^3	*w/c*	Aggregate kg/m^3	Diffusivity D_{CTH} m^2/s
1-40	Degerhamn SRPC $K_2O\% = 0.6$	420	0.40	1690	7.2×10^{-12}

Table 14.2:2. Exposure conditions for a submerged concrete structure in Öresund.

Concrete	Environment
Curing: moisture Age before exposure: 14 days Capillary saturation degree: 1	Temperature in sea water: 11±9 °C Chloride concentration: 14±4 $g_{Cl}/l_{solution}$ Dry period: 0 (submerged zone)

Table 14.2:3. Parameters used in the calculation, cf. equations in Chapter 4.

Chloride Binding	Variable Diffusivity	Activation Energy
$f_b = 3.57$ $B = 0.379$ $K_b = 0.59\times10^{-3}$ m$^3_{solution}$/kg$_{gel}$	Age dependence $\beta_t = 0.3$ $t_0 = 180$ days Depth dependence (wooden form) $\beta_x = 0.65$ $\varphi = 0.52$ $x_s = 0.04$ m	For chloride binding $E_b = 40$ kJ/mole For diffusivity $E_D = 42$ kJ/mole

A comparison of the calculated chloride profiles with the measured data is shown in Figure 14.2:1. Since the long term effect of the periodic temperature and chloride concentration on chloride penetration is unknown, annual average values of temperature 10 °C and chloride concentration 14 $kg_{Cl}/m^3_{solution}$ were used for a long term prediction in the example. Figures 14.2:2-14.2:5 shows the predicted chloride and hydroxide profiles in a concrete structure supposed to be exposed under the conditions as listed in Table 14.2:2 for a initiation period of up to 100 years. By comparing the limited hydroxide profile with the chloride profile reported by Sergi et al. [1992], the hydroxide distribution curves in Figure 14.2:4 seem reasonable.

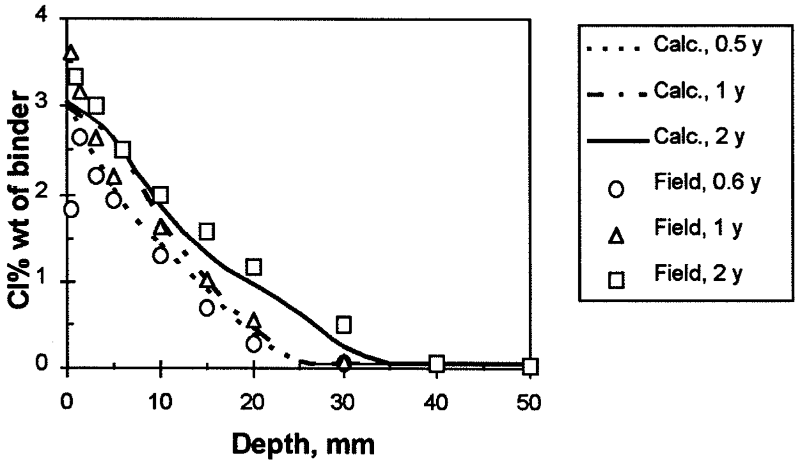


Figure 14.2:1. Comparison of the calculated chloride profiles with the measured data from the concrete slabs immersed in sea water at the Träslövsläge harbour at the west coast of Sweden for a period of two years.

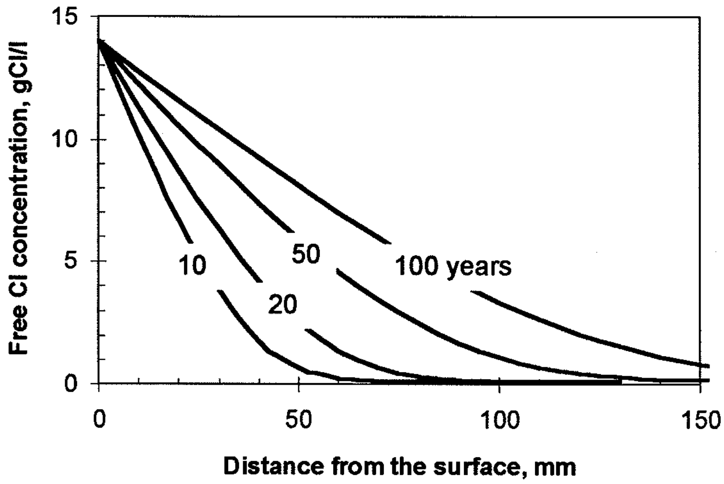


Figure 14.2:2. Predicted free chloride profiles.

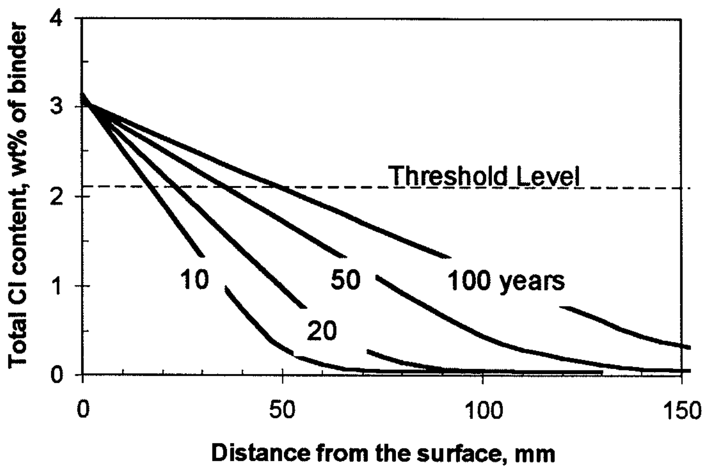


Figure 14.2:3. Predicted total chloride profiles.

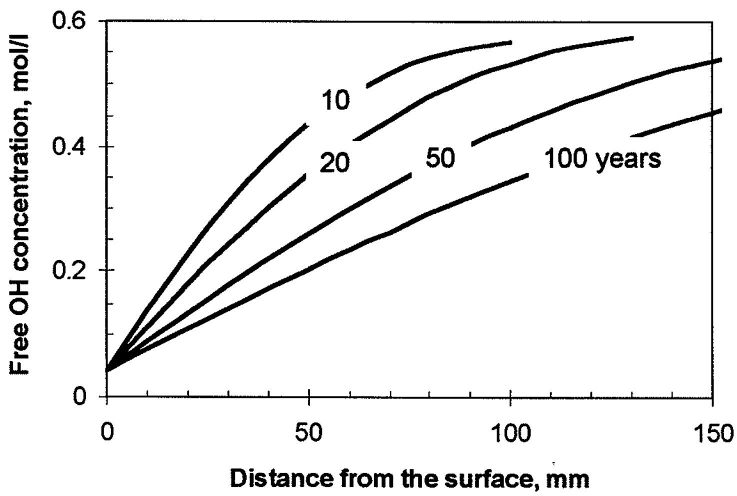


Figure 14.2.4. Predicted free hydroxide profiles.

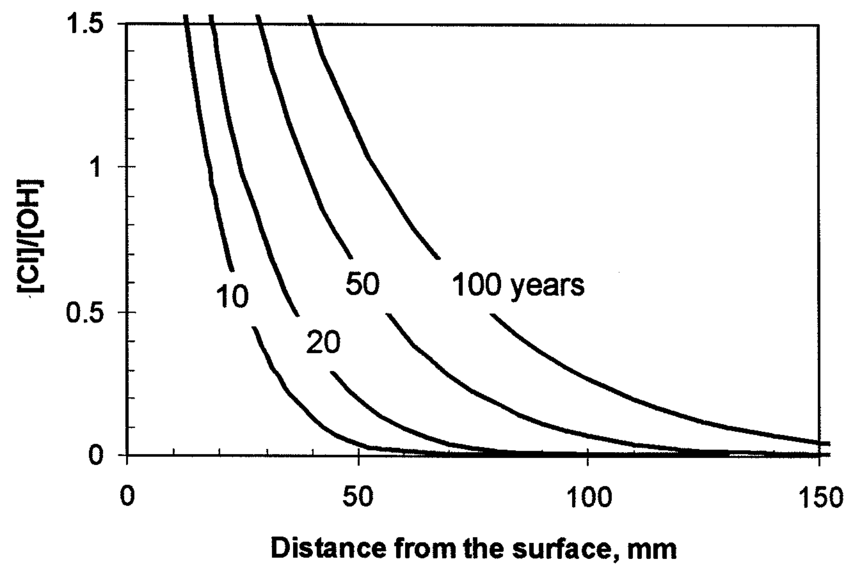


Figure 14.2:5. Ratio of free chloride concentration to hydroxide concentration.

14.3 Estimation of initiation period

In order to estimate initiation period, the critical parameter is the threshold level of the chloride concentration for initiation of corrosion. The chloride threshold level can be expressed in three ways, Glass et al. [1995]: total chloride content, free chloride concentration, and ratio of free chloride ions to hydroxide ions. The latter expression, [Cl]/[OH], seems more reasonable because it involves both the concentrations of active aggressive ions and inhibitory ions.

The threshold values reported in the literature varied very much, Glass et al. [1995]. This great variation is probably associated with 1) different exposure conditions, causing different corrosion potentials in reported field and laboratory measurements, Sandberg [1995], and 2) difficulties in the determination of free chloride and hydroxide ions in pore solution, especially near the reinforcement. Considering the current techniques, it seems more practical to express the chloride threshold level by a total chloride content, Glass et al. [1995]. Based on their well controlled experiments, Sandberg et al. [1995] recently reported a threshold value of total chloride equal to 2.1 wt% of binder for corrosion activation in submerged concrete with a quality similar to the concrete in this example. That value was used in this study, as shown in Figure 14.2:3. The corresponding depths of the critical chloride concentration for different initiation periods, as well as the corresponding values of different expressions, are listed in Table 14.3:1.

Table 14.3:1. Predicted positions of C_{cr} for different initiation periods.

Initiation period, year	10	20	50	100
Depth of C_{cr}, mm	17	23	35	50
Correspondent values of different expressions				
Free Cl, $kg/m^3_{solution}$	7.8	7.7	8.1	8.2
$[Cl^-]/[OH^-]$	1.09	1.06	1.13	1.14

It can be seen that the corresponding free chloride concentration is in a range of 7.7~8.2 g_{Cl}/l, or 0.22~0.23 moles/l, and the ratio of [Cl]/[OH] is about 1.1. Hausmann [1967], based on the laboratory study, first proposed a value of [Cl]/[OH] about 0.6, which is also valid at a higher hydroxide concentration according to Tuutti's study [1982]. The value of 0.6 is, however, valid for a steel exposed in a solution. The interface between reinforcement and concrete may have an extra protective effect, Sandberg [1995], Glass et al. [1995], Sandberg et al. [1995], resulting in a higher threshold value. So far very limited data about free chloride concentration for initiating corrosion were reported by Pettersson [1996a], and were spread in a range of 0.14~1.8 moles/l. Considering the difficulties in the measurement of free chloride and hydroxide, the values of free chloride and [Cl]/[OH] in Table 14.3:1 seem reasonable.

If a total chloride content of 0.4% by weight of binder is used as a criterion, it can be seen from Figure 14.2:3 that the thickness of concrete cover should be increased by a factor of 2~3! By comparing the results shown in Figures 14.2:2 and 14.2:3 it is found that a total chloride content of 0.4% corresponds to a free chloride concentration of about 0.9~1 g_{Cl}/l, or 0.025~0.028 moles/l. In a saturated lime water, the hydroxide concentration is 0.043 moles/l. In such a case, [Cl]/[OH] = 0.58~0.65, close to the value of 0.6. Probably the threshold value of total chloride content 0.4% holds only when the pH-value in pore solution drops down to 12.4.

It can be seen that the [Cl]/[OH] curves in Figure 14.2:5 are steeper than the other curves in Figures 14.2:2 and 14.2:3. This implies that a variation in [Cl]/[OH] results in a less change in thickness than a variation in free chloride concentration or total chloride content. Therefore, the ratio of [Cl]/[OH] might be the best expression for the criterion of the corrosion initiation.

Although the expression of [Cl]/[OH] as a criterion of the corrosion initiation is more scientific, the knowledge of hydroxide distribution in aged concrete is very limited. Further work is needed to investigate hydroxide profiles in concrete exposed in the field.

14.4 Conclusions

The modelling for chloride penetration by using a numerical approach is today a realistic way to the prediction of initiation period of a submerged part of a concrete structure. Even though good correspondence with profiles of relatively short exposure in the field was demonstrated the uncertainty of the model in long exposure periods (10, 50, 100 years) is still to be investigated. The time dependence of the governing parameters as counted for in the empirical model is not modelled by *ClinConc*.

For structural parts in the splash zone the *ClinConc* model is not yet applicable since it is limited to cases without convection of chloride. However, as a tool to be on the safe side, the model would be applicable. The new model for convection of chloride, as presented in Chapter 7, is currently only qualitative and cannot yet be used for durability analysis of structures.

15 Design of concrete covers for new RC structures

This chapter describes in details how to apply the Mejlbro-Poulsen model in the design stage for new concrete structures.

15.1 Background

The structural designer usually follows a set of standard details concerning the reinforcement specified by the Code of Practice. These details include tables of the minimum concrete cover to the reinforcement corresponding to various environmental classes and sometimes to some of the properties of the concrete, e.g. the *w/c* ratio.

However, the use of such tables for the minimum cover of reinforcement are often not proven valid for all concrete structures. There may be reasons for a special design of the concrete cover to the reinforcement bars or to carry out calculation of the initiation time, when the concrete and the cover have been specified. Among such reasons the following may be emphasised:

- The structure is so expensive to construct that the use of design tables on the safe side will lead to the increase of unnecessary expenses.
- Repair of the structure during the required initiation time is not possible, e.g. because the traffic cannot be stopped.
- Building owners may find it profitable to minimise the total cost of the construction and therefore require documentation of the initiation time even if the individual concrete structures do not themselves justify a detailed calculation of the initiation time.

When the initiation time of a new RC structure (reinforced concrete structure) in a chloride laden environment has to be predicted two concepts are possible:

- The decisive parameters may be estimated on the basis of personal experience, references in the literature or neighbouring RC structures to the structure planned.
- The decisive parameters may be found on the basis of pre-testing the concrete proposed to the environmental class in-situ.

The determination of the parameters describing the long time development will always be made with an uncertain prediction and one has to rely on parameters assumed to be constant really are constant in the initiation period, e.g. the threshold value.

15.2 Initiation period

The initiation period is defined as the time from casting the concrete until the chloride concentration at the reinforcement has reached the threshold level corresponding to the concrete and it's local environment.

In order to be able to predict the initiation time of a RC structure exposed to a chloride laden environment, a formula for the initiation time or another method of decision must be available. Here, a formula for the initiation time as well as a graphical method are presented.

When decisive parameters are given the chloride profile can be calculated at any time acc. to (3.2.3:3). That expression can however be transformed into a more convenient form, cf. Mejlbro [1996]:

$$C(x,t) = C_i + S_p \times \left(\frac{0.5x}{\sqrt{t_{ex} D_{aex}}} \right)^{2p} \Lambda_p(z) \tag{15.2:1}$$

where:

$$z = \frac{0.5x}{\sqrt{\tau \times t_{ex} D_{aex}}}$$

$$\Lambda_p(z) = \frac{\Psi_p(z)}{z^{2p}} \tag{15.2:2}$$

The functions $\Lambda_p(z)$ are tabulated versus z, cf. Mejlbro [1996].

The initiation time t_{cr} can be determined by solving the following equations:

$$C_{cr} = C_i + S_p \times \left(\frac{0.5c}{\sqrt{t_{ex} D_{aex}}} \right)^{2p} \Lambda_p(z_{cr})$$

$$z_{cr} = \frac{0.5c}{\sqrt{\tau_{cr} \times t_{ex} D_{aex}}} \tag{15.2:3}$$

$$\tau_{cr} = \left(\frac{t_{cr}}{t_{ex}} \right)^{1-\alpha} - \left(\frac{t_{ex}}{t_{cr}} \right)^{\alpha} \cong \left(\frac{t_{cr}}{t_{ex}} \right)^{1-\alpha}$$

Here c is the thickness of the reinforcement cover and C_{cr} is the threshold value of chloride in concrete corresponding to the local marine environment in question. The solution yields:

$$z_{cr} = \text{inv}\Lambda_p(y_{cr})$$

$$y_{cr} = \frac{C_{cr} - C_i}{S_p} \times \left(\frac{\sqrt{t_{ex} D_{aex}}}{0.5c} \right)^{2p} \tag{15.1:4}$$

Solved with respect to t_{cr} the solution yields:

$$t_{cr} = t_{ex} \times \left(\frac{0.5c}{\sqrt{t_{ex} D_{aex}} \times \mathrm{inv}\Lambda_p(y_{cr})} \right)^{\frac{2}{1-\alpha}} \qquad (15.2:5)$$

The initiation period t_{cr} is measured from the time of mixing the concrete. The application of (15.2:5) is shown in Chapters 16 and 17.

15.3 Corrosion domain

The above developed formula for the initiation time (15.2:5) is useful when the expected value of the initiation time must be determined. However, (15.2:5) is a deterministic model and does not give an idea of the safety of the determination of the initiation time during the period of 100 years. Here, a graphical method is presented which allows a certain estimation of the influence of the stochastic behaviour of the decisive parameters.

The "chloride ingress" is represented by the parameters: α, D_{aex}, S_p and p. The "corrosion" is represented by the parameters: C_{cr} and c. Now the domain of corrosion must be determined in a co-ordinate system with D_a as the ordinate and t as the abscissa. The domain of corrosion is defined as the set of values of (t, D_a) which yields corrosion of the reinforcement. The set of values of (t, D_a) which belongs to the border of the domain of corrosion is named (t, D_{acr}), cf. Figure 15.3:1. This set of values is determined by the following equation:

$$C_{cr} = C_i + S_p \times \left(\frac{0.5c}{\sqrt{t_{ex} D_{aex}}} \right)^{2p} \times \Lambda_p \left(\frac{0.5c}{\sqrt{(t - t_{ex}) D_{acr}}} \right) \qquad (15.3:1)$$

The solution of this equation yields:

$$D_{acr} = \left(\frac{0.5c}{\mathrm{inv}\Lambda_p(y_{cr})} \right)^2 \times \frac{1}{(t - t_{ex})}$$

$$(15.3:2)$$

$$y_{cr} = \frac{C_{cr} - C_i}{S_p} \times \left(\frac{\sqrt{t_{ex} D_{aex}}}{0.5c} \right)^{2p}$$

Since y_{cr} is a constant when the concrete, the local environmental class, the cover thickness and the exposure time are specified, the graph of the lower limit of the corrosion domain is a hyperbola in a Cartesian co-ordinate system. However, since the relevant range of time goes from approx. 0.1 year to 100 years it is more convenient to use a double logarithmic co-ordinate system, cf. Figure 15.3:1.

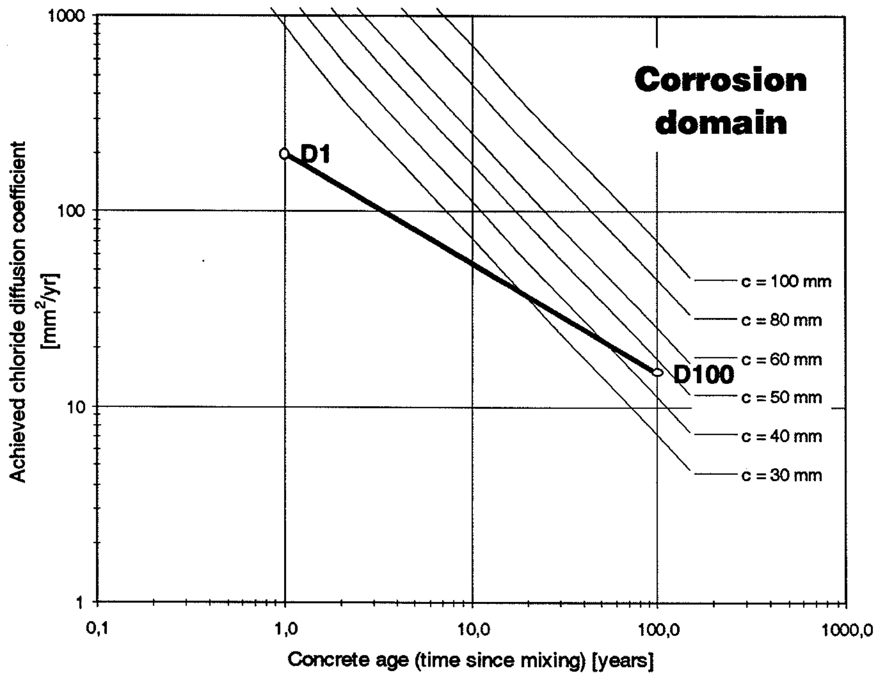


Figure 15.3:1. An example of a graphical presentation of the critical area, the so-called "corrosion domain". The curves represents different cover thicknesses and thus different border lines to the corrosion domain. The ***bold*** *line illustrates the expected trend of the achieved diffusion coefficients versus time.*

15.4 Safety concepts

Figure 15.3:1 illustrates a predicted situation. As seen no corrosion will take place after 100 years when the concrete cover of the reinforcing bars is 50 mm on condition that the problem is purely deterministic (i.e. the standard divisions of all parameters are zero) and the model applied is true. However, the problem is stochastic – not deterministic. Thus, the expectation value of the distance from point A to the corrosion domain divided by its standard deviation is the reliability index, cf. Cornell [1969].

The parameters of the concrete and it's local environment are stochastic variables. Thus, the lower limit of the corrosion domain is an uncertain graph and so is the actual set of (t, D_a).

Since (t, D_a) should remain outside the corrosion domain determined by the lower limit (t, D_{acr}) there are two possibilities of gaining safety:

- *The method of characteristic values*. The corrosion domain (t, D_{acr}) must be drawn using parameters on the safe side (characteristic values) and so must the actual set of (t, D_a). Acceptance criterion is, that (t, D_a) does not belong to the corrosion domain.
- *The method of reliability index.* The corrosion domain (t, D_{acr}) must be drawn using expectation values of the parameters and so does the actual set of (t, D_a). The distance from the expected set $E\{(t, D_a)\}$ to the expected graph $E\{(t, D_{acr})\}$ is a measure of the reliability index. The criterion is, that the reliability index is sufficiently large, but so far no Code of Practice specifies an acceptable value of the reliability

index. This is left to the designer or the building owner. The graph of the lower limit of the corrosion domain should be drawn for a series of relevant cover thicknesses keeping the parameters of the concrete and the environment at constant (expectation) values. This will allow the designer to decide the cover thickness.

The mathematical formulation of the method of reliability index β is given below, cf. Mohr [1980]:

$$\mathrm{E}\{D_{\mathrm{cr}}\} = \mathrm{E}\{D_{100}\} + \beta\sqrt{s_{\mathrm{cr}}^2 + s_{100}^2} \qquad (15.4:1)$$

where $\mathrm{E}\{D_{\mathrm{cr}}\}$ is the expectation value of the border line in the corrosion domain and s denotes the standard deviation.

However, at the moment there is no requirement for the reliability index, but examinations, cf. Karlsson et al. [1995] and Poulsen et al. [1996], have shown that for accepted marine RC structures the reliability index is significantly smaller than that of load carrying RC structures. When the reinforcement starts to corrode there is an early warning before failure and there is no risk of loss of human life. For the load capacity of a carrying RC structure the reliability index ought to be appx. 4.0, but it seems realistic that the reliability index ought to be between 0.5 and 1.0 for the initiation time of marine RC structures.

At the moment there is almost no information about the deviation of the decisive parameters for the initiation time. If the coefficients of variation, i.e. the expectation value relative to the standard deviation, of the corrosion domain and the diffusion coefficient are 50-100% and $0.5 \leq \beta \leq 1$, thus $\mathrm{E}\{D_{\mathrm{cr}}\} \approx 1 \times \mathrm{E}\{D_{100}\}$ to $2{,}4 \times \mathrm{E}\{D_{100}\}$.

15.5 Decisive parameters

The four decisive parameters α, D_{aex}, S_p and p of the concrete and its local environment are defined by:

$$D_a = D_{aex} \times \left(\frac{t_{ex}}{t}\right)^{\alpha}$$

$$C_{sa} = C_i + S_p \times \tau^p \qquad (15.5:1)$$

$$\tau = \left(\frac{t}{t_{ex}}\right)^{1-\alpha} - \left(\frac{t_{ex}}{t}\right)^{\alpha}$$

Instead of estimating the four parameters α, D_{aex}, S_p and p, it is more convenient to estimate the achieved chloride diffusion coefficients D_1 and D_{100} at time $t_1 = 1$ year and $t_{100} = 100$ years respectively, and the corresponding chloride concentrations of the exposed concrete surface C_1 and C_{100}.

From D_1, D_{100}, C_1 and C_{100} it is possible to find the corresponding values of α, D_{aex}, S_p and p by a step wise determination using the following formulae:

- **Step 1**. Estimate the achieved chloride diffusion coefficient D_1 and D_{100} at exposure time 1 year and 100 years respectively.
- **Step 2**. Estimate the achieved chloride concentration of the concrete surface C_1 and C_{100} at exposure time 1 year and 100 years respectively.
- **Step 3**. Calculate the parameter:

$$\theta = \frac{1}{2} \times \log_{10}\left(\frac{1}{t_{ex}}\right). \tag{15.5:2}$$

- **Step 4**. Calculate:

$$\alpha = \frac{1}{2} \times \log_{10}\left(\frac{D_1}{D_{100}}\right). \tag{15.5:3}$$

- **Step 5**. Calculate:

$$D_{aex} = D_1 \times \left(\frac{D_1}{D_{100}}\right)^{\theta}. \tag{15.5:4}$$

- **Step 6**. Calculate:

$$p = \frac{\log_{10}(C_{100}/C_1)}{\log_{10}\left(\frac{100 - t_{ex}}{1 - t_{ex}} \times \frac{D_{100}}{D_1}\right)}. \tag{15.5:5}$$

- **Step 7**. Calculate:

$$S_p = C_1 \times \left(\left(\frac{D_1}{D_{100}}\right)^{\theta} \times \frac{t_{ex}}{1 - t_{ex}}\right)^{p}. \tag{15.5:6}$$

It is seen that these formulas are suitable for calculation by means of a spread sheet and/or a programmable pocket calculator.

15.6 Estimation of decisive parameters

The decisive parameters form the basis of the prediction of the "safety" of the initiation time against corrosion. The expectation values or the characteristic values of these parameters can be difficult to determine. This report has in Chapter 13 presented some empirical models for estimating expectation values of the decisive parameters. The practical use of these parameters are shown in Chapters 16 and 17 for concrete in two marine structures.

16 Example of how to design concrete covers for a new marine RC structure

This chapter describes in details how to estimate the initiation period of a new marine RC structure by applying the Mejlbro-Poulsen Model in the design stage.

Chapter 15 has prepared the mathematical basis for a systematical way of handling the estimation of the initiation period. In this chapter it is demonstrated how to proceed in a "concrete" situation.

16.1 Chosen type of concrete

In order to illustrate the application of the principles and the formulas developed in Chapter 15, the initiation time of a typical marine concrete exposed to the splash zone will be determined. The concrete is under test in the Träslövsläge Marine Exposure Station in Sweden.

The test specimens No. 10-40, cf. the Appendix have been chosen. The constituent materials and composition of the concrete are presented in Table 16.1:1. It is assumed that $C_i = 0$. The time of the first chloride exposure is t_{ex} = 14 days = 0.038 years.

***Table 16.1:1.** Constituent materials and composition of concrete of specimen No. 10-40. The density is 2205 kg/m^3 concrete.*

Constituent materials	Origin	Amount	Units
SRPC	Aalborg Portland A/S	345	kg/m^3 concrete
Fly ash	Danaske A/S	75	kg/m3 concrete
Silica fume	Elkem A/S	20.5	kg/m^3 concrete
Water	Tap water	155.2	kg/m^3 concrete

16.2 Decisive parameters

The decisive parameters (i.e. D_1, D_{100}, C_1, C_{100} and C_{cr}) are derived as follows:

16.2.1 Diffusivity

In order to determine the expectation values of D_1 and D_{100} the eqv $(w/c)_D$ ratio with respect to diffusivity is determined. The efficiency factors of fly ash and micro silica are taken from Table 13.2.4:2.

$$\text{eqv } (w/c)_D = 155.2/(345 + 1 \times 75 + 7 \times 20.5) = 0.275 \qquad (16.2.1:1)$$

From (13.2.4:1') and (13.2.4:2') respectively the achieved diffusion coefficient D_1 and the "decrease parameter" α are determined.

$$D_1 = 25{,}000 \times \exp(-\sqrt{(10/0.275)}) \times k_{D,\,env} = 60.4 \times k_{D,\,env} \qquad (16.2.1:2)$$

$$\alpha = (1 - 1.5 \times 0.275) \times k_{\alpha,\, env} = 0.59 \times k_{\alpha,\, env} \quad (16.2.1:3)$$

For the three marine environments the values of $k_{D,\, env}$ and $k_{\alpha,\, env}$ are taken from Table 13.2.4:1. Having estimates of D_1 and α the value of D_{100} is determined from (3.2.1:2) for each of the environments. All the estimated diffusivity values are given in Table 16.2.1:1.

Table 16.2.1:1. Expectation values for diffusivity for the concrete in the example.

Environment:	Submerged	Splash zone	Atmosphere zone	Unit
D_1	60.4	36.2	24.2	mm²/yr
α	0.352	0.059	0.587	-
D_{100}	11.9	27.7	1.6	mm²/yr

16.2.2 Surface concentrations

In order to determine the expectation values of C_1 and C_{100} the eqv $(w/c)_b$ ratio with respect to binding is determined. The efficiency factors of fly ash and micro silica are taken from Table 13.2.2:2.

$$\text{eqv } (w/c)_b = 155.2/(345 + 0.75 \times 75 - 1.5 \times 20.5) = 0.419 \quad (16.2.2:1)$$

From (13.2.2:1') the achieved surface chloride concentration C_1 can be estimated to

$$C_1 = 3.667 \times 0.419 \times k_{C,\, env} = 1.54 \times k_{C,\, env} \quad (16.2.2:2)$$

while C_{100} is estimated from (13.2.2.2).

From the constants given in Table 13.2.2:1 the expectation values of C_1 and C_{100} are calculated for the three marine environments. All the estimated surface concentration values are given in Table 16.2.2:1.

Table 16.2.2:1. Expectation values for surface concentration for the concrete in the example.

Environment:	Submerged	Splash zone	Atmosphere zone	Unit
C_1	2.15	1.54	0.92	% mass binder
C_{100}	3.23	6.91	6.45	% mass binder

16.2.3 Threshold concentrations

The best estimates of chloride threshold values are given in Table 10.2.6:1 for several local environmental classes and various compositions and constituent materials of concrete. The threshold values are valid on condition, that:

- The concrete has no macro cracks, i.e. no crack widths $w \geq 0.10$ mm.
- The concrete cover is $c \geq 25$ mm.

If these conditions are not fulfilled, the local environment around the reinforcing bars will not be sufficiently constant. This means that other parameters than mentioned here will influence the corrosion initiation.

The *estimated threshold values* have been transformed into a "threshold model", cf. Chapter 13 in order to ease the use of spread sheet calculations. The "threshold model" do not give the values of Table 10.2.6:1 precisely, but it may be more helpful if an analysis of the effect of different concrete compositions are to be studied.

In order to determine the expectation values of C_{cr} the eqv $(w/c)_{cr}$ ratio with respect to the threshold value is determined. The efficiency factors of fly ash and micro silica are taken from Table 13.4:2.

$$\text{eqv}\ (w/c)_{cr} = 155.2/(345 - 1 \times 75 - 3.5 \times 20.5) = 0.783 \qquad (16.2.3{:}1)$$

From (13.4:1') the threshold concentrations C_{cr} can be estimated to

$$C_{cr} = k_{cr,\,env} \times (1.2 - 0.783) = 0.42\, k_{cr,\,env} \qquad (16.2.3{:}2)$$

From the constants given in Table 13.4:1 the expectation values of C_{cr} are calculated for the three marine environments. All the so estimated threshold concentration values are given in Table 16.2.3:1.

Table 16.2.3:1. Expectation values for threshold values for the concrete in the example.

Environment:	Submerged	Splash zone	Atmosphere zone	Unit
C_{cr}	0.83	0.31	0.31	% mass binder

16.2.4 Basic parameters

Not all of the decisive parameters determined as above can be directly used in the Mejlbro-Poulsen model. Therefore the "decisive" parameters are transformed into "basic" parameters as described in Chapter 15, Section 15.5. Below only the transformation for the submerged zone is shown:

$$\theta = \frac{1}{2} \times \log_{10}\left(\frac{1}{0.038}\right) = 0.708 \qquad \text{cf. } (15.5{:}2)$$

$$p = \frac{\log_{10}(3.23/2.15)}{\log_{10}\left(\frac{100 - 0.038}{1 - 0.038} \times \frac{119}{60.4}\right)} = 0.134 \qquad \text{cf. } (15.5{:}5)$$

$$S_p = 2.15 \times \left(\left(\frac{60.4}{119}\right)^{0.71} \times \frac{0.038}{1 - 0.038}\right)^{0.134} = 1.628\%\ \text{mass binder} \qquad \text{cf. } (15.5{:}6)$$

16.3 Estimation of initiation time

In order to determine the best estimate of the initiation time (15.2:5) is applied.

The initiation time in the submerged zone is found by (15.2:5) in the following way:

$$D_{aex} = \frac{D_1}{t_{ex}^{\alpha}} = \frac{60.4}{0.038^{0.352}} = 190\,\text{mm}^2/\text{yr}$$

$$y_{cr} = \frac{0.83 - 0.0}{1.628} \times \left(\frac{\sqrt{0.038 \times 190}}{0.5 \times 50} \right)^{2 \times 0.134} = 0.2821$$

$$\text{inv}\Lambda_{0.134}(y_{cr}) = 0.739$$

$$t_{cr} = 0.038 \times \left(\frac{0.5 \times 50}{\sqrt{0.038 \times 190} \times 0.739} \right)^{3.09} \approx 94 \text{ years}$$

on condition that the cover is $c = 50$ mm. In the same way the initiation time can be estimated when for other values of the cover c and for the other environments. Thus a decision on the necessary cover thickness in each of the environmental zone can be made.

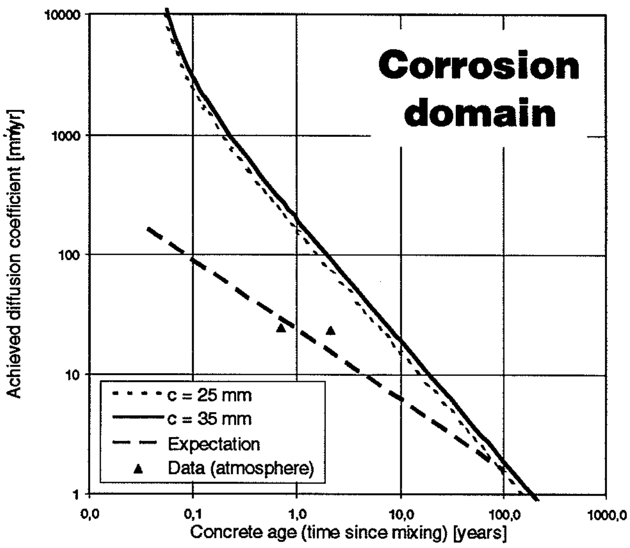
16.4 Corrosion domains

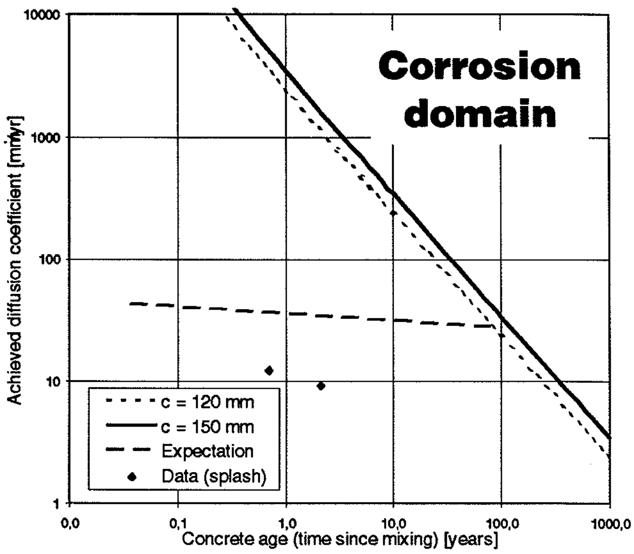
In order to determine the necessary concrete cover of the reinforcing bars the corrosion domain must be determined for different values of the concrete cover c.

Assuming that $c = 50$ mm the corrosion domain $D_{acr}(t)$ for the submerged condition is determined by (15.3:2):

$$D_{acr} = \frac{1146}{t - 0.038} \text{ mm}^2 \text{ / year}$$

The same procedure is applied when $c = 60$, 70 and 80 mm and for relevant concrete covers for the other environmental zones. The corrosion domains are shown in Figure 16.4:1 where the achieved diffusion coefficients observed in Träslövsläge and the lines D_{aex} - D_{100} are also shown. Rather large deviations between the expectation values and the field observations are observed but no conflicts are observed.





Splash↗

↑Atmosphere

Submerged→

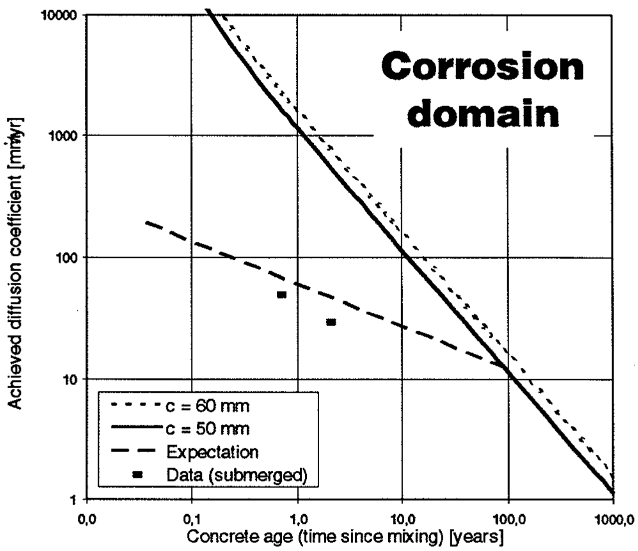


Figure 16.4:1. Corrosion domains, estimated trends of (D_a, t) and observed vaules for the three environmental zone in marine environment.

16.5 Design of reinforcement cover

Figure 16.4:1 presents the different situations in the three marine environments. As discussed in Section 15.4 all the parameters are stochastic variables and thus deviation from the shown trends are certain - as illustrated by the observed field data plotted in the graphs! The problem is still how to ensure sufficiently safety so that no corrosion occurs within the expected initiation period. By use of (15.2:5) as shown above the covers to reinforcement corresponding to different initiation periods are estimated as given in Table 16.5:1.

Table 16.5:1. Expectation values for the necessary covers to achievement of a 100 years initiation period for the concrete in the example.

Submerged zone		Splash zone		Atmosphere zone	
c [mm]	t_{cr} [year]	c [mm]	t_{cr} [year]	c [mm]	t_{cr} [year]
50	94	120	83	25	83
60	153	150	125	30	147

16.6 Conclusion

The use of an operational way (system) of designing concrete covers have been shown.

There is a remarkably large deviation between what is estimated by use of the formulas for the expectation values in Chapter 13 and what would have been estimated on the basis of the data presented in the Appendix. This was expected because of the rather large deviation between the estimates from the "models" in Chapter 13 and the original data. As a consequence it must in the final be decided by the designer what to rely on: experience, data from the field or emperical models.

The shown design of the (necessary) thickness of the concrete cover for the reinforcing bars is unambiguous and operational *except* for the safety level. It is however not the intention of this report to determine the values of the reliability index for marine RC structures against corrosion initiation.

17 Residual initiation period of an existing marine concrete structure

This chapter describes in details how to apply the Mejlbro-Poulsen model in the inspection stage for existing marine concrete structures. The data and parameters used in this chapter are taken from the literature and from earlier chapters of the report.

17.1 Background

When predicting (by calculation) the residual time to initiation of a marine RC structure which has been in service for a (longer) period of time, and the structure of which has been regularly under observation, the chloride exposure of the marine environment as well as the chloride diffusivity of the concrete can be estimated. However, systematic inspection including measurements of the chloride ingress by means of chloride profiles is of recent date.

The main difference between predicting the chloride ingress into the concrete of an existing marine RC structure and a marine RC structure under design is:

- As for the existing marine RC structure, the achieved chloride profiles at the time of inspection are (or could be) well-known, but the initial chloride diffusivity of the concrete at the time when the structure was exposed to sea water for the first time (typically between 1 month to 6 months) is rarely known, and thus has to be estimated.
- As for the marine RC structure under design, the initial chloride diffusivity is known (or could be by trial casting and pre-testing), while the future chloride diffusivity (20 or 50 years ahead) is not known and thus has to be estimated.

Earlier chapters of this report deal with the chloride diffusivity of the concrete as a response to local chloride laden environment and at various (maturity) ages. This chapter is an example of an existing marine RC structures where the chloride ingress into the concrete has been observed. An estimate of the residual initiation period is made by means of the Mejlbro-Poulsen model and the models presented in Chapters 13 and 15.

17.2 Inspection of existing marine RC structures

When inspecting an existing marine RC structure it is important to observe and measure relevant properties, characteristics and events. In general, only little information is available about the concrete from files.

17.2.1 Initial concrete data

The following characteristics of the concrete, its production and placing ought to be looked for:

- The target mix proportions of the concrete.
- The types of the constituent materials, particularly the type of binder.
- Measurements from pre-testing the concrete, if any.
- Information on curing and possible surface treatment.
- The date of casting the concrete.
- The date when the concrete was exposed to sea water for the first time.

17.2.2 Measurements during inspection

In order to achieve the highest degree of information about the concrete and its local environment, the following examinations of the concrete ought to be carried out at the location in question:

- The cover to and the position of the reinforcement by means of a covermeter.
- Plane section analysis of the near-to-surface layer of the concrete with particular reference to distribution of coarse aggregate and cracks.
- Thin section analysis of the near-to-surface layer of the concrete with particular reference to *w/c* ratio, type of binder, deterioration, cracks and chemical alterations of the cement matrix.
- Determination of the achieved chloride profile of the exposed end of a concrete core, drilled at the position in question, and determined by means of the test method APM 207.
- Determination of the potential chloride diffusivity of the virgin end of a concrete core, drilled at the position in question, and determined by means of the test method NT Build 443.
- Determination of the moisture profile of the exposed end of an extracted concrete core, drilled at the position in question.

17.3 Chloride ingress into concrete of the Farø Bridges

In order to illustrate the application of the principles and the formulae developed in Chapter 15, the chloride ingress into one of the concrete pillars of the Farø Bridges will be studied. Details of the concrete composition and the measured chloride ingress into the concrete at the splash-zone are given by Stoltzner [1995]. The chloride diffusivity of the concrete is determined on cores extracted from pillar No. SF06 at a position of 0.35 m above water level, i.e. at the splash-zone.

The concrete pillar has been exposed to a marine environment of brackish water. One of the chloride profiles from the position in question (the splash zone) have been reported by Stoltzner et al. [1994]. The residual time to initiation, defined as the initiation period, is here predicted by applying the Mejlbro-Poulsen model for chloride ingress into concrete by diffusion.

The Farø Bridges were constructed during 1981-84, but the maturity of the concrete of pillar SF06 when exposed to sea water for the first time has not been reported. However, the estimation of the chloride ingress into the concrete and the prediction of the residual time to initiation are here carried out by assuming that t_{ex} = 0.5 year.

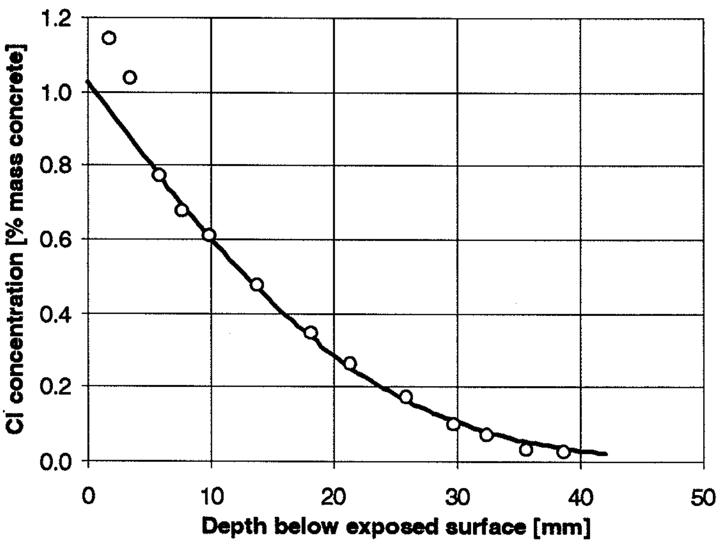


Figure 17.3:1. Chloride profile from the Farø brigde measured 0.35 m above sea level after 9 years exposure. The curve represents the best fit of the error function solution to Fick's 2nd law, Stoltzner et al. [1994].

17.3.1 Concrete composition

According to Stoltzner [1995] the mix proportions of the concrete used at the Farø Bridges are:

SRPC	330 kg/m^3 concrete
Fly ash	40 kg/m^3 concrete
Water	140 kg/m^3 concrete
Aggregates	1827 kg/m^3 concrete

17.3.2 The chloride diffusivity

The initial chloride content of the concrete is not reported. Here, it is assumed that the initial chloride content of the concrete is $C_i = 0$.

The concrete's achieved chloride diffusion coefficients have been determined at three different times (i.e. in 1989, 1991 and 1994). The observations are shown in Table 17.3.2:1.

Table 17.3.2:1. Observations made on chloride diffusivity of concrete from the Farø Bridges.

Inspection year	Concrete age, years	Achieved diffusion coefficient, mm^2/yr	Achieved chloride of surface, % mass concrete
1989	7	22.1	0.88
1991	9	18.9	1.11
1994	12	15.8	1.24

The achieved chloride diffusion coefficients in Table 17.3.2:1 are shown versus time in Figure 17.3.2:1. By a regression analysis it is learned that the achieved chloride diffusion coefficient obeys the relation:

$$D_a = D_{aex} \cdot \left(\frac{t_{ex}}{t}\right)^{\alpha} = 114 \cdot \left(\frac{0.5}{t}\right)^{0.622} \text{ mm}^2/\text{yr} \qquad (17.3.2:2)$$

on condition that $t_{ex} = 0.5$ year. From (17.3.2:2) it is learned that the achieved chloride diffusion coefficients are:

- $D_1 = 74.0$ mm²/yr at time $t_1 = 1$ yr.
- $D_{100} = 4.2$ mm²/yr at time $t_{100} = 100$ yr.

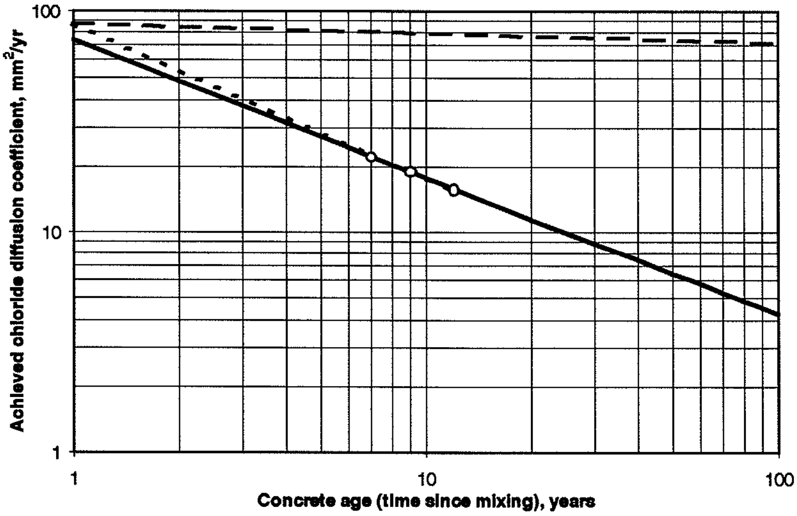


Figure 17.3.2:1. The achieved chloride diffusion coefficients of concrete from splash zone of the Farø Bridges pillar No. SF06 versus the concrete age, cf. Stoltzner [1995]. It is assumed that the concrete was mixed in 1982. From this graph it is estimated that $\alpha = 0.622$ and that $D_{aex} = 114$ mm²/yr when it is assumed that $t_{ex} = 0.5$ yr, cf. (17.2.3:1). The dotted lines are estimated with the models presented in Chapter 13 - see comments below.

The two dotted lines in Figure 17.3.2:1 intersects at $t = 1$ year because both estimates of D_1 are made with the "model" (13.2.4:1'). As seen that estimate is not in conflict with the observed data and the assumption that the time-dependence of the diffusion coefficient follows (3.2.1:2). The values of D_{aex} and α shift to 142.6 mm²/yr and 0.700 respectively if the estimate of D_1 is included in the regression analysis together with the data.

17.3.3 Chloride concentration of concrete surface

It is estimated that the chloride concentration of the surface will increase to C_{100} = 2.0 % by mass concrete when the concrete reaches the age of $t_{100} = 100$ years. The achieved chloride concentrations of the concrete surface, cf. Table 17.3.2:1 are shown versus time in Figure 17.3.3:1. By a regression analysis on the data it is learned that the achieved chloride concentration of the concrete surface obeys the relation, (cf.15.5:1):

$$C_{sa} = 0.546 \times \left(\left(\frac{t}{0.5}\right)^{0.378} - \left(\frac{0.5}{t}\right)^{0.622} \right)^{0.65} \qquad (17.3.3:1)$$

From (17.3.3:1) it is found that the achieved chloride concentrations of the concrete surface are:

- $C_1 = 0.4$ % mass concrete at time $t_1 = 1$ yr.
- $C_{100} = 2$ % mass concrete at time $t_{100} = 100$ yr.

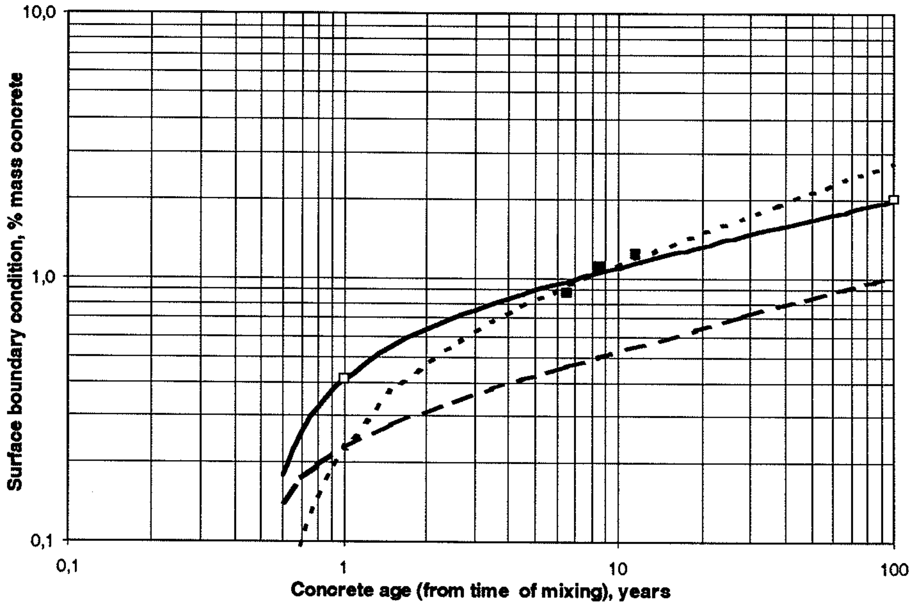


Figure 17.3.3:1. The achieved chloride concentration of concrete surface at the splash zone of the Farø Bridges pillar No. SF06 versus the concrete age, cf. Stoltzner [1995]. It is assumed that the concrete was mixed in 1982 and $t_{ex} = 0.5$ yr. By regression analysis it is found that $p = 0.65$ and that $S_p = 0.546$ % mass concrete when it is assumed that $C_{100} =$ 2.0 % mass concrete, cf. (17.3.3:1). The C_1 value is calculated to 0.41 % mass concrete. The dotted curves are estimated with the models presented in Chapter 13 - see comments below.

The two dotted curves in Figure 17.3.3:1 almost intersects at $t = 1$ year because both estimates of C_1 are made with the "model" (13.2.2:1'). As seen that estimate is not in conflict with the observed data and the assumption that the time-dependence of the surface boundary condition follows (3.2.2:3). The value of C_1 estimated with (13.2.2:1') is 0.226 %mass concrete and C_{100} shift to 2.73 % mass concrete if the estimate of C_1 is included in the regression analysis together with the data.

17.3.4 Domain of corrosion

The threshold value of chloride in the concrete of the Farø Bridges in the splash zone is estimated from Table 10.2.6:1. Since the water/binder ratio is 0.38, the fly ash/-binder ratio is 10.8 % and the binder content is 370 kg/m^3 of concrete the threshold value is estimated to be $C_{cr} = 0.10$ % mass concrete.

The corrosion domain $D_{acr}(t)$ is determined by (15.3:2) in the following way:

$$y_{cr} = \frac{0.10-0.0}{0.546} \times \left(\frac{\sqrt{0.5\times 114}}{0.5\times 50}\right)^{2\times 0.65} = 0.0387$$

$$\text{inv}\Lambda_{0.65}(y_{cr}) = 1.15 \qquad (17.3.4:1)$$

$$D_{acr} = \frac{472}{t-0.5}$$

The corrosion domain is shown in Figure 17.3.4:1 where also the observations of achieved diffusion coefficients are shown. It is seen that the observed diffusion coefficients are located outside the corrosion domain, i.e. that no corrosion will occur if the observed and estimated data and the model are valid.

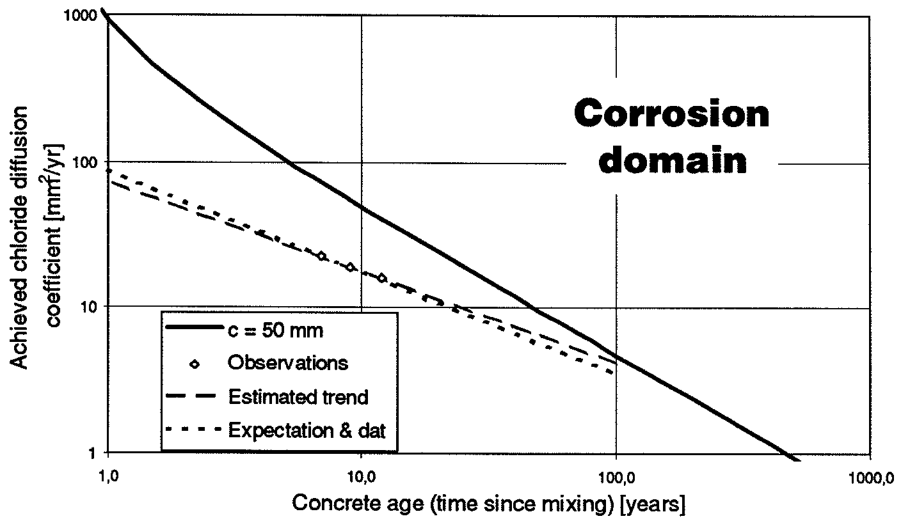


Figure 17.3.4:1. The achieved chloride coefficient versus time, cf. Figure 17.3.2:1, and the corrosion domain. It is seen that the achieved chloride diffusion coefficients are situated outside the corrosion domain for 0.5 yr ≤ t ≤ 100 yr, but the distance between the graph of the achieved chloride diffusion coefficients and the lower limit of the corrosion domain approaches zero for t → 100 years. The graphs intersect at time t_{cr} = 135 years as shown in the text, cf. (17.3.4:1). The dotted lines represent the expected trends of the achieved diffusion coefficient versus time - see also comments below.

In Figure 17.3.4:1 the two dotted lines represent:

- the estimated trend solely based on the measured data.
- the trend when combining the one year expectation value of the achieved diffusion coefficient with the measured data.

The development of the chloride profiles for the splash zone of the Farø Bridges were calculated by using the error function solution, i.e. (3.2.1:3) and the Mejlbro-Poulsen model, i.e. (3.2.3:3). The parameters for the error function solution are D_a and C_{sa} as found for the 12 years profile, cf. Table 17.3.2:1. The two sets parameters for the Mejlbro-Poulsen model are given in Table 17.3.4:1.

Table 17.3.4:1. The basic parameters behind the curves in figure 17.3.4:2

Parameters	Set # 1	Set # 2 Unit
D_{aex}	142.6	114.2 mm²/yr
α	0.700	0.622 -
S_p	0.405	0.546 %mass
p	1.204	0.650 -

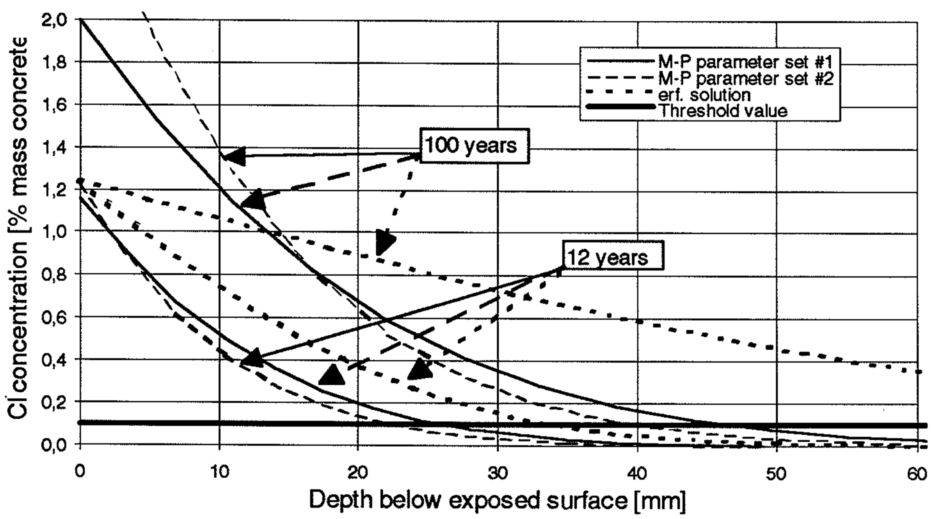


Figure 17.3.4:2. The development of chloride profiles in the splash zone of the Farø Brigdes estimated with two different mathematical models and with three set of parameters.

17.3.5 Predicted initiation period

In order to determine the best estimate of the time to initiation, the formula (15.2:5) is applied. From (17.3.4:1) it is known that $\Lambda_{0.65}(y_{cr}) = 1.15$ and then the initiation period yields:

$$t_{cr} = 0.5 \times \left(\frac{0.5 \times 50}{\sqrt{0.5 \times 114} \times 1.15} \right)^{5.3} \approx 135 \text{ years} \qquad (17.3.5:1)$$

Today (1997) the Farø Bridges are 15 years old, and therefore the residual initiation period yields:

$$\text{res}\{t_{cr}\} \approx 135 - 15 = 120 \text{ years} \qquad (17.3.5:2)$$

If the estimates of C_1 and D_1 were made from the "models" in Chapter 13 the corrosion domain and trend of the achieved diffusion coefficient versus time (Figure 17.3.4:1) would have changed a little but the expected residual initiation period would have shifted to 233 – 15 = 218 years.

17.3.6 Conclusion

The above shown determination of the residual initiation period is uncertain and that has been shown clearly by the comparative study of the effect of changing just a little in the data. It is evident, cf. Figure 17.3.3:1 and Figure 17.3.2:1, that the lack of observations during the first period of the service life, $t < 7$ years, makes it difficult to estimate the decisive parameters with a promissing accuracy. However, when the Farø Bridges were planned, designed and constructed, no information and guidelines existed of how to carry out inspection of marine structures with respect to chloride ingress into the concrete and service lifetime!

This example shows that it is important to inspect and examine a marine structure during the first 10 years of service life. The informations and observations gained during the first 10 years of service life are more important for the accuracy of the predicted lifetime than the next decade.

In the Figures 17.3.2:1 and 17.3.3:1 some dotted curves are shown . A few comments to those are given below:

- In Figure 17.3.2:1 the upper dotted line respresents the trend if the "models" of Chapter 13 were relied on (or had been used as design basis). From Chapter 13 it is known that that is a very uncertain procedure due to the rather poor estimates of the future parameters.
- The "lower" dotted line in Figure 17.3.2:1 (almost equal to the black line) shows the rather good agreement between the observed data, the extrapolation and the value of D_1, i.e. the achieved diffusion coefficient after 1 year of exposure estimated by using the "models" of Chapter 13 (i.e.(13.2.4:1')).
- The "lower" dotted curve in Figure 17.3.3:1 respresents the trend if the "models" of Chapter 13 were relied on (or had been used as design basis). From Chapter 13 it is known that this procedure is very uncertain due to the rather poor estimates of the future parameters.
- The "upper" dotted curve in Figure 17.3.3:1 shows the rather good agreement between the observed data and the value of C_1, i.e. the achieved surface concentration after 1 year of exposure estimated by using the "models" of Chapter 13 (i.e.(13.2.2:1')).

From the above it is seen that the models applied are suited for the traditional type of measurements and that the earlier more or less unexplainable differences in the observations from time to time can be modelled very well. It is also seen that the "models" for C_1 and D_1 in Chapter 13 also applies to other situations than those of the Träslövsläge marine exposure station. In fact a quite good agreement with the models *and* the observation was found in this case.

This is an example of the possibility for calibrating the model to existing structures when data from the different local environments are collected. This is treated further in Chapter 18.

18 Calibration with existing structures

The presented models provide the basis needed for enabling a calibration of the "models" developed in Chapter 13. Here it is shown how to perform such a calibration on the few available data from real structures.

The most obvious problem about the models developed in Chapter 13 is the lack of old data. Only data after about 2½ years of exposure in Träslövsläge were used to develop the models for predicting the 100 years achieved values of the surface concentration and the diffusion coefficient. This must be expected to introduce a lot of (unknown) uncertainty into the models. In this Chapter the first attempt to calibrate the models for predicting those 100 years values are presented. The available data are very few and the information too limited to replace the models of Chapter 13 at this stage. Therefore this chapter only serves as an example of how to make the calibration when more details data are available.

18.1 Available and usable data

The available data are those that have been published in the literature or have been produced by the ACCE consortium with rights to publishing. The usable data are those from the Danish or Southern Swedish climatic zone. Three existing structures of considerable ages (more than 10 years of exposure) have been analysed and from each of them data that can be used to calibrate the prediction models of Chapter 13 in the three local environments were chosen.

18.1.1 Data from Esbjerg Harbour

The BMB-group has made an investigation on a sheet pile that was part of a pier in Esbjerg Harbour. Because of the tide water the atmosphere zone was not represented on that structure. The concrete suffered from frost attack in the splash zone but the constantly submerged part of the structure may represent the submerged local environment.

The original concrete composition and details from the casting and curing etc. of the pile elements are not known precisely. The concrete composition therefore was determined by thin section analysis. The estimated original data are given in Table 18.1.1:1.

Table 18.1.1:1. The estimated original data for the investigated sheet pile from Esbjerg Harbour. The concrete composition was estimated by use of thin section analysis.

Cement	384	kg/m^3 concrete
Water	200	kg/m^3 concrete
Density	2255	kg/m^3
Age at exposure	28	days

Chloride profiles of the submerged zone were measured. From those data the achieved values of the diffusion coefficient and the surface boundary condition can be extracted.

In Figure 18.1.1:1 two measured chloride profiles and their descriptive parameters are shown.

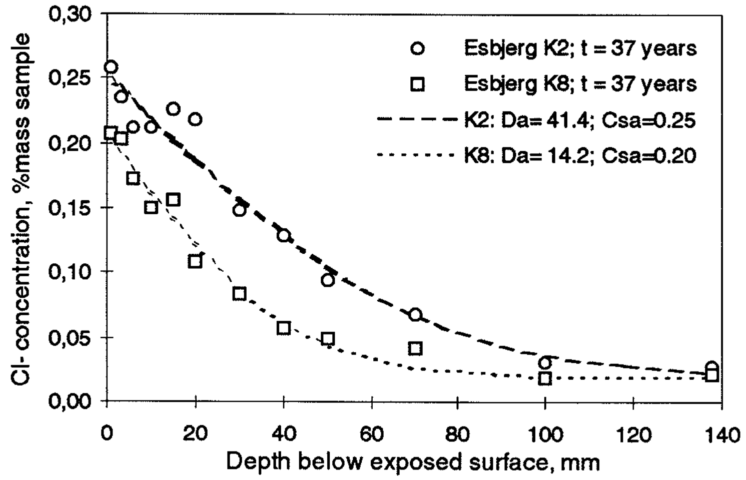


Figure 18.1.1:1 Two measured chloride profiles and their descriptive parameters for the sheet pile from Esbjerg Harbour. The units of the D_a and C_{sa} values on the graph are mm²/yr and % chloride by mass of dry sample (concrete) respectively. The corresponding graphs of the error function solution are shown as dotted curves.

18.1.2 Data from the Farø Bridges

The data from the splash zone of the Farø Bridges must be regarded as the best available published data sets from Denmark. The original data and the parameters D_a and C_{sa} for the chloride profiles are given in Chapter 17.

18.1.3 Data from the Vejle Fjord Bridge

The BMB-group has made an investigation on the pillar No. 8 in the atmosphere zone and in the splash zone. In the splash zone the concrete is made of slag cement. In the atmosphere zone, above level +2.3 m the concrete is made with SRPC.

The original concrete composition and details from the casting and curing etc. of the concrete in the atmosphere zone are not known precisely. The concrete composition therefore was estimated to be equal to that of the super structure. The estimated original data are given in Table 18.1.3:1.

Table 18.1.3:1. The estimated original data for the atmosphere zone of the Vejle Fjord Bridge. The concrete composition was estimated to be the same as used in the super structure.

Cement	415	kg/m³ concrete
Water	170	kg/m³ concrete
Density	2320	kg/m³
Age at exposure	14	days

Chloride profiles of the atmosphere zone were measured. From those data the achieved values of the diffusion coefficient and the surface boundary condition can be extracted. In Figure 18.1.3:1 two measured chloride profiles and their descriptive parameters are shown.

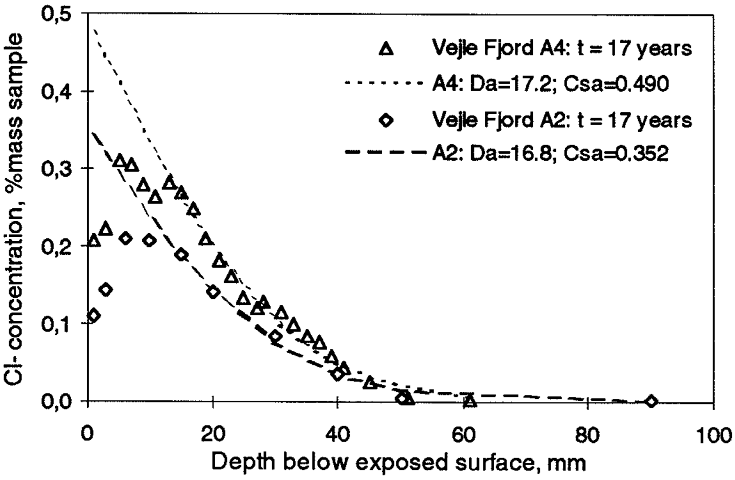


Figure 18.1.3:1 Two measured chloride profiles and their descriptive parameters for the pillar No. 8 of the Vejle Fjord Bridge. The units of the D_a and C_{sa} values on the graph are mm^2/yr and % chloride by mass of dry sample (concrete) respectively. The corresponding graphs of the error function solution are shown as dotted curves. The chloride measurements from the outer 15 mm have been omitted in the regression analysis of both profiles.

18.2 Calibration procedure

The goal of the calibration is to "adjust" the long time predictions that can be made from the empirical models of Chapter 13. Those models are based on a fairly short exposure time in Träslövsläge, cf. Chapter 13. It is now assumed that the estimation of the achieved parameters (C_1 and D_1) after 1 year of exposure in Träslövsläge is "precise" and valid for marine structures placed in Denmark. This makes it possible to obtain estimates of the development of the parameters C_{sa} and D_a from only one measurement (in time) on long time exposed structures.

The results of such a calibration are shown in Figures 18.2:1 and 18.2:2. The consequence of the calibration procedure on the models of Chapter 13 for the C_1, C_{100}, D_1 and D_{100} are shown by the arrows in the Figures.

The calibrated factors of the models in Chapter 13 are given in Table 18.2:1.

Table 18.2:1. The calibrated factors of the models in Chapter 13, cf. Tables 13.2.2:1 and 13.2.4:1.

	Calibrated values		
	Marine Submerged	Marine Splash	Marine Atmosphere
$k_{time! env}$	0.4	12	4.7
$k_{\alpha,env}$	3.1	1.6	1.3

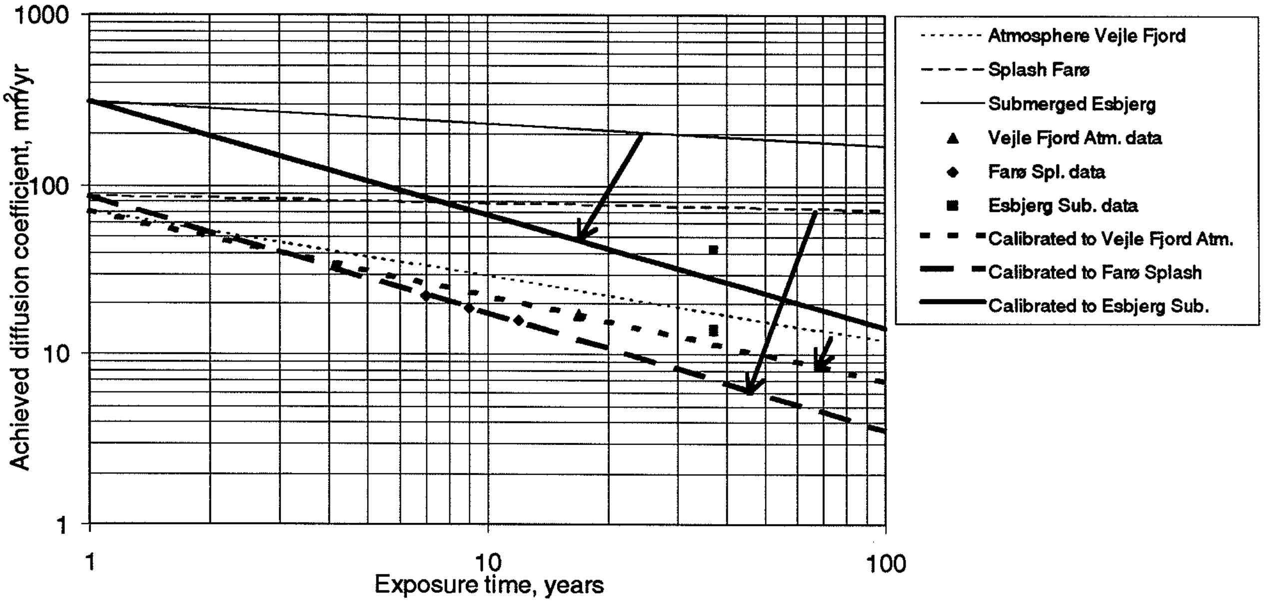


Figure 18.2:1. Graph of the expected development in time of the achieved chloride diffusion coefficient of concrete. Data points from three different local environments on three different real structures are shown together with trends predicted by the empirical models of Chapter 13 before and after calibration. The arrows show the effect of the calibration.

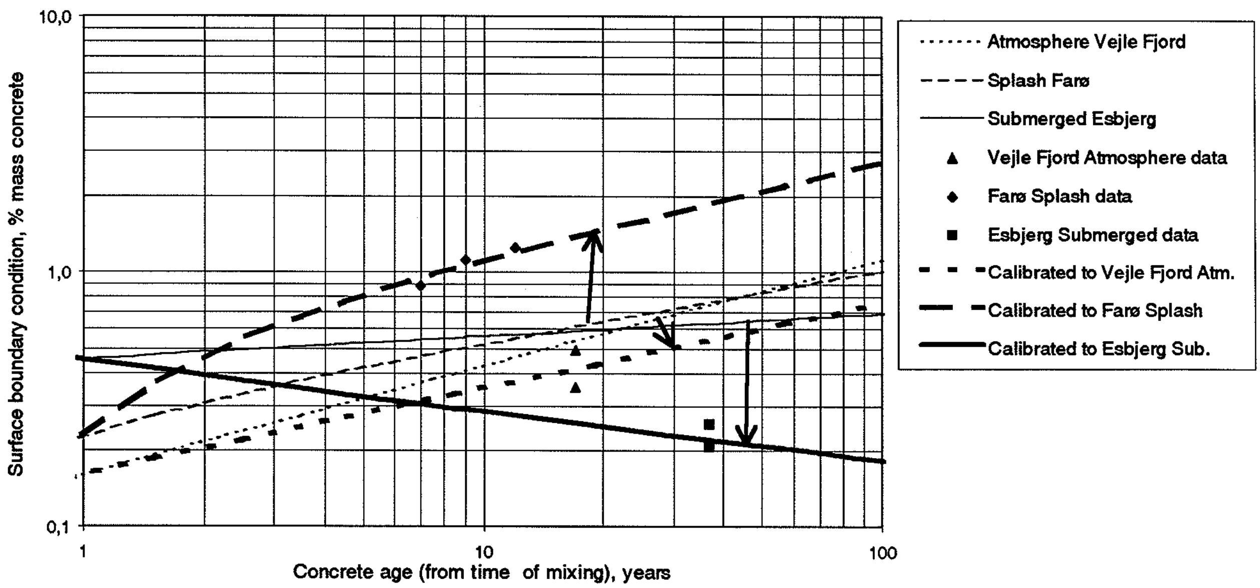


Figure 18.2:2. Graph of the expected development in time of the achieved surface chloride concentration of concrete. Data points from three different local environments on three different real structures are shown together with trends predicted by the empirical models of Chapter 13 before and after calibration. The arrows show the effect of the calibration.

18.3 Discussion

In Figure 18.2:1 and 18.2:2 expected trends of the achieved chloride diffusion coefficient and the achieved surface chloride concentration are shown for three different

- types of concrete,
- structures and
- local environments.

The graphs in Figure 18.2:1 all suggest that the predictions made with the models from Chapter 13 should be adjusted so that the decrease of the achieved diffusion coefficient with time are more pronounced, i.e. the diffusion coefficient should decrease more than predicted on the basis of the Träslövsläge measurements, cf. Chapter 13. The consequence of this would be a less conservative prediction, all other parameters equal.

The graphs representing the submerged and atmosphere zones in Figure 18.2:2 suggest that the predictions made with the models from Chapter 13 should be adjusted. In the atmosphere zone the increase of the achieved surface chloride concentration with time should be less pronounced, while in the submerged zone the achieved surface chloride concentration zone should reduce with time. That was also suggested by *ClinConc* in Chapter 6. The consequence of this would in both cases be a less conservative prediction, all other parameters equal.

For the splash zone the calibration acc. to Figure 18.2.:2 would lead to a more pronounced increase of the achieved surface chloride concentration. That would give a more conservative prediction for the splash zone, all other parameters equal.

Compared to the data of Träslövsläge, cf. Chapter 12 and 13, the data used here must be judged "better" because of their origin in old existing structures. On the other hand the data must be judged "poorer" than those of Träslövsläge because the three environmental zones only are represented by three different types of concrete of different age and in different environments. More data collected on the same type of concrete in the same structure but distributed in the three local marine environments as defined in this report are needed before the data of Träslövsläge can be "overruled" by data from real structures.

The most obvious benefit of this investigation is, that now it is reasonable to measure once on many different old structures in at least three different environments in stead of measuring many times on the same old structure. This is because the logarithmic behaviour of the decrease/increase of the governing parameters makes it impossible to gain general knowledge quickly from one structure.

19 Summary and conclusions

Most of the chapters of the report are concluded locally. Here the main results and conclusions for the report as a whole are highlihted.

19.1 The model basis

Three models describing chloride ingress into concrete have been presented:

- An empirically based analytical model called the *Mejlbro-Poulsen model* that is based on the complete solution to Fick's 2nd law , cf. Chapter 3.
- A scientifically based numerical model called *ClinConc* that is based on Fick's 2nd law, cf. Chapter 4.
- A semi-scientifically based numerical model for convection of chloride, cf. Chapter 7.

These models are regarded as up-to-date models representing the state-of-the-art for modelling chloride ingress into concrete. Qualitatively the models all perform well.

From field data the four governing parameters of the *Mejlbro-Poulsen model* can be estimated and the development of the profiles calculated with the same parameters can be performed with good agreement up to the exposure period of the field data. From that point the agreement can not be documented - naturally! The further development of the chloride ingress is however not in conflict with what is the suggestion of field data from the literature.

The *ClinConc* model is capable of modelling the chloride ingress into concrete in laboratory experiments and in short term field tests with a satisfying precision. The *ClinConc* model was in two examples (cf. Chapters 6 and 14) used to predict the future development of the chloride ingress into a type of concrete that is under test in the marine exposure station in Träslövsläge. The features of *ClinConc* are very sophisticated but it requires detailed knowledge of the physio-chemical behaviour of the type of binder used in the concrete. At present sufficient data only exist for few commercial cements and that obstruct the use of *ClinConc* in practical applications. At the moment *ClinConc* must be regarded as one of the most promising numerical models for the submerged zone.

A comparison of the Mejlbro-Poulsen model and the *ClinConc* model was demonstrated in Chapter 6. Large deviations were revealed. That was the first sign of the expected uncertainty of the models.

The *convection model* (capable of modelling simultaneous moisture flow and chloride diffusion and binding) should at this moment only be regarded as a "qualitative" model. In Chapter 7 a number of different situations have been modelled and the results are not in conflict with the engineering intuition. The results can at present be used as illustrative examples of typical types of exposure where convection is involved. Relevant test methods to provide regular input data for the convection model are still missing.

The effect of cracks perpendicular to the surface and *not* passing through the reinforcement cover was studied theoretically and it was found that over a unit distance less fine cracks (<0.1) are to be preferred compared many fine cracks, if the sum of the crack widths are constant. In other words: the crack width is of less importance than the number of cracks for this specific type cracking.

On the other hand it was in Chapter 9 stressed that it is very important to asses the risk of macro cell corrosion in partly submerged regions of a RC structure.

19.2 The data basis

The state of knowledge about threshold values for corrosion initiation is based on very scattered information. In spite of this the available data have been assembled and put into a detailed table that differentiates between w/b ratio, type of binder and type of environment.

Systematically data about the road environment is scarce, but the few data obtained during this HETEK sub-task have been evaluated and supported by preliminary results of the Swedish BTB project. It is evident that the road environment must be divided into two groups: the "wet" and the "dry" road environment. Indications of the variations with height and with time were found, cf. Chapter 11. It was also found that the Mejlbro-Poulsen model can be applied to the road environment in a similar way as done for the marine environment.

Intensive research about the marine environment have been performed during the last 5-7 years all over the world. One of the most comprehensive studies is the one performed by the Swedish BMB project in the Träslövsläge marine exposure station. Because of the unlimited access to and the relevance for the Danish marine environment, those data have been the most important basis for this report.

19.3 The design basis

After a rather intensive data processing it was possible to find a connection between the field data from the BMB project and the laboratory data from this HETEK sub-task. That is one of the greatest achievements of this project. Simple empirical expressions can now be used to estimate the decisive parameters in a durability design. The uncertainty of the predictions is however still the problem.

The *ClinConc* model was as an example used to find the depth of the threshold value for different exposure times in the submerged marine zone. From that stage and to the stage where the cover to the reinforcement can be designed some safety aspects must be included.

A way of handling the necessary safety level is presented in Chapter 15 and combined with the Mejlbro-Poulsen model in order to free the designer from numerical approaches.

In Chapter 16 it was illustrated how to make the durability design in the marine environment for an arbitrary concrete composition. At the same time it was shown by choosing one of the concrete types from the BMB project that the deviation from field observations is rather big if that approach is used.

In Chapter 17 it was illustrated how to asses the residual initiation period of an existing structure on the basis of the field observations on the particular structure solely and in combination with the empirical approaches from Chapter 13. Again it was discovered that the uncertainty of the prediction must be expected to be fairly large.

In Chapter 18 it was demonstrated how to calibrate the proposed models from Chapter 13 with data from existing structures. That is believed to be the fastest way ahead in order to improve the models. The investigation revealed that the models maybe are to be considered as conservative at the moment.

19.4 Main conclusion

The overall conclusion of the report is that the existence of a *complete system* for estimation of the chloride ingress now is documented, but careful and regular inspections must start from beginning of the initiation period, i.e. from the first exposure of the structure. The inspections should be made with logarithmic increasing time spans in order to make the inspections as cost-effective as possible.

It is believed that the studies on the Träslövsläge marine exposure station first will provide us with the needed data series and that that will strengthen the model and data basis significantly.

Calibration of the presented models can take place now. That is believed to improve the accuracy significantly. Both the technical and the economical benefits may be large.

20 Notation

This chapter contains a collection of the notation used throughout the report. The list below serves as "the rule". Deviations from these rules may however be found in the report.

Symbol	Unit[1]	Description and reference to definition in text
Latin Letters		
B	1	Empirical coefficient for chloride binding.
b	1	Empirical efficiency factor of a pozzolan - to be multiplied to the amount of pozzolan before addition with the amount of cement when calculating the equivalent cement content and the eqv $(w/c)_b$.
c	m	Thickness of concrete cover above reinforcement.
c_f	kg/m^3	Concentration of free chloride ions by volume of material.
c_b	kg/m^3	Concentration of bound chloride ions by volume of material.
c_{tot}	kg/m^3	Concentration of free and bound chloride ions by volume of material.
c'_f	kg/m^3	Concentration of free chlorides by volume of pore solution.
$c'_{f,s}$	kg/m^3	Concentration of free chlorides by volume of pore solution at saturation.
$C(x,t)$	mass%	Chloride concentration of concrete at a depth x beyond the concrete surface at the time t.
C_{cr}	mass%	Chloride threshold value.
C_f	mass%	Concentration of free chloride ions in material.
C_i	mass%	Initial chloride content of concrete.
C_r	mass%	Reference chloride content of concrete.
C_s	mass%	Surface chloride concentration of concrete.
C_{sa}	mass%	Surface chloride concentration of concrete, determined by regression analysis of an achieved chloride profile from natural exposure.
C_{sp}	mass%	Surface chloride concentration of concrete, determined by regression analysis of an chloride profile from a standard laboratory exposure.
C_1	mass%	Surface chloride concentration (boundary condition) of an achieved chloride profile after one year of natural exposure.

[1] Unless otherwise specified in text the stated unit is used.

C_{100}	mass%	Surface chloride concentration (boundary condition) of an achieved chloride profile after 100 years of natural exposure.
D	m^2/s	Diffusion coefficient.
D_0	m^2/s	The intrinsic diffusion coefficient, cf. Tang [1996].
D_a	m^2/s	Achieved transport coefficient characterising a chloride profile after a natural exposure for a non-specified time.
D_1	m^2/s	Achieved transport coefficient characterising a chloride profile after one year of natural exposure.
D_{100}	m^2/s	Achieved transport coefficient characterising a chloride profile after 100 years of natural exposure.
D_{acr}	m^2/s	The estimated critical value of D_a..
D_{aex}	m^2/s	Achieved transport coefficient characterising a chloride profile after a natural exposure at time t_{ex}.
D_{Cl}	m^2/s	Chloride ion diffusion coefficient in bulk solution.
D_{CTH}	m^2/s	Measured transport coefficient using the CTH migration test method.
D_{F1}	m^2/s	Diffusion coefficient in Fick's 1st law.
D_{F2}	m^2/s	Diffusion coefficient in Fick's 2nd law.
D_{OH}	m^2/s	Hydroxide ion diffusion coefficient in bulk solution.
D_p	m^2/s	Potential transport coefficient characterising a chloride profile after a standard exposure in laboratory for a non-specified time.
D_{pex}	m^2/s	Potential transport coefficient characterising a chloride profile after a standard exposure in laboratory at time t_{ex}.
e	1	Empirical efficiency factor of a pozzolan - to be multiplied to the amount of pozzolan before addition with the amount of cement when calculating the equivalent cement content and the eqv $(w/c)_{cr}$.
E_b	J/mol	Activation energy for chloride binding.
E_D	J/mol	Activation energy for chloride diffusivity.
eqv $(w/c)_b$	1	The equivalent w/c ratio with respect to the surface boundary conditions C_1 and C_{100}.
eqv $(w/c)_{cr}$	1	The equivalent w/c ratio with respect to the threshold value for corrosion initiation.
eqv $(w/c)_D$	1	The equivalent w/c ratio with respect to the achieved diffusion coefficient after one year of exposure D_1.
$f(x)$	1	Depth-dependent effect for chloride diffusivity.
f_b	1	Chloride binding parameter.
$f_D(T)$	1	Temperature-dependent coefficient for chloride diffusivity.
$g(t)$	1	Age-dependent function for chloride diffusivity.
$k_{\alpha, env}$	1	Factor encountering the effect of a local environment on the "time decrease factor" α.
$k_{b, env}$	1	Factor encountering the effect of a local environment on the surface boundary conditions C_1 and C_{100}.
$k_{cr, env}$	1	Factor encountering the effect of a local environment on the threshold value for corrosion initiation.

$k_{D,\,env}$	1	Factor encountering the effect of a local environment on the achieved diffusion coefficient after one year of exposure D_1.
k_{FA}	1	Efficiency factor of fly ash for chloride ingress.
k_P	s	Water permeability.
k_{RH}	kg/ms	Liquid flow coefficient.
k_{MS}	1	Efficiency factor of silica fume for chloride diffusivity.
K_b	1	Chloride binding coefficient.
$K_b(OH)$	1	Hydroxide binding coefficient.
$k_{time\,\vert\,env}$	1	Factor encountering the effect of time for a local environment on the surface boundary condition C_{100}.
m	kg	Mass.
p	1	Exponent mainly depending on environment and binder type.
p_{sol}	m^3/m^3	Porosity containing pore water that acts as a solute.
P_w	Pa	Pore water pressure.
q_{Cl}	kg/m^2s	Flux of chloride ions.
q_l	kg/m^2s	Liquid flow.
q_{tot}	kg/m^2s	Total moisture flow
q_v	kg/m^2s	Vapour flow.
$Q(total)$	kg/m^3	Total quantity of chloride ions.
R	J/(mol K)	Gas constant (8.31441 J/mol K).
s_{cap}	1	Degree of capillary saturation.
S	$mass\%/m^{2p}$	Variable depending on chloride aggressiveness of the environment, cement type and binder composition.
S_p	mass%	Parameter defined by equation (3.2.2:4).
t	s	Time.
t	s	The age of the concrete.
t_0	s	The age when the diffusion coefficient becomes constant.
t_{cr}	s	The initiation time for reinforcement corrosion.
t_{ex}	s	The time of exposure (to a chlorine environment).
t_{in}	s	The time of inspection.
t'	s	The duration of exposure (to chlorides).
Δt	s	The duration of exposure (to chlorides).
Δt	s	Small time interval.
T	K	Absolute temperature.
T_0	K	Reference temperature.
u	1	Integrand.
v	kg/m^3	Vapour concentration.
v_s	kg/m^3	Vapour concentration at saturation.
V_w	m^3/mole	Molar volume of water (18×10^{-6}).
w	m	Crack width.
w	kg/m^3	Moisture content.
w_{cap}	kg/m^3	Moisture content at capillary saturation.
w_{cr}	kg/m^3	Critical moisture content.
w_{nsol}	kg/m^3	Content of pore water that does not act as a solvent.
w_{sol}	kg/m^3	Content of pore water that acts as a solvent.
W_{gel}	1	CSH-gel content.
W_n	1	Non-evaporable water content.

x	m	Length coordinate.
x	m	Distance below the exposed concrete surface.
x_r	m	Depth below a chloride exposed concrete surface to which the reference chloride concentration has penetrated.
x_s	m	Thickness of surface zone in the depth dependent function $f(x)$.
x_{cr}	m	Depth below a chloride exposed concrete surface to which the critical chloride concentration has penetrated.

Greek Letters

α	1	A parameter describing the decrease with time of the achieved chloride diffusion coefficient.
α_h	1	Degree of hydration.
β	1	A parameter describing the change with time in the potential chloride diffusion coefficient.
β_t	1	A constant in the age dependent function $g(t)$.
β_x	1	A constant in the depth dependent function $f(x)$.
δ_{tot}	m^2/s	Total moisture flow coefficient.
δ_v	m^2/s	Vapour flow coefficient.
ε	1	Porosity.
ε_{air}	1	Air-filled porosity of concrete.
$\varepsilon_{capillary}$	1	Capillary porosity of concrete.
φ	%RH	Relative humidity of air.
φ_{eq}	%RH	Equivalent relative humidity.
φ_{sat}	%RH	Relative humidity above a saturated solution.
γ	1	A parameter describing the decrease with time of the ratio between D_a and D_p.
ρ	kg/m^3	Density (mass).
τ	1	Time parameter.
τ_{cr}	1	Time parameter, the value at t_{cr}.

Indices

0	Reference point (e.g. time or temperature)
s	Solid, surface.
sa	Surface, achieved.
l	Liquid.
m	Material, molecular.
b	Bound.
a	Achieved.
f	Free.
ex	Exposure.
$F1$	Ficks 1st law.
$F2$	Ficks 2nd law.
p	Potential and base of Mejlbro's Λ and Ψ functions.
x	Depth.
min	Minimum.

max	Maximum.
i	Initial.
cr	Critical.

Mathematical functions

erf	Error function.
erf^{-1}	Inverse of the error function.
erfc	Error function complement (1-erf).
$erfc^{-1}$	Inverse of the error function complement $(1\text{-erf})^{-1}$.
exp	Natural exponential function (exp 1 = 2.718281828...).
inv	Inverse function
ln	Natural logarithm.
$\log_{10}$	Logarithm to the base 10.
Λ_p	Mejlbro's Λ functions.
Ψ_p	Mejlbro's Ψ functions.

Abbrevations

w/b	kg/kg	Water/binder ratio (*water:* the total amount of free water in the mixture; *binder:* Portland cement, pulverized fuel ash, micro silica, and/or ground granulated blast furnace slag).
w/c	kg/kg	Water/cement ratio (water: the total amount of free water in the mixture; *cement:* Portland cement).
ACCE		AEC, Chalmers, CEmenta.
BMB		"Beständighet Marina Betongkonstruktioner" - A Swedish research programme.
BTB		"Beständighet Tösaltade Betongkonstruktioner" - A Swedish research programme.
CE		Cement.
ClinConc		A Windows program (Chloride in Concrete).
eqv		Equivalent.
FA		Fly ash.
FDM		Finite Difference Method.
NT		Nordtest.
pH		Acidity (pH-value).
HETEK		The abbrevation for the Danish research project High Performance Concrete - Contractor Technology (in Danish: Højkvalitetsbeton - Entreprenørens TEKnologi.)
OPC		Ordinary portland cement
RH		Relative humidity
SF		Silica fume.
SRPC		Sulphate-resisting portland cement.
TOW		Time Of Wetness.

21 References

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Appendix

This appendix gives the results from ourve-fitting of the Mejlbro-Poulsen model on data obtained in the BMB-projeot from the marine field exposure station in Träslövsläge, Sweden.

The basis for the results are explained in Chapter 6.6 and the results are used in Chaptes 12 and 13. The mix designs are given in Chapter 12.

The various concrete types and exposure zones are each presented on a single page listed in the following order:

Concrete type	Exposure zone
3-75	Submerged
1-50	Submerged
1-50	Splash
1-50	Atmosphere
2-50	Submerged
3-50	Submerged
Ö	Submerged
Ö	Splash
Ö	Atmosphere
2-40	Submerged
2-40	Splash
2-40	Atmosphere
3-40	Submerged
3-40	Splash
3-40	Atmosphere
H4	Submerged
H4	Splash
H4	Atmosphere
10-40	Submerged
10-40	Splash
10-40	Atmosphere

Concrete type	Exposure zone
10-35	Submerged
10-35	Splash
10-35	Atmosphere
H3	Submerged
H3	Splash
H3	Atmosphere
H1	Submerged
H1	Splash
H1	Atmosphere
H2	Submerged
H2	Splash
H2	Atmosphere
H8	Submerged
H8	Splash
H8	Atmosphere
H5	Submerged
H5	Splash
H5	Atmosphere

Basic properties of some of the concretes from the Träslövsläge marine exposure station. The obtained chloride profiles from the natural exposure of these concretes are given on the following pages.

ID Number	w/b ratio	Cement	Silica fume	Fly ash	Water	Cement paste	Cementitious content	Calculated density
3-75	0.75	232.8	12.3	0.0	184.0	26.3	12%	2109
1-50	0.50	370.0	0.0	0.0	185.0	30.2	17%	2152
2-50	0.50	390.0	0.0	0.0	195.0	31.9	18%	2134
3-50	0.50	351.5	18.5	0.0	185.0	30.5	17%	2145
Ô	0.38	420.0	0.0	0.0	159.6	29.3	19%	2217
2-40	0.40	420.0	0.0	0.0	168.0	30.1	19%	2217
3-40	0.40	399.0	21.0	0.0	168.0	30.4	19%	2210
H4	0.40	399.0	21.0	0.0	168.0	30.4	19%	2210
10-40	0.35	345.0	20.5	75.0	155.2	30.8	20%	2205
12-35	0.33	382.5	22.5	45.0	146.5	29.9	20%	2245
H3	0.30	492.0	0.0	0.0	148.0	30.4	20%	2460
H1	0.30	475.0	25.0	0.0	150.0	31.2	20%	2448
H2	0.30	450.0	50.0	0.0	150.0	31.6	21%	2439
H8	0.26	493.0	0.0	123.0	159.0	37.1	26%	2399
H5	0.25	525.0	26.3	0.0	137.8	31.6	22%	2501
Unit	by mass	kg/m^3 concrete	kg/m^3 concrete	kg/m^3 concrete	kg/m^3 concrete	% volume concrete	% mass concrete	kg/m^3 concrete

Estimation of Chloride Ingress into Concrete

Model developed by Ervin Poulsen and Leif Mejlbro. Programmed by Jens M. Frederiksen.

AEClaboratory
Staktoften 20
DK-2950 Vedbæk

Sample identification
Träslövsläge: 3-75 (submerg.)

Date: 1997-03-20
Time: 16:08
Init: HES

Input

Basic constants

t_{ex} =	0,04	yr
C_i =	0	% mass
w/c =	0,75	[-]

Calculated parameter

D_{pex} =	1298	mm^2/yr

Governing parameters

α =	1,000	[-]
S =	0,450	$\%mass/mm^{2p}$
S_p =	0,450	%mass
p =	0,000	[-]
k_D =	6,848	[-]

Measured profiles, natural exposure

t_{in} [yr] = 0,822		t_{in} [yr] = 0,000		t_{in} [yr] = 1,241	
x [mm]	$C(x,t)$ [% mass]	x [mm]	$C(x,t)$ [% mass]	x [mm]	$C(x,t)$ [% mass]
1,5	0,419			1,5	0,487
3	0,362			3	0,396
5	0,337			5	0,374
7	0,349			7	0,381
10	0,320			10	0,364
15	0,270			15	0,219
20	0,206			20	0,185
30	0,104			30	0,100
				40	0,055

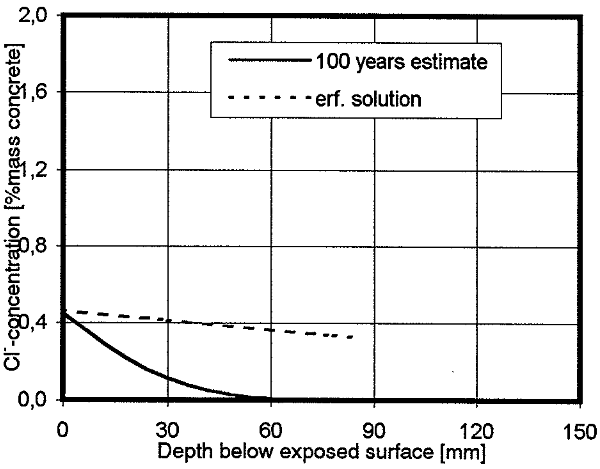
Parameters for each chloride profile

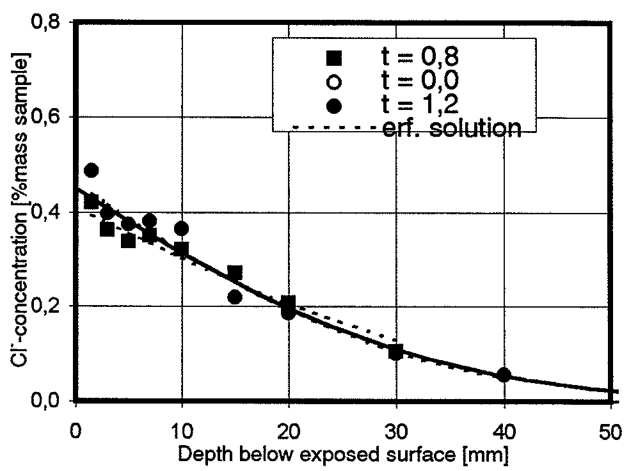
	Estimate	Da = 527,8 Csa=0,411	Da = 193,4 Csa=0,519	Da = 244,0 Csa=0,462
t =	100 yr	0,8		1,2
$D_a(t)$ =	3,4 mm^2/yr	414,7		274,6
C_{sa} =	0,450 w/w %	0,450		0,450
Δx =	6 mm	6	6	6

Estimated chloride profile / Calculated chloride profiles (Mejlbro-Poulsen)

x	$C(x,t)$	erf-sol. $C(x,t)$	x	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$
0	0,450	0,462	0	0,450			0	0,450
6	0,368	0,452	6	0,366			6	0,367
12	0,291	0,442	12	0,287			12	0,288
18	0,221	0,432	18	0,216			18	0,218
24	0,161	0,422	24	0,156			24	0,158
30	0,113	0,412	30	0,108			30	0,109
36	0,076	0,402	36	0,071			36	0,073
42	0,048	0,392	42	0,045			42	0,046
48	0,030	0,382	48	0,027			48	0,028
54	0,017	0,373	54	0,015			54	0,016
60	0,010	0,363	60	0,008			60	0,009
66	0,005	0,353	66	0,004			66	0,005
72	0,003	0,344	72	0,002			72	0,002
78	0,001	0,334	78	0,001			78	0,001
84	0,001	0,325	84	0,000			84	0,000

C_1 = 0,450 D_1 = 340,9 C_{100} = 0,450 D_{100} = 3,4





Estimation of Chloride Ingress into Concrete

Model developed by Ervin Poulsen and Leif Mejlbro. Programmed by Jens M. Frederiksen.

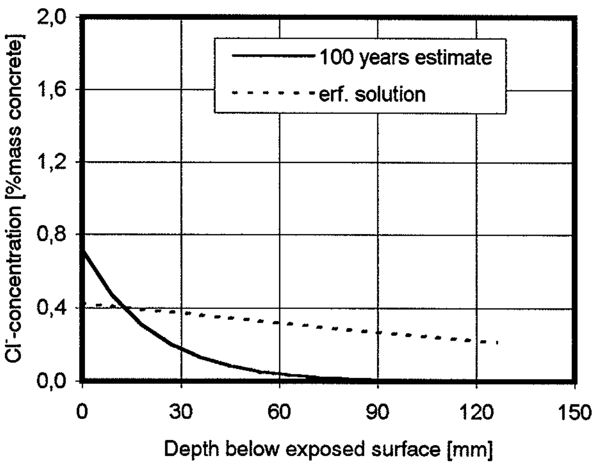
AEClaboratory		Date: 1997-03-24
Staktoften 20	**Sample identification**	Time: 16:32
DK-2950 Vedbæk	Träslövsläge: 1-50 (zone Su)	Init: HES

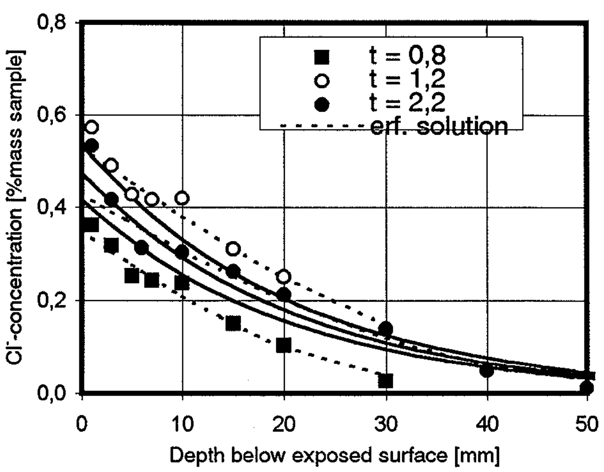
Input			**Measured profiles, natural exposure**					
Basic constants			t_{in} [yr] =	0,822	t_{in} [yr] =	1,241	t_{in} [yr] =	2,184
t_{ex} =	0,04	yr	x	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$
C_i =	0,000	% mass	[mm]	[% mass]	[mm]	[% mass]	[mm]	[% mass]
w/c =	0,50	[-]	1	0,362	1	0,573	1	0,533
Calculated parameter			3	0,317	3	0,490	3	0,417
D_{pex} =	571	mm^2/yr	5	0,253	5	0,427	6	0,313
Governing parameters			7	0,243	7	0,416	10	0,304
α =	0,993	[-]	10	0,237	10	0,420	15	0,262
S =	0,000	$\%mass/mm^{2p}$	15	0,150	15	0,311	20	0,212
S_p =	0,498	%mass	20	0,104	20	0,251	30	0,138
p =	6,753	[-]	30	0,026	30	0,139	40	0,050
k_D =	142,758	[-]					50	0,012

Parameters for eaoh ohloride profile			Da = 219,2	Csa=0,350	Da = 313,9	Csa=0,529	Da = 177,5	Csa=0,427
t =	100	yr	t =	0,8	t =	1,2	t =	2,2
$D_a(t)$ =	33,0	mm^2/yr	$D_a(t)$ =	3886,3	$D_a(t)$ =	2581,1	$D_a(t)$ =	1472,5
C_{sa} =	0,716	w/w %	C_{sa} =	0,416	C_{sa} =	0,473	C_{sa} =	0,533
Δx =	9	mm	Δx =	6	Δx =	6	Δx =	7

Estimated ohloride profile		**erf-sol.**	**Calculated chloride profiles (Mejlbro-Poulsen)**					
x	$C(x,t)$	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$
0	0,716	0,427	0	0,416	0	0,473	0	0,533
9	0,472	0,411	6	0,311	6	0,355	7	0,383
18	0,309	0,395	12	0,232	12	0,266	14	0,273
27	0,201	0,378	18	0,173	18	0,199	21	0,195
36	0,130	0,362	24	0,128	24	0,148	28	0,138
45	0,083	0,346	30	0,095	30	0,110	35	0,098
54	0,053	0,331	36	0,070	36	0,081	42	0,069
63	0,034	0,315	42	0,051	42	0,060	49	0,048
72	0,021	0,300	48	0,038	48	0,044	56	0,033
81	0,013	0,285	54	0,027	54	0,032	63	0,023
90	0,008	0,270	60	0,020	60	0,023	70	0,016
99	0,005	0,256	66	0,015	66	0,017	77	0,011
108	0,003	0,242	72	0,010	72	0,012	84	0,008
117	0,002	0,228	78	0,008	78	0,009	91	0,005
126	0,001	0,215	84	0,005	84	0,006	98	0,004

C_1 =	0,445	D_1 =	3198,6	C_{100} =	0,716	D_{100} =	33,0





Estimation of Chloride Ingress into Concrete

Model developed by Ervin Poulsen and Leif Mejlbro. Programmed by Jens M. Frederiksen.

AEClaboratory
Staktoften 20
DK-2950 Vedbæk

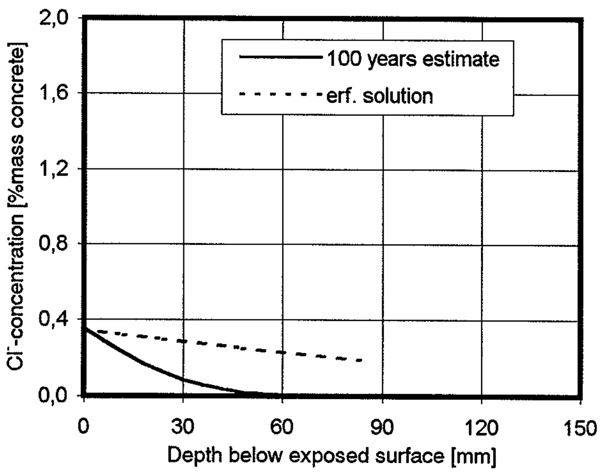
Date: 1997-03-20
Time: 11:48
Init: HES

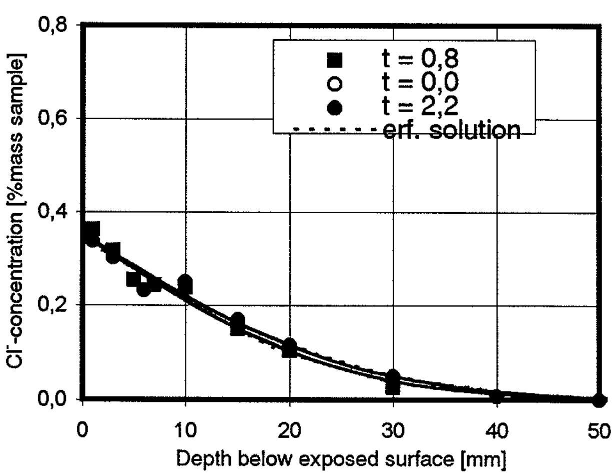
Sample identification
Träslövsläge: 1-50 (zone Sp)

Input			**Measured profiles, natural exposure**					
Basic constants			t_{in} [yr] =	0,822	t_{in} [yr] =		t_{in} [yr] =	2,184
t_{ex} =	0,04	yr	x	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$
C_i =	0	% mass	[mm]	[% mass]	[mm]	[% mass]	[mm]	[% mass]
w/c =	0,50	[-]	1	0,362			1	0,337
Calculated parameter			3	0,317			3	0,302
D_{pex} =	571	mm^2/yr	5	0,253			6	0,231
Governing parameters			7	0,243			10	0,250
α =	0,881	[-]	10	0,237			15	0,168
S =	0,352	$\%mass/mm^{2p}$	15	0,150			20	0,114
S_p =	0,352	%mass	20	0,104			30	0,049
p =	0,000	[-]	30	0,026			40	0,007
k_D =	5,947	[-]					50	0,000

Parameters for each chloride profile			Da = 203,1	Csa=0,362	Da = 1,0	Csa=0,000	Da = 101,1	Csa=0,343
t =	100	yr	t =	0,8	t =	0,0	t =	2,2
$D_a(t)$ =	3,3	mm^2/yr	$D_a(t)$ =	228,2	$D_a(t)$ =		$D_a(t)$ =	96,5
C_{sa} =	0,352	w/w %	C_{sa} =	0,352	C_{sa} =		C_{sa} =	0,352
Δx =	6	mm	Δx =	4	Δx =		Δx =	4

Estimated chloride profile		**erf-sol.**	**Calculated chloride profiles (Mejlbro-Poulsen)**					
x	$C(x,t)$	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$
0	0,352	0,343	0	0,352			0	0,352
6	0,288	0,331	4	0,293			4	0,298
12	0,226	0,319	8	0,237			8	0,245
18	0,171	0,308	12	0,185			12	0,196
24	0,124	0,297	16	0,140			16	0,152
30	0,086	0,285	20	0,102			20	0,115
36	0,057	0,274	24	0,072			24	0,084
42	0,036	0,263	28	0,049			28	0,060
48	0,022	0,252	32	0,032			32	0,041
54	0,013	0,241	36	0,020			36	0,027
60	0,007	0,231	40	0,012			40	0,017
66	0,004	0,220	44	0,007			44	0,011
72	0,002	0,210	48	0,004			48	0,006
78	0,001	0,200	52	0,002			52	0,004
84	0,000	0,190	56	0,001			56	0,002
C_1 =	0,352	D_1 =	192,0		C_{100} =	0,352	D_{100} =	3,3





Estimation of Chloride Ingress into Concrete

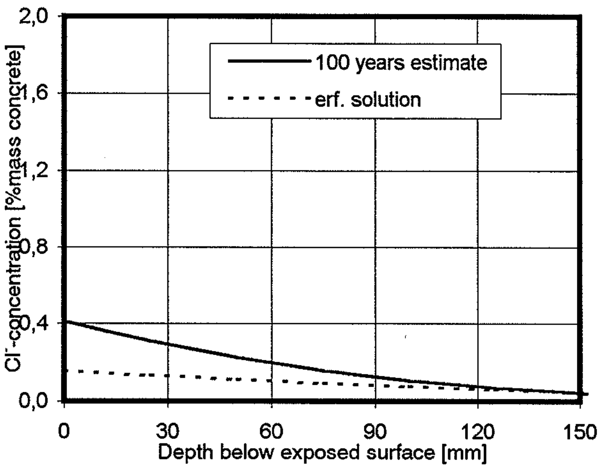
Model developed by Ervin Poulsen and Leif Mejlbro. Programmed by Jens M. Frederiksen.

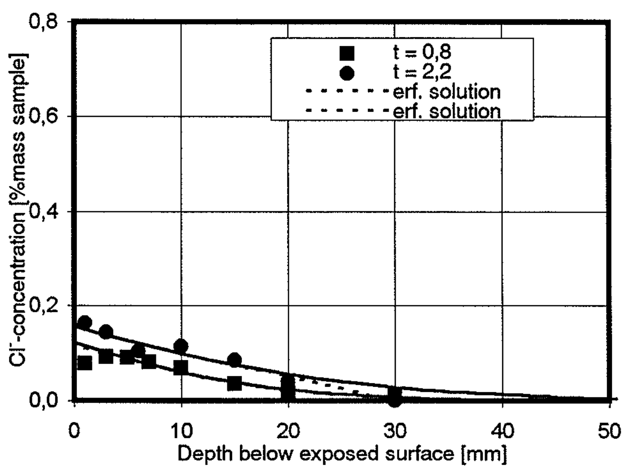
AEClaboratory		Date: 1997-03-26
Staktoften 20	**Sample identification**	Time: 20:52
DK-2950 Vedbæk	Träslövsläge: 1-50 (zone At)	Init: HES

Input			**Measured profiles, natural exposure**					
Basic constants			t_{in} [yr] =	0,822	t_{in} [yr] =		t_{in} [yr] =	2,184
t_{ex} =	0,04	yr	x	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$
C_i =	0	% mass	[mm]	[% mass]	[mm]	[% mass]	[mm]	[% mass]
w/c =	0,50	[-]	1	0,077			1	0,162
Calculated parameter			3	0,091			3	0,141
D_{pex} =	571	mm²/yr	5	0,089			6	0,102
Governing parameters			7	0,079			10	0,112
α =	0,278	[-]	10	0,067			15	0,084
S =	0,019	%mass/mm^{2P}	15	0,035			20	0,041
S_p =	0,057	%mass	20	0,017			30	0,000
p =	0,347	[-]	30	0,012				
k_D =	0,875	[-]						

Parameters for each chloride profile			Da = 151,2	Csa=0,115	Da = 313,9	Csa=0,529	Da = 103,3	Csa=0,154
t =	100	yr	t =	0,8	t =		t =	2,2
$D_a(t)$ =	56,0	mm²/yr	$D_a(t)$ =	213,1	$D_a(t)$ =		$D_a(t)$ =	162,4
C_{sa} =	0,408	w/w %	C_{sa} =	0,121	C_{sa} =		C_{sa} =	0,156
Δx =	25	mm	Δx =	3	Δx =	0	Δx =	5

Estimated chloride profile		**erf-sol.**	**Calculated chloride profiles (Mejlbro-Poulsen)**					
x	$C(x,t)$	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$
0	0,408	0,154	0	0,121			0	0,156
25	0,307	0,132	3	0,099			5	0,124
50	0,223	0,112	6	0,080			10	0,097
75	0,157	0,092	9	0,064			15	0,074
100	0,105	0,075	12	0,050			20	0,055
125	0,068	0,059	15	0,039			25	0,040
150	0,042	0,046	18	0,029			30	0,028
175	0,025	0,034	21	0,021			35	0,019
200	0,014	0,025	24	0,015			40	0,013
225	0,008	0,018	27	0,011			45	0,008
250	0,004	0,013	30	0,008			50	0,005
275	0,002	0,009	33	0,005			55	0,003
300	0,001	0,006	36	0,003			60	0,002
325	0,000	0,004	39	0,002			65	0,001
350	0,000	0,002	42	0,001			70	0,001
C_1 =	0,127	D_1 =	201,8		C_{100} =	0,408	D_{100} =	56,0





Estimation of Chloride Ingress into Concrete

Model developed by Ervin Poulsen and Leif Mejlbro. Programmed by Jens M. Frederiksen.

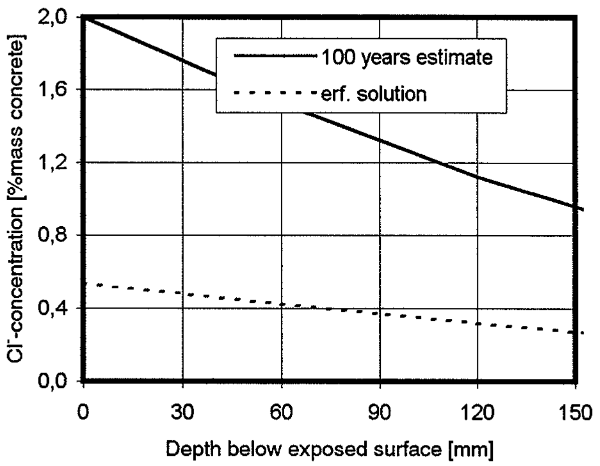
AEClaboratory		Date: 1997-03-26
Staktoften 20	**Sample identification**	Time: 20:50
DK-2950 Vedbæk	Träslövsläge 2-50 Submerged	Init: HES

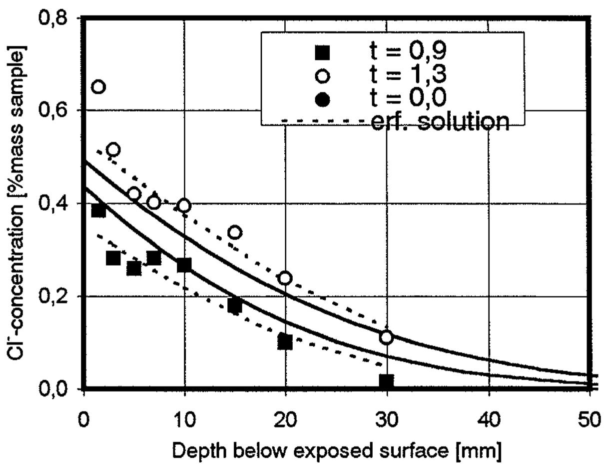
Input			**Measured profiles, natural exposure**					
Basic constants			t_{in} [yr] =	0,953	t_{in} [yr] =	1,373	t_{in} [yr] =	0,000
t_{ex} =	0,038	yr	x	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$
C_i =	0	% mass	[mm]	[% mass]	[mm]	[% mass]	[mm]	[% mass]
w/c =	0,50	[-]	1,5	0,383	1,5	0,650		
Calculated parameter			3,0	0,282	3,0	0,514		
D_{pex} =	571	mm^2/yr	5,0	0,260	5,0	0,419		
Governing parameters			7,0	0,281	7,0	0,402		
α =	0,000	[-]	10,0	0,266	10,0	0,394		
S =	0,057	$\%mass/mm^{2p}$	15,0	0,179	15,0	0,337		
S_p =	0,155	%mass	20,0	0,099	20,0	0,238		
p =	0,325	[-]	30,0	0,015	30,0	0,110		
k_D =	0,591	[-]						

Parameters for each chloride profile			Da = 228,6	Csa=0,351	Da = 251,4	Csa=0,539	Da = 1,0	Csa=0,000
t =	100	yr	t =	0,9	t =	1,3	t =	0,0
$D_a(t)$ =	337,7	mm^2/yr	$D_a(t)$ =	337,7	$D_a(t)$ =	337,7	$D_a(t)$ =	
C_{sa} =	2,000	w/w %	C_{sa} =	0,435	C_{sa} =	0,492	C_{sa} =	
Δx =	60	mm	Δx =	5	Δx =	6	Δx =	7

Estimated chloride profile		**erf-sol.**	**Calculated chloride profiles (Mejlbro-Poulsen)**					
x	$C(x,t)$	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$
0	2,000	0,539	0	0,435	0	0,492		
60	1,523	0,425	5	0,344	6	0,389		
120	1,121	0,319	10	0,265	12	0,300		
180	0,797	0,227	15	0,199	18	0,226		
240	0,545	0,153	20	0,145	24	0,165		
300	0,359	0,097	25	0,103	30	0,117		
360	0,227	0,058	30	0,071	36	0,081		
420	0,137	0,033	35	0,047	42	0,054		
480	0,080	0,017	40	0,030	48	0,035		
540	0,044	0,009	45	0,019	54	0,022		
600	0,024	0,004	50	0,011	60	0,013		
660	0,012	0,002	55	0,007	66	0,008		
720	0,006	0,001	60	0,004	72	0,004		
780	0,003	0,000	65	0,002	78	0,002		
840	0,001	0,000	70	0,001	84	0,001		

C_1 =	0,442	D_1 =	337,7	C_{100} =	2,000	D_{100} =	337,7





Estimation of Chloride Ingress into Concrete

Model developed by Ervin Poulsen and Leif Mejlbro. Programmed by Jens M. Frederiksen.

AEClaboratory		Date:	1997-03-26
Staktoften 20	**Sample identification**	Time:	20:58
DK-2950 Vedbæk	Träslövsläge 3-50 Submerged	Init:	JMF

Input / **Measured profiles, natural exposure**

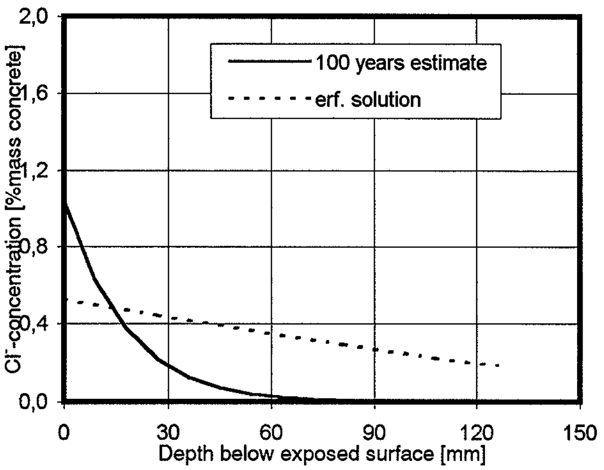
Basic constants			t_{in} [yr] =	0,819	t_{in} [yr] =	1,238	t_{in} [yr] =	2,219
t_{ex} =	0,038	yr	x	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$
C_i =	0	% mass	[mm]	[% mass]	[mm]	[% mass]	[mm]	[% mass]
w/c =	0,50	[-]	1,0	0,556	1,0	0,705	1,0	0,618
Calculated parameter			3,0	0,358	3,0	0,459	3,0	0,469
D_{pex} =	571	mm^2/yr	5,0	0,281	5,0	0,405	6,0	0,419
Governing parameters			7,0	0,266	7,0	0,406	10,0	0,285
α =	0,973	[-]	10,0	0,263	10,0	0,359	15,0	0,246
S =	0,000	%mass/mm^{2p}	15,0	0,168	15,0	0,250	20,0	0,196
S_p =	0,391	%mass	20,0	0,095	20,0	0,171	30,0	0,066
p =	4,693	[-]	30,0	0,023	30,0	0,095	40,0	0,019
k_D =	59,959	[-]					50,0	0,012

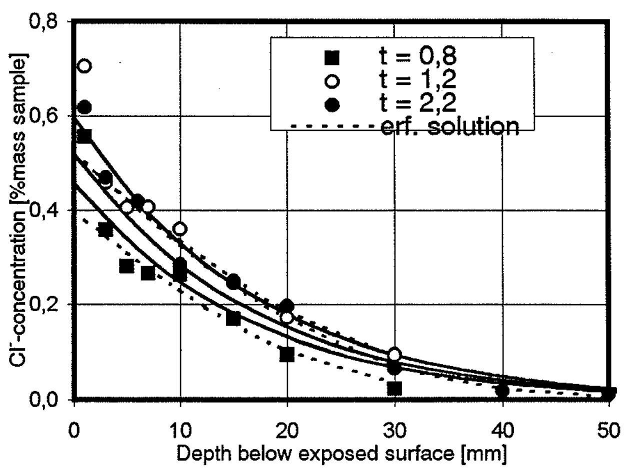
Parameters for each chloride profile			Da = 204,3	Csa=0,398	Da = 199,5	Csa=0,519	Da = 94,8	Csa=0,525
t =	100	yr	t =	0,8	t =	1,2	t =	2,2
$D_a(t)$ =	16,2	mm^2/yr	$D_a(t)$ =	1739,2	$D_a(t)$ =	1163,1	$D_a(t)$ =	659,2
C_{sa} =	1,040	w/w %	C_{sa} =	0,457	C_{sa} =	0,520	C_{sa} =	0,597
Δx =	9	mm	Δx =	6	Δx =	6	Δx =	6

Estimated chloride profile / **erf-sol.** / **Calculated chloride profiles (Mejlbro-Poulsen)**

x	$C(x,t)$	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$
0	1,039	0,525	0	0,457	0	0,520	0	0,597
9	0,628	0,498	6	0,317	6	0,363	6	0,419
18	0,374	0,470	12	0,219	12	0,251	12	0,292
27	0,220	0,443	18	0,149	18	0,173	18	0,202
36	0,128	0,417	24	0,102	24	0,118	24	0,139
45	0,073	0,390	30	0,068	30	0,080	30	0,095
54	0,041	0,365	36	0,046	36	0,054	36	0,064
63	0,023	0,340	42	0,030	42	0,036	42	0,043
72	0,013	0,315	48	0,020	48	0,024	48	0,029
81	0,007	0,292	54	0,013	54	0,016	54	0,019
90	0,004	0,269	60	0,009	60	0,010	60	0,013
99	0,002	0,248	66	0,005	66	0,007	66	0,008
108	0,001	0,227	72	0,004	72	0,004	72	0,005
117	0,000	0,208	78	0,002	78	0,003	78	0,003
126	0,000	0,189	84	0,001	84	0,002	84	0,002

C_1 =	0,489	D_1 =	1432,2	C_{100} =	1,040	D_{100} =	16,2





Estimation of Chloride Ingress into Concrete

Model developed by Ervin Poulsen and Leif Mejlbro. Programmed by Jens M. Frederiksen.

AEClaboratory	**Sample identification**	Date: 1997-03-24
Staktoften 20	Träslövsläge: Ö (zone Su)	Time: 13:56
DK-2950 Vedbæk		Init: JMF

Input

Basic constants		
t_{ex} =	0,04	yr
C_i =	0	% mass
w/c =	0,40	[-]
Calculated parameter		
D_{pex} =	337	mm^2/yr
Governing parameters		
α =	1,000	[-]
S =	0,000	%mass/mm^{2P}
S_p =	0,749	%mass
p =	4,206	[-]
k_D =	48,200	[-]

Measured profiles, natural exposure

t_{in} [yr] =	0,614	t_{in} [yr] =	1,033	t_{in} [yr] =	2,014
x [mm]	$C(x,t)$ [% mass]	x [mm]	$C(x,t)$ [% mass]	x [mm]	$C(x,t)$ [% mass]
0,5	0,730	0,5	0,763	1	0,710
1,5	0,607	1,5	0,517	3	0,503
3	0,434	3	0,389	6	0,394
5	0,348	5	0,354	10	0,327
10	0,247	10	0,300	15	0,239
15	0,121	15	0,166	20	0,165
20	0,048	20	0,084	30	0,065
30	0,009	30	0,014	40	0,000
				50	0,000

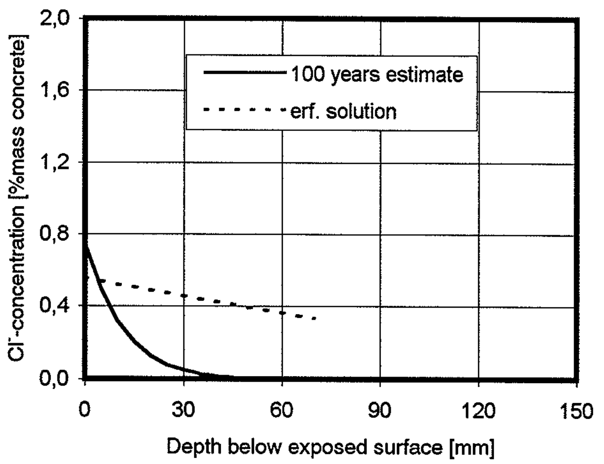
Parameters for each chloride profile

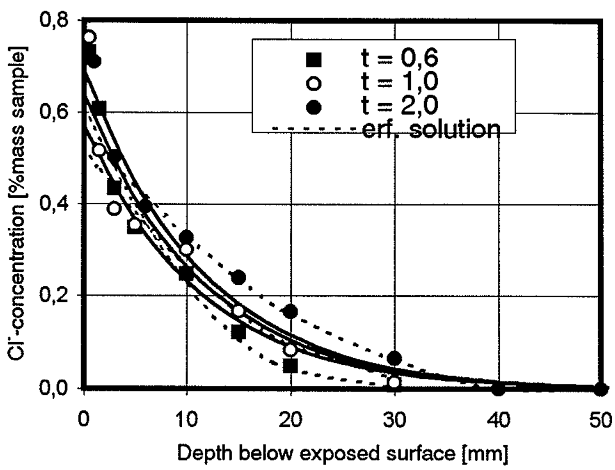
		Da = 106,8	Csa=0,609	Da = 114,2	Csa=0,515	Da = 90,1	Csa=0,555
t =	100 yr	t =	0,6	t =	1,0	t =	2,0
$D_a(t)$ =	6,2 mm^2/yr	$D_a(t)$ =	1014,9	$D_a(t)$ =	603,0	$D_a(t)$ =	309,3
C_{sa} =	0,748 w/w %	C_{sa} =	0,571	C_{sa} =	0,639	C_{sa} =	0,691
Δx =	5 mm	Δx =	5	Δx =	5	Δx =	5

Estimated chloride profile / Calculated chloride profiles (Mejlbro-Poulsen)

x	$C(x,t)$	erf-sol. $C(x,t)$	x	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$
0	0,747	0,555	0	0,571	0	0,639	0	0,691
5	0,487	0,538	5	0,367	5	0,413	5	0,448
10	0,314	0,522	10	0,233	10	0,264	10	0,288
15	0,200	0,505	15	0,146	15	0,167	15	0,183
20	0,126	0,489	20	0,091	20	0,104	20	0,115
25	0,079	0,473	25	0,056	25	0,064	25	0,071
30	0,049	0,457	30	0,034	30	0,039	30	0,044
35	0,030	0,441	35	0,020	35	0,024	35	0,026
40	0,018	0,425	40	0,012	40	0,014	40	0,016
45	0,011	0,409	45	0,007	45	0,008	45	0,009
50	0,006	0,394	50	0,004	50	0,005	50	0,005
55	0,004	0,378	55	0,002	55	0,003	55	0,003
60	0,002	0,363	60	0,001	60	0,002	60	0,002
65	0,001	0,348	65	0,001	65	0,001	65	0,001
70	0,001	0,334	70	0,000	70	0,000	70	0,001

C_1 = 0,635 D_1 = 622,8 C_{100} = 0,748 D_{100} = 6,2





Estimation of Chloride Ingress into Concrete

Model developed by Ervin Poulsen and Leif Mejlbro. Programmed by Jens M. Frederiksen.

AEClaboratory
Staktoften 20
DK-2950 Vedbæk

Sample identification	
Träslövsläge:	Ö (splash zone)

Date: 1997-03-24
Time: 13:56
Init: JMF

Input

Basic constants

t_{ex} =	0,04	yr
C_i =	0,000	% mass
w/c =	0,40	[-]

Calculated parameter

D_{pex} =	337	mm^2/yr

Governing parameters

α =	0,967	[-]
S =	0,000	$\%mass/mm^{2p}$
S_p =	0,318	%mass
p =	7,098	[-]
k_D =	61,486	[-]

Measured profiles, natural exposure

t_{in} [yr] =	0,614	t_{in} [yr] =		t_{in} [yr] =	2,014
x [mm]	$C(x,t)$ [% mass]	x [mm]	$C(x,t)$ [% mass]	x [mm]	$C(x,t)$ [% mass]
1	0,197			1	0,762
3	0,178			3	0,512
5	0,151			6	0,435
7	0,128			10	0,297
10	0,078			15	0,274
15	0,030			20	0,164
20	0,013			30	0,034
30	0,009			40	0,001
				50	0,000

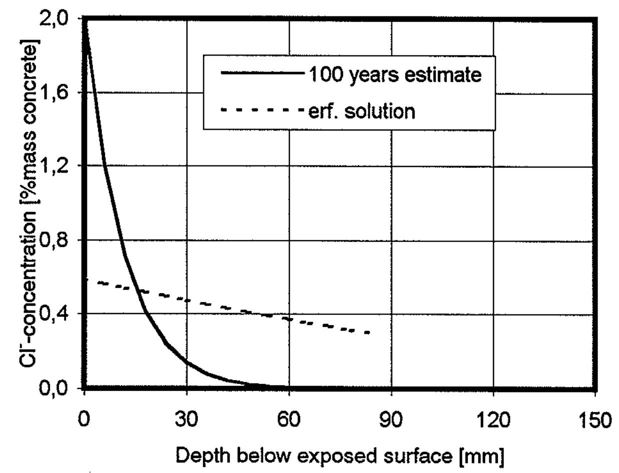
Parameters for each chloride profile

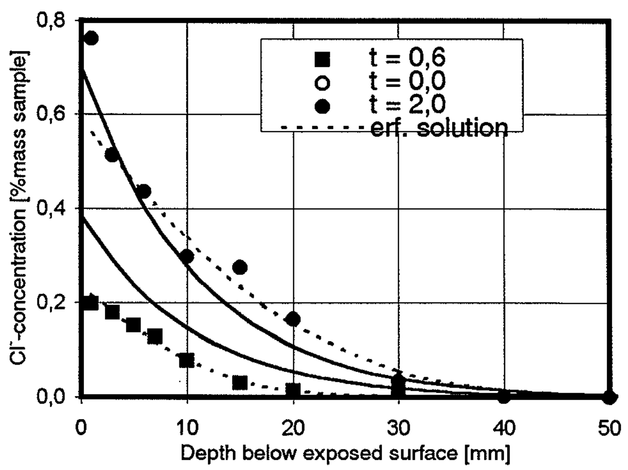
			Da = 95,3	Csa=0,236	Da = 1,0	Csa=0,000	Da = 81,4	Csa=0,584
t =	100	yr	t =	0,6	t =		t =	2,0
$D_a(t)$ =	10,3	mm^2/yr	$D_a(t)$ =	1418,7	$D_a(t)$ =		$D_a(t)$ =	449,6
C_{sa} =	2,000	w/w %	C_{sa} =	0,385	C_{sa} =		C_{sa} =	0,701
Δx =	6	mm	Δx =	5	Δx =		Δx =	5

Estimated chloride profile / erf-sol. / Calculated chloride profiles (Mejlbro-Poulsen)

x	$C(x,t)$	$C(x,t)$ erf-sol.	x	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$
0	2,000	0,584	0	0,385			0	0,701
6	1,199	0,562	5	0,238			5	0,443
12	0,713	0,540	10	0,147			10	0,278
18	0,420	0,519	15	0,089			15	0,173
24	0,245	0,497	20	0,054			20	0,107
30	0,141	0,476	25	0,032			25	0,066
36	0,081	0,454	30	0,019			30	0,040
42	0,046	0,434	35	0,011			35	0,024
48	0,026	0,413	40	0,007			40	0,015
54	0,014	0,393	45	0,004			45	0,009
60	0,008	0,373	50	0,002			50	0,005
66	0,004	0,353	55	0,001			55	0,003
72	0,002	0,334	60	0,001			60	0,002
78	0,001	0,316	65	0,000			65	0,001
84	0,001	0,298	70	0,000			70	0,001

C_1 =	0,516	D_1 =	884,8	C_{100} =	2,000	D_{100} =	10,3





Estimation of Chloride Ingress into Concrete

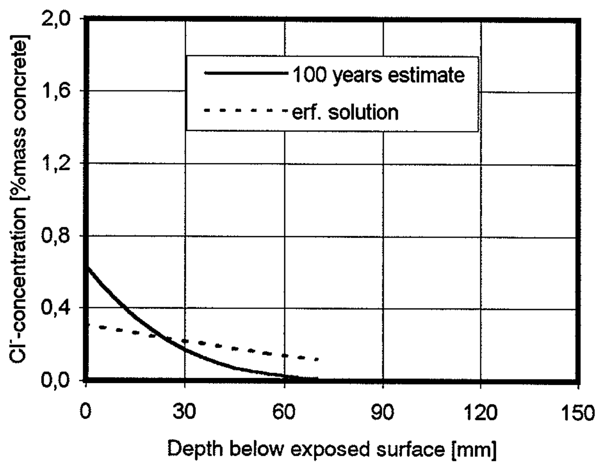
Model developed by Ervin Poulsen and Leif Mejlbro. Programmed by Jens M. Frederiksen.

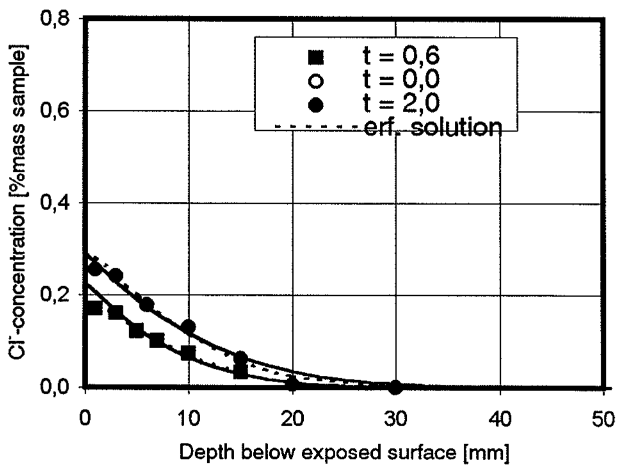
AEClaboratory		Date: 1997-03-24
Staktoften 20	**Sample identification**	Time: 14:05
DK-2950 Vedbæk	Träslövsläge: Ö (zone At)	Init: HES

Input			**Measured profiles, natural exposure**					
Basic constants			t_{in} [yr] =	0,614	t_{in} [yr] =		t_{in} [yr] =	2,014
t_{ex} =	0,04	yr	x	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$
C_i =	0	% mass	[mm]	[% mass]	[mm]	[% mass]	[mm]	[% mass]
w/c =	0,40	[-]	1	0,170			1	0,256
Calculated parameter			3	0,160			3	0,241
D_{pex} =	337	mm²/yr	5	0,121			6	0,178
Governing parameters			7	0,100			10	0,129
α =	0,598	[-]	10	0,074			15	0,062
S =	0,039	%mass/mm^{2p}	15	0,033			20	0,007
S_p =	0,136	%mass					30	0,000
p =	0,486	[-]						
k_D =	1,947	[-]						

Parameters for each chloride profile			Da = 100,9	Csa=0,198	Da = 1,0	Csa=0,000	Da = 33,3	Csa=0,305
t =	100	yr	t =	0,6	t =		t =	2,0
$D_a(t)$ =	5,9	mm²/yr	$D_a(t)$ =	125,0	$D_a(t)$ =		$D_a(t)$ =	61,4
C_{sa} =	0,633	w/w %	C_{sa} =	0,226	C_{sa} =		C_{sa} =	0,292
Δx =	5	mm	Δx =	5	Δx =		Δx =	5

Estimated chloride profile		**erf-sol.**	**Calculated chloride profiles (Mejlbro-Poulsen)**					
x	$C(x,t)$	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$
0	0,633	0,305	0	0,226			0	0,292
5	0,525	0,290	5	0,128			5	0,190
10	0,430	0,275	10	0,065			10	0,116
15	0,348	0,261	15	0,029			15	0,066
20	0,278	0,246	20	0,011			20	0,035
25	0,219	0,232	25	0,004			25	0,017
30	0,170	0,217	30	0,001			30	0,008
35	0,130	0,204	35	0,000			35	0,003
40	0,098	0,190	40	0,000			40	0,001
45	0,072	0,177	45	0,000			45	0,000
50	0,053	0,165	50	0,000			50	0,000
55	0,038	0,153	55	0,000			55	0,000
60	0,027	0,141	60	0,000			60	0,000
65	0,019	0,130	65	0,000			65	0,000
70	0,013	0,119	70	0,000			70	0,000
C_1 =	0,252	D_1 =	93,3		C_{100} =	0,633	D_{100} =	5,9





Estimation of Chloride Ingress into Concrete

Model developed by Ervin Poulsen and Leif Mejlbro. Programmed by Jens M. Frederiksen.

AEClaboratory
Staktoften 20
DK-2950 Vedbæk

Sample identification
Träslövsläge: 2-40 (zone Su)

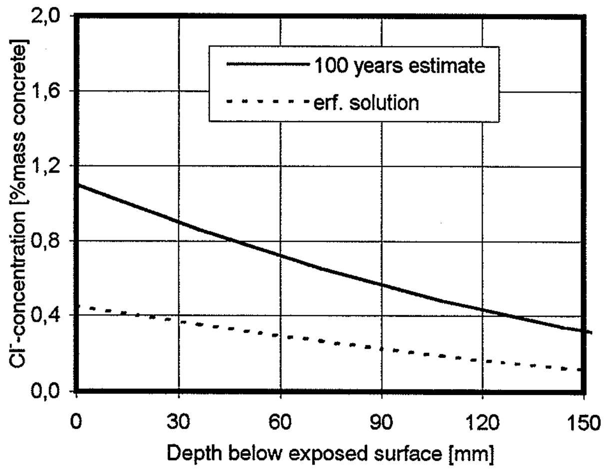
Date: 1997-03-26
Time: 21:10
Init: HES

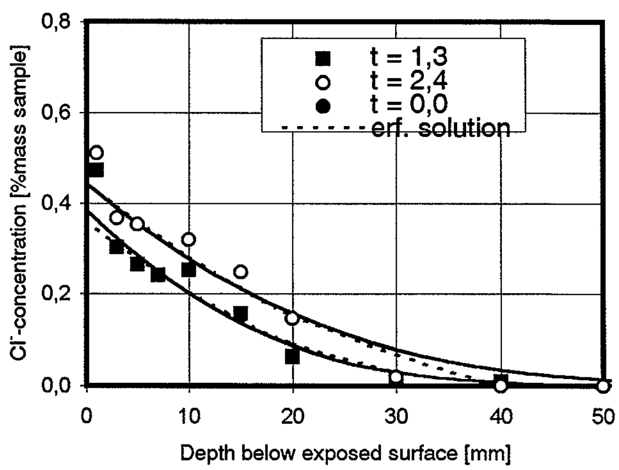
Input			Measured profiles, natural exposure					
Basic constants			t_{in} [yr] =	1,362	t_{in} [yr] =	2,400	t_{in} [yr] =	0,000
t_{ex} =	0,038	yr	x	C(x,t)	x	C(x,t)	x	C(x,t)
C_i =	0,000	% mass	[mm]	[% mass]	[mm]	[% mass]	[mm]	[% mass]
w/c =	0,40	[-]	1	0,473	1	0,511		
Calculated parameter			3	0,303	3	0,368		
D_{pex} =	337	mm²/yr	5	0,265	5	0,354		
Governing parameters			7	0,241	10	0,320		
α =	0,000	[-]	10	0,252	15	0,248		
S =	0,088	%mass/mm^{2p}	15	0,155	20	0,145		
S_p =	0,163	%mass	20	0,064	30	0,020		
p =	0,242	[-]	30	0,012	40	0,000		
k_D =	0,391	[-]	40	0,010	50	0,000		

Parameters for each chloride profile			Da = 115,2 Csa=0,361		Da = 94,0 Csa=0,445		Da = 1,0 Csa=0,000	
t =	100	yr	t =	1,3	t =	2,4	t =	
$D_a(t)$ =	131,7	mm²/yr	$D_a(t)$ =	131,7	$D_a(t)$ =	131,7	$D_a(t)$ =	
C_{sa} =	1,097	w/w %	C_{sa} =	0,385	C_{sa} =	0,443	C_{sa} =	
Δx =	36	mm	Δx =	4	Δx =	5	Δx =	

Estimated chloride profile		**erf-sol.**	**Calculated chloride profiles (Mejlbro-Poulsen)**					
x	C(x,t)	C(x,t)	x	C(x,t)	x	C(x,t)	x	C(x,t)
0	1,097	0,445	0	0,385	0	0,443		
36	0,859	0,353	4	0,304	5	0,355		
72	0,651	0,267	8	0,233	10	0,278		
108	0,477	0,192	12	0,173	15	0,212		
144	0,338	0,131	16	0,125	20	0,157		
180	0,231	0,084	20	0,087	25	0,113		
216	0,152	0,051	24	0,058	30	0,078		
252	0,096	0,029	28	0,038	35	0,053		
288	0,058	0,016	32	0,024	40	0,035		
324	0,034	0,008	36	0,014	45	0,022		
360	0,019	0,004	40	0,008	50	0,013		
396	0,010	0,002	44	0,005	55	0,008		
432	0,005	0,001	48	0,002	60	0,005		
468	0,003	0,000	52	0,001	65	0,003		
504	0,001	0,000	56	0,001	70	0,001		

C_1 =	0,356	D_1 =	131,7	C_{100} =	1,097	D_{100} =	131,7





Estimation of Chloride Ingress into Concrete

Model developed by Ervin Poulsen and Leif Mejlbro. Programmed by Jens M. Frederiksen.

AEClaboratory
Staktoften 20
DK-2950 Vedbæk

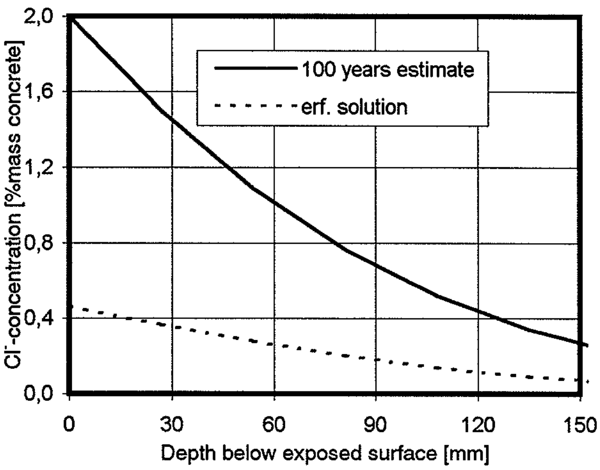
Date: 1997-03-26
Time: 21:15
Init: HES

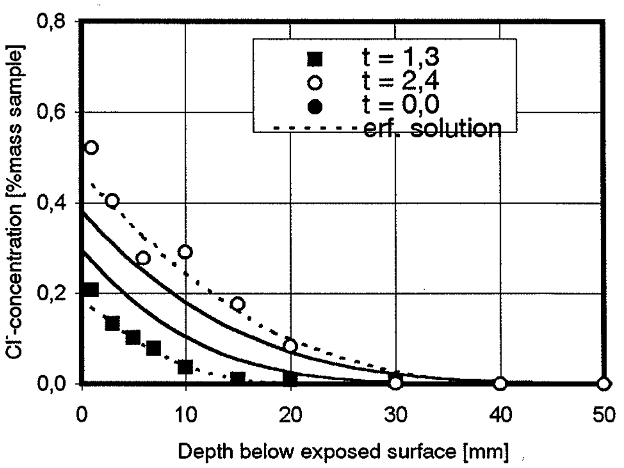
Sample identification
Träslövsläge: 2-40 (zone Sp)

Input			**Measured profiles, natural exposure**					
Basic constants			t_{in} [yr] = 1,362		t_{in} [yr] = 2,400		t_{in} [yr] =	
t_{ex} =	0,04	yr	x	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$
C_i =	0,000	% mass	[mm]	[% mass]	[mm]	[% mass]	[mm]	[% mass]
w/c =	0,40	[-]	1	0,207	1	0,521		
Calculated parameter			3	0,133	3	0,404		
D_{pex} =	337	mm^2/yr	5	0,102	6	0,278		
Governing parameters			7	0,078	10	0,292		
α =	0,000	[-]	10	0,036	15	0,176		
S =	0,020	%mass/mm^{2p}	15	0,010	20	0,083		
S_p =	0,062	%mass	20	0,009	30	0,002		
p =	0,442	[-]	30	0,007	40	0,000		
k_D =	0,212	[-]			50	0,000		

Parameters for each chloride profile			Da = 24,6	Csa=0,189	Da = 54,7	Csa=0,461	Da = 1,0	Csa=0,000
t =	100	yr	t =	1,3	t =	2,4	t =	
$D_a(t)$ =	71,3	mm^2/yr	$D_a(t)$ =	71,3	$D_a(t)$ =	71,3	$D_a(t)$ =	
C_{sa} =	2,000	w/w %	C_{sa} =	0,295	C_{sa} =	0,382	C_{sa} =	
Δx =	27	mm	Δx =	3	Δx =	4	Δx =	

Estimated chloride profile		**erf-sol.**	**Calculated chloride profiles (Mejlbro-Poulsen)**					
x	$C(x,t)$	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$
0	2,000	0,461	0	0,295	0	0,382		
27	1,499	0,367	3	0,224	4	0,289		
54	1,089	0,279	6	0,165	8	0,213		
81	0,765	0,202	9	0,117	12	0,152		
108	0,519	0,139	12	0,081	16	0,105		
135	0,339	0,091	15	0,054	20	0,070		
162	0,214	0,056	18	0,035	24	0,045		
189	0,129	0,033	21	0,022	28	0,028		
216	0,075	0,018	24	0,013	32	0,017		
243	0,042	0,009	27	0,007	36	0,010		
270	0,022	0,005	30	0,004	40	0,005		
297	0,011	0,002	33	0,002	44	0,003		
324	0,006	0,001	36	0,001	48	0,001		
351	0,003	0,000	39	0,001	52	0,001		
378	0,001	0,000	42	0,000	56	0,000		
C_1 =	0,257	D_1 =	71,3		C_{100} =	2,000	D_{100} =	71,3





Estimation of Chloride Ingress into Concrete

Model developed by Ervin Poulsen and Leif Mejlbro. Programmed by Jens M. Frederiksen.

AEClaboratory		Date: 1997-03-26
Staktoften 20	**Sample identification**	Time: 21:20
DK-2950 Vedbæk	Träslövsläge: 2-40 (zone At)	Init: HES

Input

Basic constants

t_{ex} =	0,04	yr
C_i =	0,000	% mass
w/c =	0,40	[-]

Calculated parameter

D_{pex} =	337	mm^2/yr

Governing parameters

α =	0,000	[-]
S =	0,004	$\%mass/mm^{2p}$
S_p =	0,020	%mass
p =	0,586	[-]
k_D =	0,157	[-]

Measured profiles, natural exposure

t_{in} [yr] =	1,362	t_{in} [yr] =	2,400	t_{in} [yr] =	
x [mm]	$C(x,t)$ [% mass]	x [mm]	$C(x,t)$ [% mass]	x [mm]	$C(x,t)$ [% mass]
1	0,176	1	0,185		
3	0,099	3	0,160		
5	0,074	5	0,166		
7	0,056	10	0,129		
10	0,024	15	0,050		
15	0,005	20	0,004		
20	0,005	30	0,003		

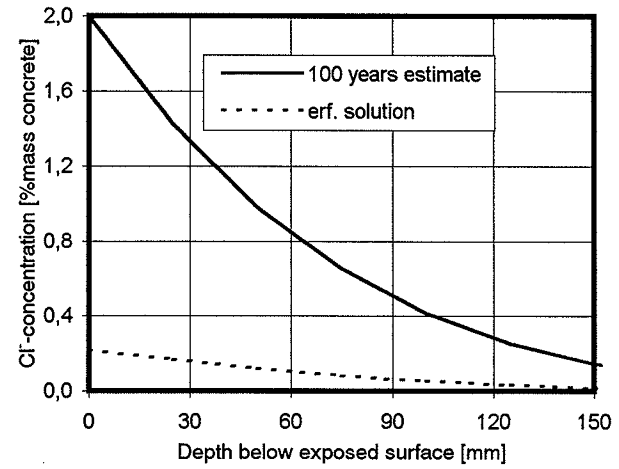
Parameters for each chloride profile

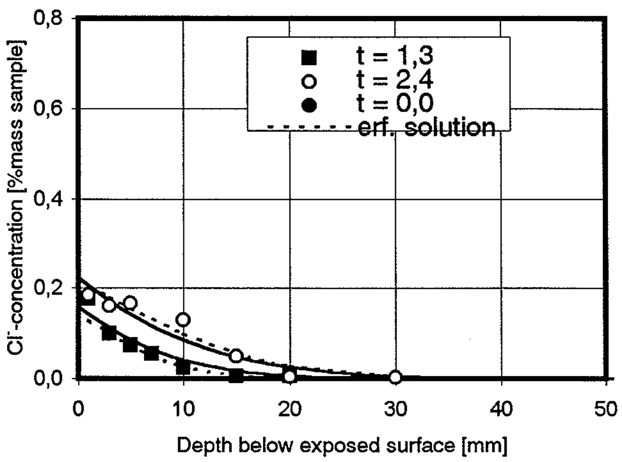
		Da = 21,9	Csa=0,144	Da = 37,4	Csa=0,219	Da = 1,0	Csa=0,000
t =	100 yr	t =	1,3	t =	2,4	t =	
$D_a(t)$ =	52,8 mm^2/yr	$D_a(t)$ =	52,8	$D_a(t)$ =	52,8	$D_a(t)$ =	
C_{sa} =	2,000 w/w %	C_{sa} =	0,159	C_{sa} =	0,223	C_{sa} =	
Δx =	25 mm	Δx =	2	Δx =	3	Δx =	

Estimated chloride profile / Calculated chloride profiles (Mejlbro-Poulsen)

x	$C(x,t)$	$C(x,t)$ erf-sol.	x	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$
0	2,000	0,219	0	0,159	0	0,223		
25	1,427	0,169	2	0,126	3	0,172		
50	0,982	0,123	4	0,098	6	0,129		
75	0,651	0,085	6	0,075	9	0,095		
100	0,414	0,054	8	0,057	12	0,069		
125	0,253	0,033	10	0,042	15	0,048		
150	0,148	0,018	12	0,030	18	0,033		
175	0,082	0,009	14	0,021	21	0,022		
200	0,044	0,005	16	0,015	24	0,014		
225	0,022	0,002	18	0,010	27	0,009		
250	0,011	0,001	20	0,007	30	0,006		
275	0,005	0,000	22	0,004	33	0,003		
300	0,002	0,000	24	0,003	36	0,002		
325	0,001	0,000	26	0,002	39	0,001		
350	0,000	0,000	28	0,001	42	0,001		

C_1 =	0,132	D_1 =	52,8	C_{100} =	2,000	D_{100} =	52,8





Estimation of Chloride Ingress into Concrete

Model developed by Ervin Poulsen and Leif Mejlbro. Programmed by Jens M. Frederiksen.

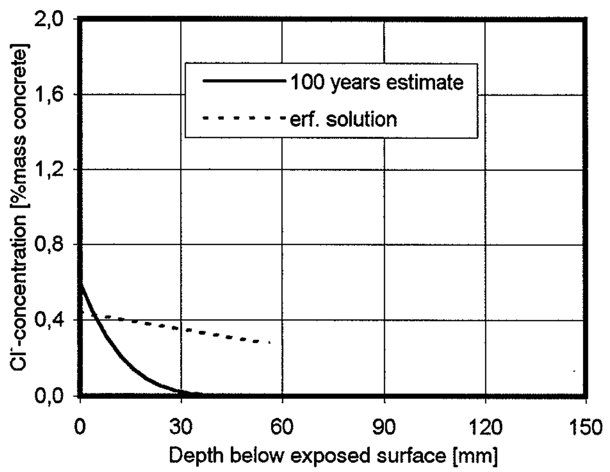
AEClaboratory		Date: 1997-03-26
Staktoften 20	**Sample identification**	Time: 21:33
DK-2950 Vedbæk	Träslövsläge: 3-40 (zone Su)	Init: HES

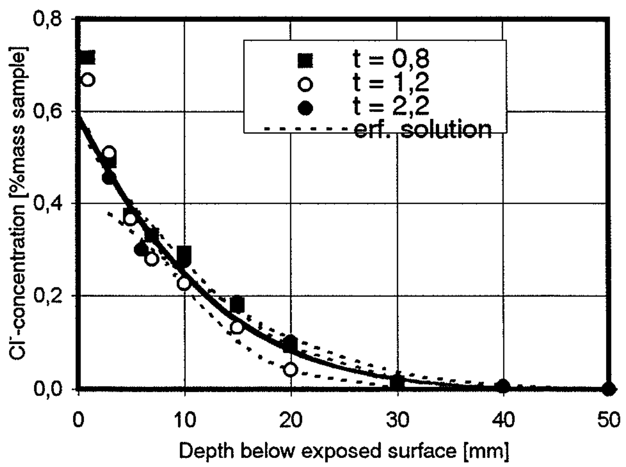
Input			**Measured profiles, natural exposure**					
Basic constants			t_{in} [yr] =	0,819	t_{in} [yr] =	1,238	t_{in} [yr] =	2,277
t_{ex} =	0,038	yr	x	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$
C_i =	0	% mass	[mm]	[% mass]	[mm]	[% mass]	[mm]	[% mass]
w/c =	0,40	[-]	1	0,716	1	0,667	3	0,455
Calculated parameter			3	0,491	3	0,509	6	0,299
D_{pex} =	337	mm^2/yr	5	0,374	5	0,366	10	0,274
Governing parameters			7	0,329	7	0,279	15	0,185
α =	1,000	[-]	10	0,291	10	0,226	20	0,100
S =	0,143	$\%mass/mm^{2p}$	15	0,179	15	0,131	30	0,017
S_p =	0,600	%mass	20	0,092	20	0,042	40	0,005
p =	0,561	[-]	30	0,013	30	0,012	50	0,000
k_D =	11,552	[-]						

Parameters for each chloride profile			Da = 136,6	Csa=0,553	Da = 50,2	Csa=0,603	Da = 67,2	Csa=0,440
t =	100	yr	t =	0,8	t =	1,2	t =	2,2
$D_a(t)$ =	1,5	mm^2/yr	$D_a(t)$ =	182,2	$D_a(t)$ =	120,5	$D_a(t)$ =	65,6
C_{sa} =	0,600	w/w %	C_{sa} =	0,584	C_{sa} =	0,589	C_{sa} =	0,594
Δx =	4	mm	Δx =	4	Δx =	4	Δx =	4

Estimated chloride profile		**erf-sol.**	**Calculated chloride profiles (Mejlbro-Poulsen)**					
x	$C(x,t)$	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$
0	0,600	0,440	0	0,584	0	0,589	0	0,594
4	0,437	0,428	4	0,422	4	0,427	4	0,432
8	0,308	0,416	8	0,295	8	0,300	8	0,304
12	0,210	0,404	12	0,199	12	0,203	12	0,206
16	0,138	0,392	16	0,129	16	0,132	16	0,135
20	0,087	0,380	20	0,080	20	0,083	20	0,085
24	0,053	0,368	24	0,048	24	0,050	24	0,051
28	0,031	0,356	28	0,028	28	0,029	28	0,030
32	0,017	0,344	32	0,015	32	0,016	32	0,017
36	0,009	0,333	36	0,008	36	0,008	36	0,009
40	0,005	0,321	40	0,004	40	0,004	40	0,004
44	0,002	0,310	44	0,002	44	0,002	44	0,002
48	0,001	0,299	48	0,001	48	0,001	48	0,001
52	0,000	0,288	52	0,000	52	0,000	52	0,000
56	0,000	0,277	56	0,000	56	0,000	56	0,000

C_1 = 0,587 D_1 = 149,3 C_{100} = 0,600 D_{100} = 1,5





Estimation of Chloride Ingress into Concrete

Model developed by Ervin Poulsen and Leif Mejlbro. Programmed by Jens M. Frederiksen.

AEClaboratory
Staktoften 20
DK-2950 Vedbæk

Date:	1997-04-07
Time:	15:02
Init:	HES

Sample identification

Träslövsläge: 3-40 (zone Sp)

Input

Basic constants

t_{ex} =	0,04	yr
C_i =	0,000	% mass
w/c =	0,40	[-]

Calculated parameter

D_{pex} =	337	mm^2/yr

Governing parameters

α =	0,414	[-]
S =	0,028	$\%mass/mm^{2p}$
S_p =	0,115	%mass
p =	0,551	[-]
k_D =	0,703	[-]

Measured profiles, natural exposure

t_{in} [yr] =	0,819	t_{in} [yr] =	2,277	t_{in} [yr] =	
x [mm]	$C(x,t)$ [% mass]	x [mm]	$C(x,t)$ [% mass]	x [mm]	$C(x,t)$ [% mass]
1	0,227	1	0,528		
3	0,194	3	0,321		
5	0,149	6	0,221		
7	0,119	10	0,171		
10	0,063	15	0,078		
15	0,018	20	0,001		
20	0,010	30	0,001		
30	0,014	40	0,000		
		50	0,000		

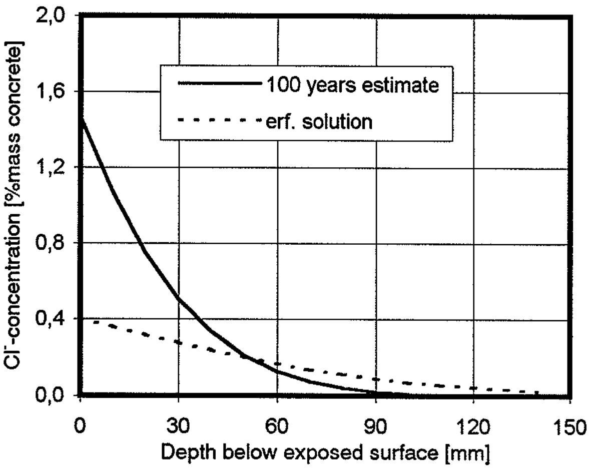
Parameters for each chloride profile

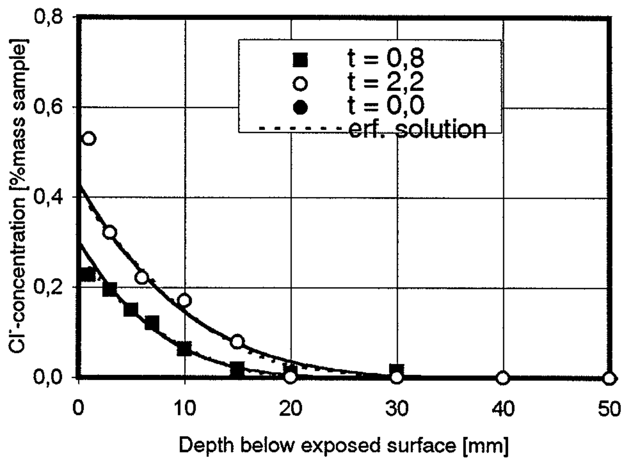
		Da = 48,0	Csa=0,268	Da = 27,5	Csa=0,404	Da = 1,0	Csa=0,000
t =	100 yr	t =	0,8	t =	2,2	t =	
$D_a(t)$ =	9,1 mm^2/yr	$D_a(t)$ =	66,7	$D_a(t)$ =	43,7	$D_a(t)$ =	
C_{sa} =	1,465 w/w %	C_{sa} =	0,302	C_{sa} =	0,428	C_{sa} =	
Δx =	10 mm	Δx =	2	Δx =	3	Δx =	

Estimated chloride profile / erf-sol. — **Calculated chloride profiles (Mejlbro-Poulsen)**

x	$C(x,t)$	$C(x,t)$ erf-sol.	x	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$
0	1,465	0,404	0	0,302	0	0,428		
10	1,065	0,361	2	0,232	3	0,320		
20	0,750	0,318	4	0,174	6	0,233		
30	0,509	0,277	6	0,127	9	0,164		
40	0,333	0,238	8	0,091	12	0,113		
50	0,210	0,202	10	0,063	15	0,075		
60	0,127	0,169	12	0,043	18	0,048		
70	0,074	0,140	14	0,028	21	0,030		
80	0,041	0,113	16	0,018	24	0,018		
90	0,022	0,091	18	0,011	27	0,010		
100	0,011	0,072	20	0,007	30	0,006		
110	0,005	0,056	22	0,004	33	0,003		
120	0,002	0,043	24	0,002	36	0,002		
130	0,001	0,032	26	0,001	39	0,001		
140	0,000	0,024	28	0,001	42	0,000		

C_1 =	0,324	D_1 =	61,4	C_{100} =	1,465	D_{100} =	9,1





Estimation of Chloride Ingress into Concrete

Model developed by Ervin Poulsen and Leif Mejlbro. Programmed by Jens M. Frederiksen.

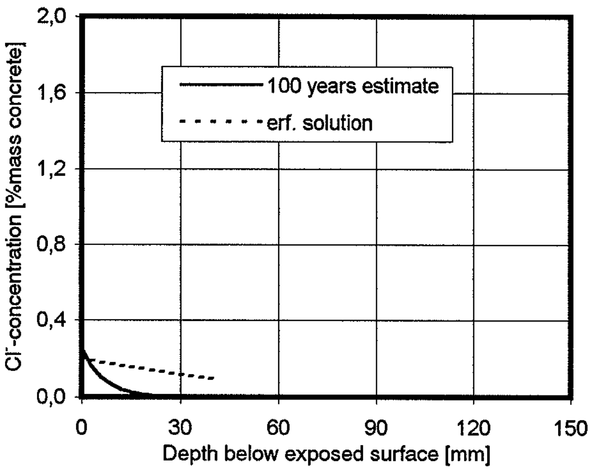
AEClaboratory		Date: 1997-03-26
Staktoften 20	**Sample identification**	Time: 22:02
DK-2950 Vedbæk	Träslövsläge: 3-40 (zone At)	Init: HES

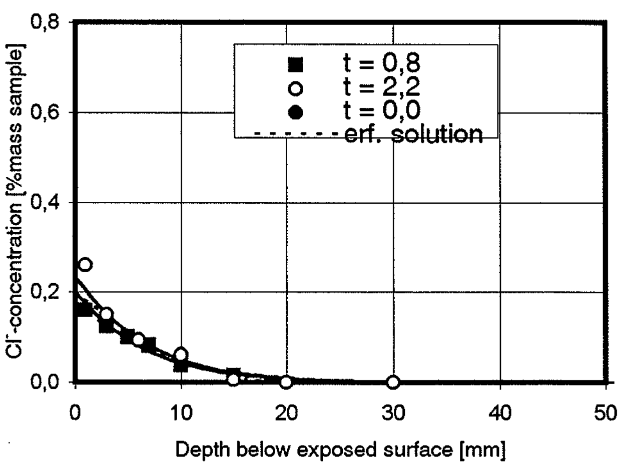
Input			**Measured profiles, natural exposure**					
Basic constants			t_{in} [yr] =	0,819	t_{in} [yr] =	2,277	t_{in} [yr] =	
t_{ex} =	0,04	yr	x	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$
C_i =	0	% mass	[mm]	[% mass]	[mm]	[% mass]	[mm]	[% mass]
w/c =	0,40	[-]	1	0,159	1	0,260		
Calculated parameter			3	0,122	3	0,149		
D_{pex} =	337	mm^2/yr	5	0,099	6	0,092		
Governing parameters			7	0,081	10	0,061		
α =	1,000	[-]	10	0,039	15	0,005		
S =	0,000	$\%mass/mm^{2p}$	15	0,016	20	0,000		
S_p =	0,255	%mass			30	0,000		
p =	5,010	[-]						
k_D =	19,237	[-]						

Parameters for each chloride profile			Da = 51,9	Csa=0,169	Da = 16,2	Csa=0,204	Da = 1,0	Csa=0,000
t =	100	yr	t =	0,8	t =	2,2	t =	
$D_a(t)$ =	2,5	mm^2/yr	$D_a(t)$ =	303,5	$D_a(t)$ =	109,2	$D_a(t)$ =	
C_{sa} =	0,255	w/w %	C_{sa} =	0,201	C_{sa} =	0,234	C_{sa} =	
Δx =	3	mm	Δx =	3	Δx =	3	Δx =	

Estimated chloride profile		**erf-sol.**	**Calculated chloride profiles (Mejlbro-Poulsen)**					
x	$C(x,t)$	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$
0	0,255	0,204	0	0,201	0	0,234		
3	0,164	0,195	3	0,128	3	0,150		
6	0,104	0,187	6	0,080	6	0,095		
9	0,066	0,178	9	0,050	9	0,060		
12	0,041	0,170	12	0,031	12	0,037		
15	0,025	0,161	15	0,019	15	0,023		
18	0,016	0,153	18	0,011	18	0,014		
21	0,009	0,145	21	0,007	21	0,008		
24	0,006	0,137	24	0,004	24	0,005		
27	0,003	0,130	27	0,002	27	0,003		
30	0,002	0,122	30	0,001	30	0,002		
33	0,001	0,115	33	0,001	33	0,001		
36	0,001	0,107	36	0,000	36	0,001		
39	0,000	0,101	39	0,000	39	0,000		
42	0,000	0,094	42	0,000	42	0,000		

C_1 =	0,210	D_1 =	248,6	C_{100} =	0,255	D_{100} =	2,5





Estimation of Chloride Ingress into Concrete

Model developed by Ervin Poulsen and Leif Mejlbro. Programmed by Jens M. Frederiksen.

AEClaboratory		Date: 1997-03-21
Staktoften 20	**Sample identification**	Time: 14:15
DK-2950 Vedbæk	Träslövsläge: H4 (zone Su)	Init: HES

Input

Basic constants		
t_{ex} =	0,04	yr
C_i =	0,000	% mass
w/c =	0,40	[-]
Calculated parameter		
D_{pex} =	337	mm^2/yr
Governing parameters		
α =	1,000	[-]
S =	0,327	$\%mass/mm^{2p}$
S_p =	0,721	%mass
p =	0,284	[-]
k_D =	4,117	[-]

Measured profiles, natural exposure

t_{in} [yr] =	0,627	t_{in} [yr] =	1,047	t_{in} [yr] =	2,027
x [mm]	$C(x,t)$ [% mass]	x [mm]	$C(x,t)$ [% mass]	x [mm]	$C(x,t)$ [% mass]
1,5	0,644	1,5	0,635	1	0,647
3	0,504	3	0,446	2	0,481
5	0,379	5	0,298	6	0,338
7	0,288	7	0,234	10	0,219
10	0,186	10	0,167	15	0,101
15	0,062	15	0,051	20	0,027
20	0,014	20	0,018	30	0,002
30	0,009	30	0,013	40	0,001
				50	0,000

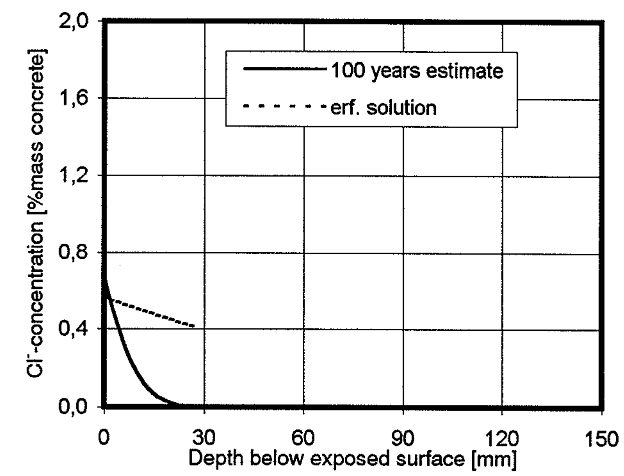
Parameters for each chloride profile

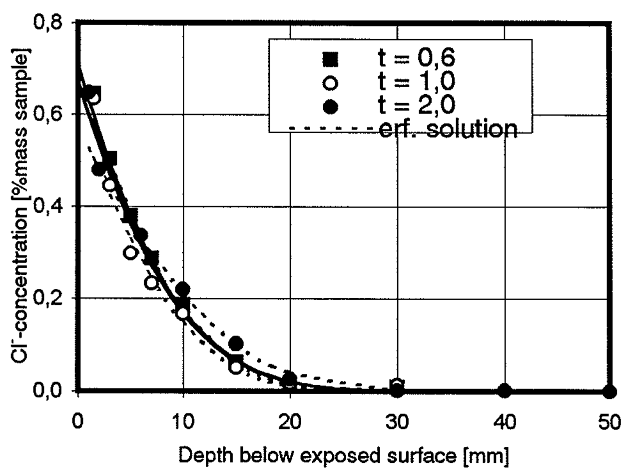
		Da = 67,5	Csa=0,675	Da = 37,8	Csa=0,579	Da = 31,5	Csa=0,566
t =	100 yr	t =	0,6	t =	1,0	t =	2,0
$D_a(t)$ =	0,5 mm^2/yr	$D_a(t)$ =	84,8	$D_a(t)$ =	50,8	$D_a(t)$ =	26,2
C_{sa} =	0,676 w/w %	C_{sa} =	0,708	C_{sa} =	0,669	C_{sa} =	0,673
Δx =	2 mm	Δx =	2	Δx =	2	Δx =	2

Estimated chloride profile / Calculated chloride profiles (Mejlbro-Poulsen)

x	$C(x,t)$	erf-sol. $C(x,t)$	x	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$
0	0,676	0,566	0	0,708	0	0,669	0	0,673
2	0,543	0,554	2	0,564	2	0,535	2	0,539
4	0,425	0,543	4	0,438	4	0,417	4	0,421
6	0,325	0,532	6	0,331	6	0,317	6	0,321
8	0,242	0,520	8	0,244	8	0,234	8	0,238
10	0,176	0,509	10	0,174	10	0,168	10	0,172
12	0,124	0,498	12	0,121	12	0,118	12	0,121
14	0,085	0,487	14	0,081	14	0,080	14	0,082
16	0,056	0,475	16	0,053	16	0,052	16	0,054
18	0,036	0,464	18	0,033	18	0,033	18	0,035
20	0,023	0,453	20	0,020	20	0,021	20	0,022
22	0,014	0,442	22	0,012	22	0,012	22	0,013
24	0,008	0,431	24	0,007	24	0,007	24	0,008
26	0,005	0,420	26	0,004	26	0,004	26	0,004
28	0,003	0,410	28	0,002	28	0,002	28	0,002

C_1 =	0,713	D_1 =	53,2	C_{100} =	0,721	D_{100} =	0,5





Estimation of Chloride Ingress into Concrete

Model developed by Ervin Poulsen and Leif Mejlbro. Programmed by Jens M. Frederiksen.

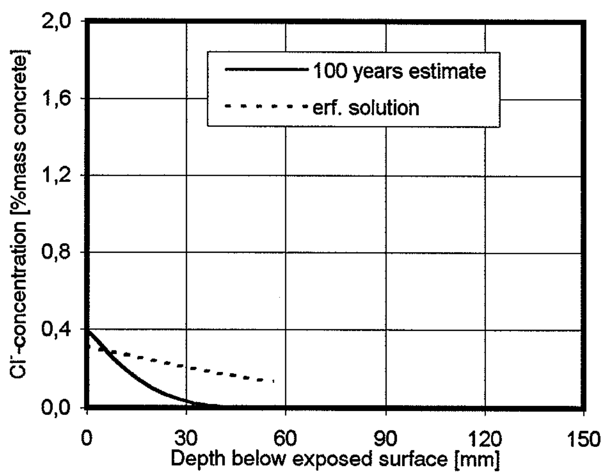
AEClaboratory		Date: 1997-03-21
Staktoften 20	**Sample identification**	Time: 14:38
DK-2950 Vedbæk	Träslövsläge: H4 (zone Sp)	Init: HES

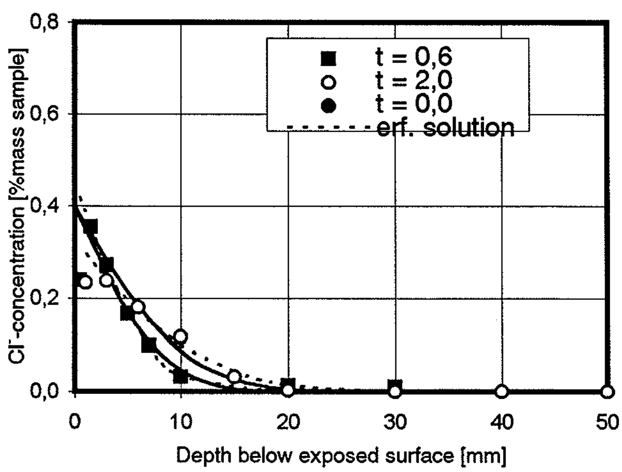
Input			**Measured profiles, natural exposure**					
Basic constants			t_{in} [yr] =	0,627	t_{in} [yr] =	2,027	t_{in} [yr] =	
t_{ex} =	0,04	yr	x	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$
C_i =	0	% mass	[mm]	[% mass]	[mm]	[% mass]	[mm]	[% mass]
w/c =	0,40	[-]	0,5	0,239	1	0,233		
Calculated parameter			1,5	0,354	3	0,237		
D_{pex} =	337	mm^2/yr	3	0,271	6	0,180		
Governing parameters			5	0,167	10	0,117		
α =	0,608	[-]	7	0,098	15	0,032		
S =	0,399	$\%mass/mm^{2p}$	10	0,032	20	0,003		
S_p =	0,399	%mass	20	0,012	30	0,000		
p =	0,000	[-]	30	0,010	40	0,000		
k_D =	0,552	[-]			50	0,000		

Parameters for each chloride profile			Da = 27,0	Csa=0,450	Da = 25,7	Csa=0,318	Da = 1,0	Csa=0,000
t =	100	yr	t =	0,6	t =	2,0	t =	
$D_a(t)$ =	1,6	mm^2/yr	$D_a(t)$ =	34,0	$D_a(t)$ =	16,7	$D_a(t)$ =	
C_{sa} =	0,399	w/w %	C_{sa} =	0,399	C_{sa} =	0,399	C_{sa} =	
Δx =	4	mm	Δx =	1,5	Δx =	2	Δx =	

Estimated chloride profile		**erf-sol.**	**Calculated chloride profiles (Mejlbro-Poulsen)**					
x	$C(x,t)$	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$
0	0,399	0,318	0	0,399	0	0,399		
4	0,328	0,303	2	0,325	2	0,322		
8	0,260	0,289	3	0,254	4	0,249		
12	0,198	0,275	5	0,191	6	0,184		
16	0,145	0,261	6	0,137	8	0,130		
20	0,103	0,248	8	0,094	10	0,088		
24	0,069	0,234	9	0,062	12	0,056		
28	0,045	0,221	11	0,039	14	0,034		
32	0,028	0,208	12	0,023	16	0,020		
36	0,016	0,195	14	0,013	18	0,011		
40	0,009	0,183	15	0,007	20	0,006		
44	0,005	0,171	17	0,004	22	0,003		
48	0,003	0,160	18	0,002	24	0,001		
52	0,001	0,149	20	0,001	26	0,001		
56	0,001	0,138	21	0,000	28	0,000		

C_1 =	0,399	D_1 =	25,6	C_{100} =	0,399	D_{100} =	1,6





Estimation of Chloride Ingress into Concrete

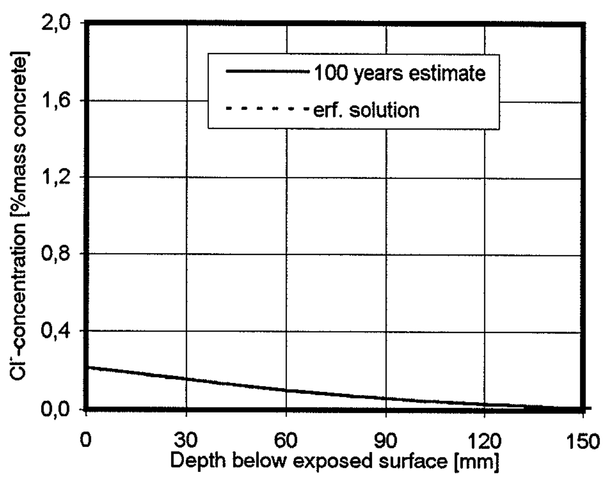
Model developed by Ervin Poulsen and Leif Mejlbro. Programmed by Jens M. Frederiksen.

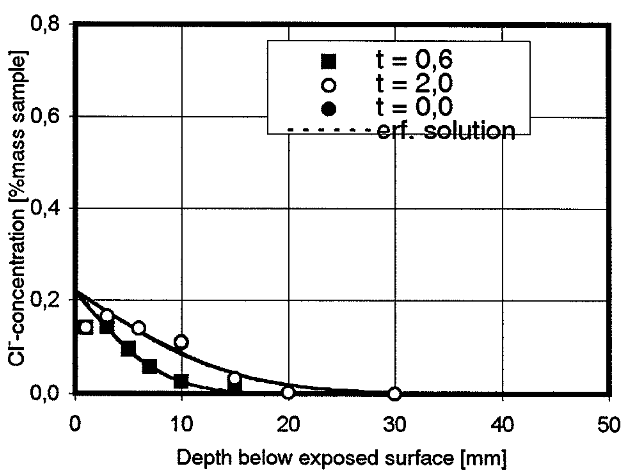
AEClaboratory		Date: 1997-03-21
Staktoften 20	**Sample identification**	Time: 14:28
DK-2950 Vedbæk	Träslövsläge: H4 (zone At)	Init: HES

Input			**Measured profiles, natural exposure**					
Basic constants			t_{in} [yr] =	0,627	t_{in} [yr] =	2,027	t_{in} [yr] =	
t_{ex} =	0,04	yr	x	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$
C_i =	0	% mass	[mm]	[% mass]	[mm]	[% mass]	[mm]	[% mass]
w/c =	0,40	[-]	1	0,140	1	0,140		
Calculated parameter			3	0,141	3	0,165		
D_{pex} =	337	mm^2/yr	5	0,096	6	0,139		
Governing parameters			7	0,058	10	0,110		
α =	0,000	[-]	10	0,026	15	0,033		
S =	0,219	$\%mass/mm^{2p}$	15	0,014	20	0,003		
S_p =	0,219	%mass			30	0,000		
p =	0,000	[-]						
k_D =	0,104	[-]						

Parameters for each chloride profile			Da = 35,5	Csa=0,218	Da = 34,9	Csa=0,219	Da = 1,0	Csa=0,000
t =	100	yr	t =	0,6	t =	2,0	t =	
$D_a(t)$ =	35,1	mm^2/yr	$D_a(t)$ =	35,1	$D_a(t)$ =	35,1	$D_a(t)$ =	
C_{sa} =	0,219	w/w %	C_{sa} =	0,219	C_{sa} =	0,219	C_{sa} =	
Δx =	20	mm	Δx =	2	Δx =	3	Δx =	

Estimated chloride profile		**erf-sol.**	**Calculated chloride profiles (Mejlbro-Poulsen)**					
x	$C(x,t)$	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$
0	0,219	0,219	0	0,219	0	0,219		
20	0,178	0,178	2	0,166	3	0,175		
40	0,139	0,139	4	0,117	6	0,134		
60	0,104	0,104	6	0,077	9	0,098		
80	0,074	0,074	8	0,047	12	0,068		
100	0,051	0,051	10	0,026	15	0,045		
120	0,033	0,033	12	0,014	18	0,028		
140	0,021	0,021	14	0,006	21	0,017		
160	0,012	0,012	16	0,003	24	0,009		
180	0,007	0,007	18	0,001	27	0,005		
200	0,004	0,004	20	0,000	30	0,002		
220	0,002	0,002	22	0,000	33	0,001		
240	0,001	0,001	24	0,000	36	0,001		
260	0,000	0,000	26	0,000	39	0,000		
280	0,000	0,000	28	0,000	42	0,000		
C_1 =	0,219	D_1 =	35,1		C_{100} =	0,219	D_{100} =	35,1





Estimation of Chloride Ingress into Concrete

Model developed by Ervin Poulsen and Leif Mejlbro. Programmed by Jens M. Frederiksen.

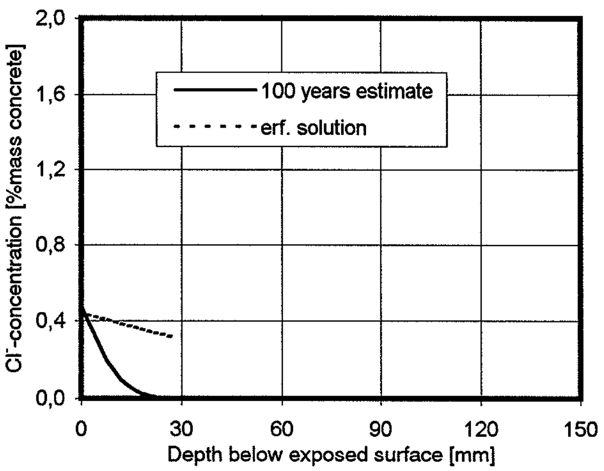
AEClaboratory		Date: 1997-03-26
Staktoften 20	**Sample identification**	Time: 22:19
DK-2950 Vedbæk	Träslövsläge: 10-40 (zone Su)	Init: HES

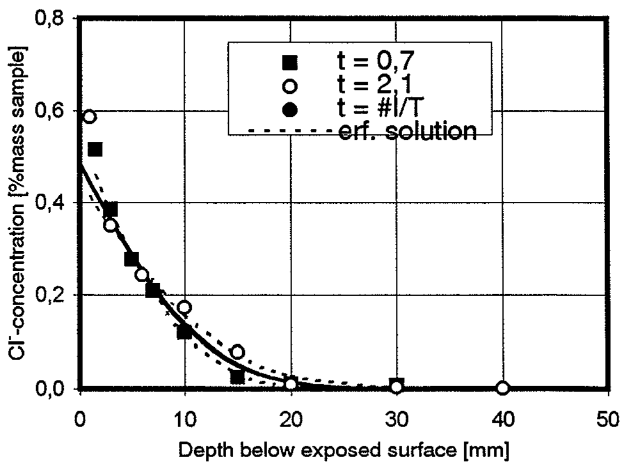
Input			**Measured profiles, natural exposure**					
Basic constants			t_{in} [yr] =	0,710	t_{in} [yr] =	2,110	t_{in} [yr] =	
t_{ex} =	0,04	yr	x	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$
C_i =	0	% mass	[mm]	[% mass]	[mm]	[% mass]	[mm]	[% mass]
w/c =	0,40	[-]	1,5	0,514	1	0,586		
Calculated parameter			3	0,385	3	0,351		
D_{pex} =	337	mm^2/yr	5	0,276	6	0,243		
Governing parameters			7	0,208	10	0,173		
α =	1,000	[-]	10	0,120	15	0,079		
S =	0,485	%mass/mm^{2p}	15	0,025	20	0,010		
S_p =	0,485	%mass	20	0,011	30	0,004		
p =	0,000	[-]	30	0,008	40	0,001		
k_D =	3,466	[-]						

Parameters for each chloride profile			Da = 47,6	Csa=0,538	Da = 28,3	Csa=0,444	Da = 1,0	Csa=0,000
t =	100	yr	t =	0,7	t =	2,1	t =	
$D_a(t)$ =	0,4	mm^2/yr	$D_a(t)$ =	63,1	$D_a(t)$ =	21,2	$D_a(t)$ =	
C_{sa} =	0,485	w/w %	C_{sa} =	0,485	C_{sa} =	0,485	C_{sa} =	
Δx =	2	mm	Δx =	2	Δx =	2	Δx =	

Estimated chloride profile		**erf-sol.**	**Calculated chloride profiles (Mejlbro-Poulsen)**					
x	$C(x,t)$	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$
0	0,485	0,444	0	0,485	0	0,485		
2	0,404	0,434	2	0,402	2	0,403		
4	0,326	0,425	4	0,322	4	0,325		
6	0,255	0,415	6	0,250	6	0,253		
8	0,193	0,406	8	0,187	8	0,191		
10	0,141	0,397	10	0,134	10	0,139		
12	0,099	0,387	12	0,093	12	0,097		
14	0,067	0,378	14	0,062	14	0,066		
16	0,044	0,369	16	0,040	16	0,043		
18	0,028	0,360	18	0,025	18	0,027		
20	0,017	0,351	20	0,014	20	0,016		
22	0,010	0,342	22	0,008	22	0,009		
24	0,005	0,333	24	0,004	24	0,005		
26	0,003	0,324	26	0,002	26	0,003		
28	0,001	0,315	28	0,001	28	0,001		

C_1 = 0,485 D_1 = 44,8 C_{100} = 0,485 D_{100} = 0,4





Estimation of Chloride Ingress into Concrete

Model developed by Ervin Poulsen and Leif Mejlbro. Programmed by Jens M. Frederiksen.

AEClaboratory
Staktoften 20
DK-2950 Vedbæk

Sample identification	
Träslövsläge:	10-40 (zone Sp)

Date:	1997-03-26
Time:	22:23
Init:	HES

Input

Basic constants

t_{ex} =	0,04	yr
C_i =	0,000	% mass
w/c =	0,40	[-]

Calculated parameter

D_{pex} =	337	mm^2/yr

Governing parameters

α =	0,316	[-]
S =	0,068	$\%mass/mm^{2p}$
S_p =	0,174	%mass
p =	0,366	[-]
k_D =	0,121	[-]

Measured profiles, natural exposure

t_{in} [yr] =	0,710	t_{in} [yr] =	2,110	t_{in} [yr] =	#I/T
x [mm]	$C(x,t)$ [% mass]	x [mm]	$C(x,t)$ [% mass]	x [mm]	$C(x,t)$ [% mass]
1,5	0,238	1	0,390		
3	0,152	3	0,273		
5	0,069	6	0,129		
7	0,027	10	0,056		
10	0,013	15	0,006		
15	0,009	20	0,001		
20	0,008	30	0,000		

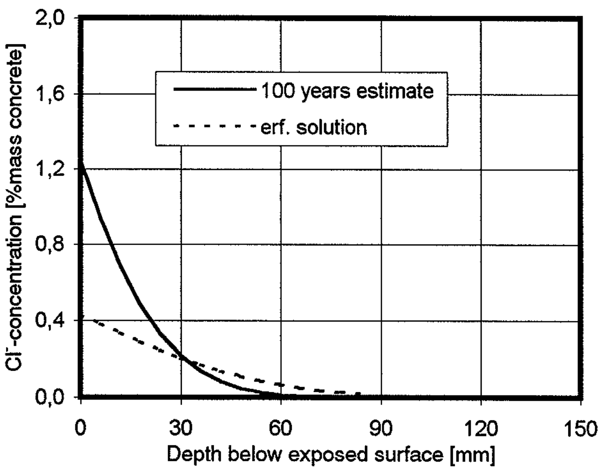
Parameters for each chloride profile

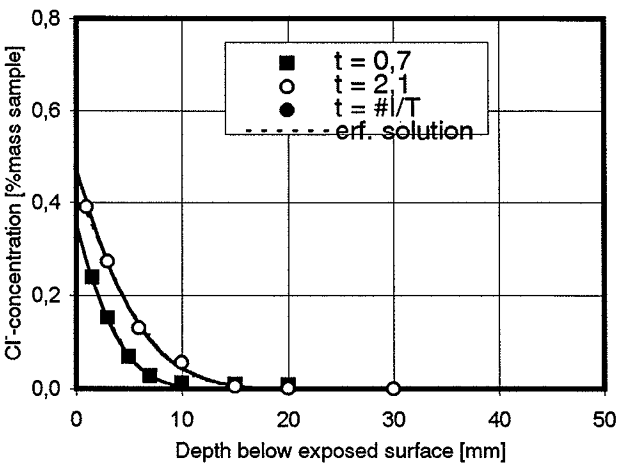
			Da = 12,2	Csa=0,329	Da = 9,0	Csa=0,432	Da = 1,0	Csa=0,000
t =	100	yr	t =	0,7	t =	2,1	t =	
$D_a(t)$ =	3,4	mm^2/yr	$D_a(t)$ =	16,3	$D_a(t)$ =	11,5	$D_a(t)$ =	
C_{sa} =	1,248	w/w %	C_{sa} =	0,354	C_{sa} =	0,472	C_{sa} =	
Δx =	6	mm	Δx =	1	Δx =	1,5	Δx =	

Estimated chloride profile / Calculated chloride profiles (Mejlbro-Poulsen)

Estimated: x	$C(x,t)$	erf-sol. $C(x,t)$	x	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$
0	1,248	0,432	0	0,354	0	0,472		
6	0,944	0,383	1	0,274	2	0,363		
12	0,691	0,335	2	0,205	3	0,271		
18	0,488	0,290	3	0,149	5	0,196		
24	0,332	0,247	4	0,105	6	0,137		
30	0,218	0,207	5	0,072	8	0,093		
36	0,137	0,171	6	0,047	9	0,061		
42	0,083	0,139	7	0,030	11	0,038		
48	0,048	0,111	8	0,019	12	0,023		
54	0,027	0,088	9	0,011	14	0,014		
60	0,014	0,068	10	0,006	15	0,008		
66	0,007	0,052	11	0,003	17	0,004		
72	0,003	0,039	12	0,002	18	0,002		
78	0,002	0,028	13	0,001	20	0,001		
84	0,001	0,021	14	0,000	21	0,001		

C_1 =	0,389	D_1 =	14,6	C_{100} =	1,248	D_{100} =	3,4





Estimation of Chloride Ingress into Concrete

Model developed by Ervin Poulsen and Leif Mejlbro. Programmed by Jens M. Frederiksen.

AEClaboratory
Staktoften 20
DK-2950 Vedbæk

Date: 1997-03-26
Time: 22:28
Init: HES

Sample identification
Träslövsläge: 10-40 (zone At)

Input

Basic constants

t_{ex} =	0,04	yr
C_i =	0	% mass
w/c =	0,40	[-]

Calculated parameter

D_{pex} =	337	mm^2/yr

Governing parameters

α =	0,057	[-]
S =	0,008	$\%mass/mm^{2p}$
S_p =	0,032	%mass
p =	0,557	[-]
k_D =	0,131	[-]

Measured profiles, natural exposure

t_{in} [yr] = 0,710		t_{in} [yr] = 2,110		t_{in} [yr] =	
x	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$
[mm]	[% mass]	[mm]	[% mass]	[mm]	[% mass]
1	0,150	1	0,285		
3	0,083	3	0,190		
5	0,043	6	0,120		
7	0,026	10	0,073		
10	0,018	15	0,040		
15	0,012	20	0,007		
		30	0,005		

Parameters for each chloride profile

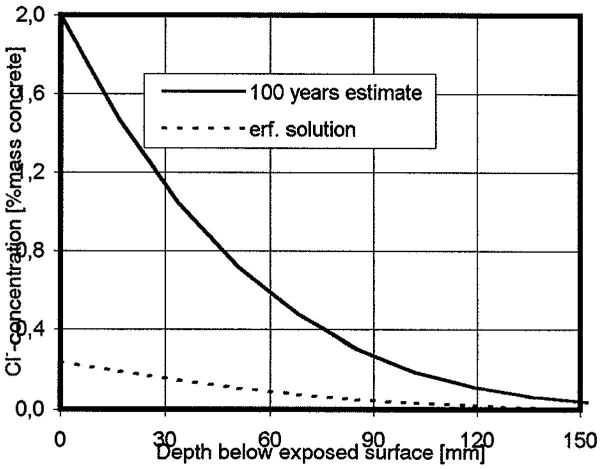
t =	100	yr
$D_a(t)$ =	28,1	mm^2/yr
C_{sa} =	2,000	w/w %
Δx =	17	mm

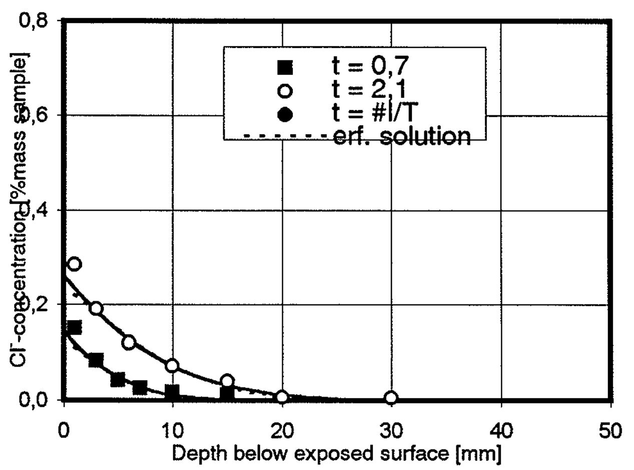
Da = 24,0 Csa=0,132		Da = 23,0 Csa=0,242		Da = 1,0 Csa=0,000	
t =	0,7	t =	2,1	t =	
$D_a(t)$ =	37,3	$D_a(t)$ =	35,0	$D_a(t)$ =	
C_{sa} =	0,145	C_{sa} =	0,261	C_{sa} =	
Δx =	1,5	Δx =	2	Δx =	

Estimated chloride profile / **erf-sol.** / **Calculated chloride profiles (Mejlbro-Poulsen)**

x	$C(x,t)$	$C(x,t)$ (erf-sol.)	x	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$
0	2,000	0,242	0	0,145	0	0,261		
17	1,468	0,194	2	0,108	2	0,209		
34	1,045	0,149	3	0,079	4	0,165		
51	0,719	0,109	5	0,056	6	0,127		
68	0,478	0,077	6	0,039	8	0,097		
85	0,307	0,051	8	0,026	10	0,072		
102	0,189	0,032	9	0,017	12	0,053		
119	0,112	0,019	11	0,010	14	0,038		
136	0,064	0,011	12	0,006	16	0,027		
153	0,035	0,006	14	0,004	18	0,018		
170	0,018	0,003	15	0,002	20	0,012		
187	0,009	0,001	17	0,001	22	0,008		
204	0,004	0,001	18	0,001	24	0,005		
221	0,002	0,000	20	0,000	26	0,003		
238	0,001	0,000	21	0,000	28	0,002		

C_1 = 0,175 D_1 = 36,6 C_{100} = 2,000 D_{100} = 28,1





Estimation of Chloride Ingress into Concrete

Model developed by Ervin Poulsen and Leif Mejlbro. Programmed by Jens M. Frederiksen.

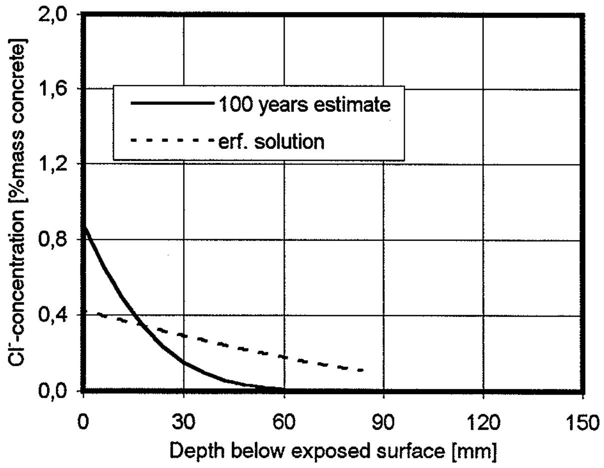
AEClaboratory		Date: 1997-03-26
Staktoften 20	**Sample identification**	Time: 22:42
DK-2950 Vedbæk	Träslövsläge: 12-35 (zone Su)	Init: HES

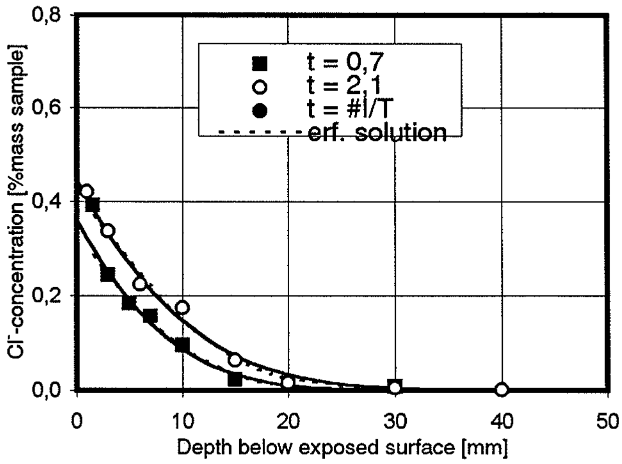
Input			**Measured profiles, natural exposure**					
Basic constants			t_{in} [yr] = 0,726		t_{in} [yr] = 2,129		t_{in} [yr] = #I/T	
t_{ex} =	0,04	yr	x	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$
C_i =	0	% mass	[mm]	[% mass]	[mm]	[% mass]	[mm]	[% mass]
w/c =	0,35	[-]	1,5	0,392	1	0,421		
Calculated parameter			3	0,244	3	0,337		
D_{pex} =	239	mm^2/yr	5	0,184	6	0,224		
Governing parameters			7	0,157	10	0,174		
α =	0,636	[-]	10	0,095	15	0,064		
S =	0,076	$\%mass/mm^{2p}$	15	0,023	20	0,017		
S_p =	0,222	%mass	20	0,010	30	0,005		
p =	0,482	[-]	30	0,008	40	0,002		
k_D =	2,299	[-]						

Parameters for each chloride profile			Da = 61,8	Csa=0,327	Da = 27,9	Csa=0,423	Da = 1,0	Csa=0,000
t =	100	yr	t =	0,7	t =	2,1	t =	
$D_a(t)$ =	3,7	mm^2/yr	$D_a(t)$ =	84,5	$D_a(t)$ =	42,6	$D_a(t)$ =	
C_{sa} =	0,882	w/w %	C_{sa} =	0,362	C_{sa} =	0,445	C_{sa} =	
Δx =	6	mm	Δx =	2	Δx =	3	Δx =	

Estimated chloride profile		**erf-sol.**	**Calculated chloride profiles (Mejlbro-Poulsen)**					
x	$C(x,t)$	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$
0	0,882	0,423	0	0,362	0	0,445		
6	0,661	0,396	2	0,285	3	0,332		
12	0,481	0,369	4	0,219	6	0,240		
18	0,339	0,342	6	0,165	9	0,168		
24	0,231	0,316	8	0,122	12	0,113		
30	0,152	0,291	10	0,088	15	0,074		
36	0,097	0,266	12	0,061	18	0,047		
42	0,059	0,243	14	0,042	21	0,028		
48	0,035	0,220	16	0,028	24	0,016		
54	0,020	0,199	18	0,018	27	0,009		
60	0,011	0,179	20	0,012	30	0,005		
66	0,006	0,160	22	0,007	33	0,003		
72	0,003	0,142	24	0,004	36	0,001		
78	0,001	0,125	26	0,002	39	0,001		
84	0,001	0,110	28	0,001	42	0,000		

C_1 =	0,386	D_1 =	68,9	C_{100} =	0,882	D_{100} =	3,7





Estimation of Chloride Ingress into Concrete

Model developed by Ervin Poulsen and Leif Mejlbro. Programmed by Jens M. Frederiksen.

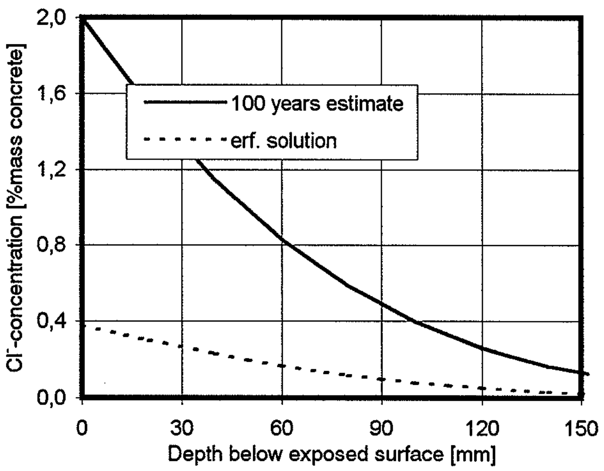
AEClaboratory		Date: 1997-03-26
Staktoften 20	**Sample identification**	Time: 22:36
DK-2950 Vedbæk	Träslövsläge: 12-35 (zone Sp)	Init: HES

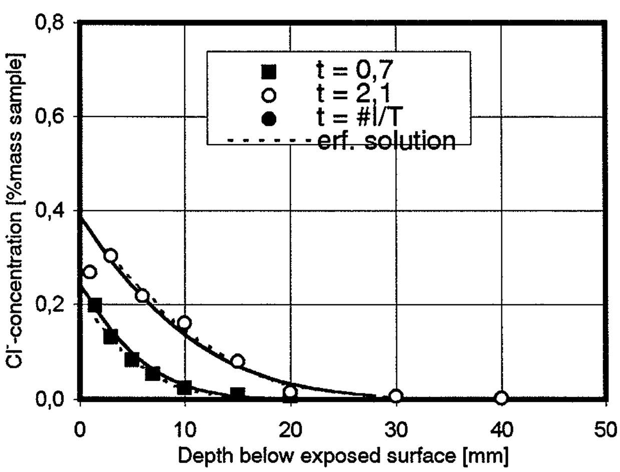
Input			**Measured profiles, natural exposure**					
Basic constants			t_{in} [yr] =	0,726	t_{in} [yr] =	2,129	t_{in} [yr] =	
t_{ex} =	0,04	yr	x	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$
C_i =	0	% mass	[mm]	[% mass]	[mm]	[% mass]	[mm]	[% mass]
w/c =	0,35	[-]	1,5	0,197	1	0,268		
Calculated parameter			3	0,132	3	0,303		
D_{pex} =	239	mm^2/yr	5	0,085	6	0,218		
Governing parameters			7	0,054	10	0,161		
α =	0,000	[-]	10	0,025	15	0,081		
S =	0,028	$\%mass/mm^{2p}$	15	0,009	20	0,017		
S_p =	0,071	%mass	20	0,007	30	0,007		
p =	0,424	[-]			40	0,003		
k_D =	0,189	[-]						

Parameters for each chloride profile			Da = 29,4	Csa=0,204	Da = 32,9	Csa=0,376	Da = 1,0	Csa=0,000
t =	100	yr	t =	0,7	t =	2,1	t =	
$D_a(t)$ =	45,0	mm^2/yr	$D_a(t)$ =	45,0	$D_a(t)$ =	45,0	$D_a(t)$ =	
C_{sa} =	2,000	w/w %	C_{sa} =	0,242	C_{sa} =	0,388	C_{sa} =	
Δx =	20	mm	Δx =	2	Δx =	2	Δx =	

Estimated chloride profile		**erf-sol.**	**Calculated chloride profiles (Mejlbro-Poulsen)**					
x	$C(x,t)$	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$
0	2,000	0,376	0	0,242	0	0,388		
20	1,535	0,303	2	0,175	2	0,324		
40	1,146	0,234	4	0,122	4	0,267		
60	0,831	0,173	6	0,081	6	0,217		
80	0,585	0,122	8	0,052	8	0,174		
100	0,399	0,082	10	0,031	10	0,138		
120	0,263	0,052	12	0,018	12	0,107		
140	0,168	0,032	14	0,010	14	0,082		
160	0,103	0,018	16	0,005	16	0,062		
180	0,061	0,010	18	0,003	18	0,046		
200	0,035	0,005	20	0,001	20	0,034		
220	0,019	0,003	22	0,001	22	0,024		
240	0,010	0,001	24	0,000	24	0,017		
260	0,005	0,001	26	0,000	26	0,012		
280	0,003	0,000	28	0,000	28	0,008		

C_1 =	0,279	D_1 =	45,0	C_{100} =	2,000	D_{100} =	45,0





Estimation of Chloride Ingress into Concrete

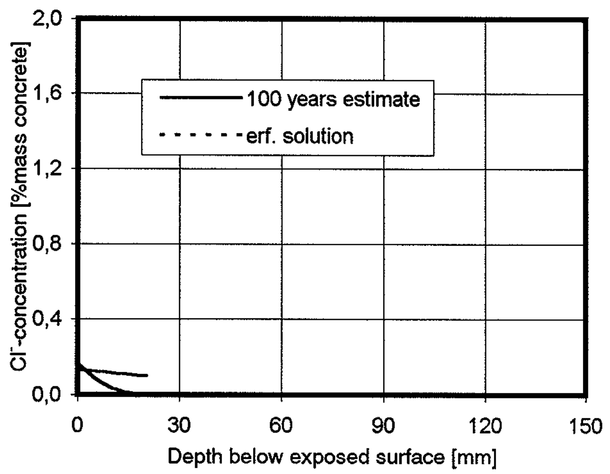
Model developed by Ervin Poulsen and Leif Mejlbro. Programmed by Jens M. Frederiksen.

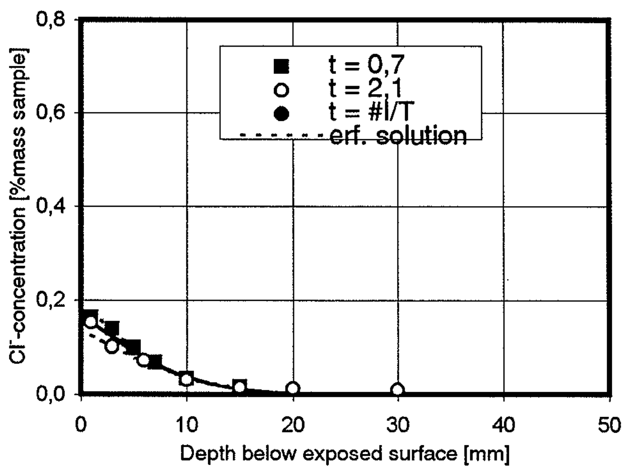
AEClaboratory		Date:	1997-03-26
Staktoften 20	**Sample identification**	Time:	22:32
DK-2950 Vedbæk	Träslövsläge: 12-35 (zone At)	Init:	HES

Input			Measured profiles, natural exposure					
Basic constants			t_{in} [yr] =	0,726	t_{in} [yr] =	2,129	t_{in} [yr] =	
t_{ex} =	0,04	yr	x	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$
C_i =	0	% mass	[mm]	[% mass]	[mm]	[% mass]	[mm]	[% mass]
w/c =	0,35	[-]	1	0,163	1	0,152		
Calculated parameter			3	0,139	3	0,102		
D_{pex} =	239	mm^2/yr	5	0,099	6	0,072		
Governing parameters			7	0,069	10	0,032		
α =	1,000	[-]	10	0,034	15	0,015		
S =	0,169	$\%mass/mm^{2p}$	15	0,016	20	0,013		
S_p =	0,169	%mass			30	0,010		
p =	0,000	[-]						
k_D =	3,843	[-]						

Parameters for each chloride profile			Da = 40,7	Csa=0,199	Da = 20,2	Csa=0,137	Da = 1,0	Csa=0,000
t =	100	yr	t =	0,7	t =	2,1	t =	
$D_a(t)$ =	0,4	mm^2/yr	$D_a(t)$ =	48,4	$D_a(t)$ =	16,5	$D_a(t)$ =	
C_{sa} =	0,169	w/w %	C_{sa} =	0,169	C_{sa} =	0,169	C_{sa} =	
Δx =	1,5	mm	Δx =	2	Δx =	2	Δx =	

Estimated chloride profile		erf-sol.	Calculated chloride profiles (Mejlbro-Poulsen)					
x	$C(x,t)$	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$
0	0,169	0,137	0	0,169	0	0,169		
2	0,145	0,134	2	0,136	2	0,137		
3	0,122	0,131	4	0,105	4	0,106		
5	0,100	0,129	6	0,078	6	0,079		
6	0,080	0,126	8	0,055	8	0,057		
8	0,063	0,124	10	0,037	10	0,039		
9	0,048	0,121	12	0,024	12	0,025		
11	0,036	0,119	14	0,015	14	0,016		
12	0,026	0,116	16	0,008	16	0,009		
14	0,018	0,114	18	0,005	18	0,005		
15	0,012	0,111	20	0,002	20	0,003		
17	0,008	0,109	22	0,001	22	0,001		
18	0,005	0,106	24	0,001	24	0,001		
20	0,003	0,104	26	0,000	26	0,000		
21	0,002	0,101	28	0,000	28	0,000		
C_1 =	0,169	D_1 =	35,2		C_{100} =	0,169	D_{100} =	0,4





Estimation of Chloride Ingress into Concrete

Model developed by Ervin Poulsen and Leif Mejlbro. Programmed by Jens M. Frederiksen.

AEClaboratory
Staktoften 20
DK-2950 Vedbæk

Sample identification
Träslövsläge: H3 (zone Su)

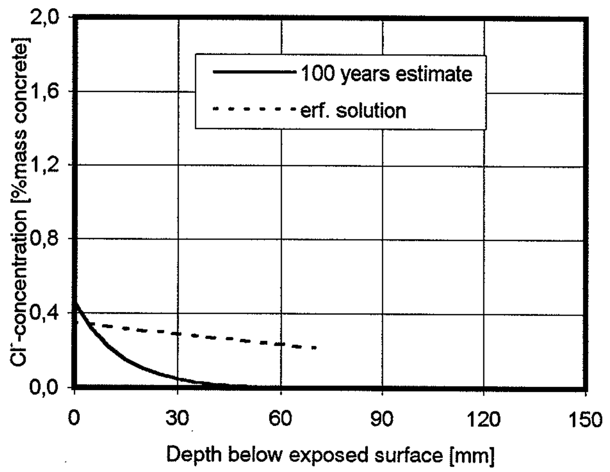
Date: 1997-03-26
Time: 22:44
Init: HES

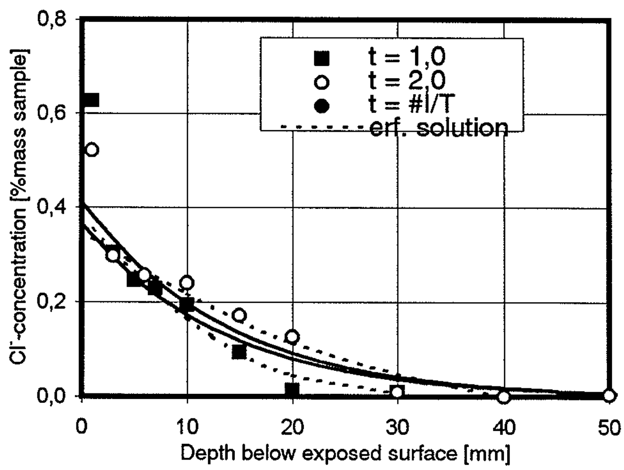
Input				**Measured profiles, natural exposure**					
Basic constants				t_{in} [yr] =	1,047	t_{in} [yr] =	2,088	t_{in} [yr] =	
t_{ex} =	0,04	yr		x	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$
C_i =	0	% mass		[mm]	[% mass]	[mm]	[% mass]	[mm]	[% mass]
w/c =	0,30	[-]		1	0,627	1	0,521		
Calculated parameter				3	0,303	3	0,297		
D_{pex} =	155	mm²/yr		5	0,246	6	0,256		
Governing parameters				7	0,229	10	0,240		
α =	1,000	[-]		10	0,193	15	0,172		
S =	0,000	%mass/mm^{2p}		15	0,094	20	0,127		
S_p =	0,463	%mass		20	0,014	30	0,010		
p =	6,354	[-]		30	0,009	40	0,000		
k_D =	213,308	[-]				50	0,004		

Parameters for each chloride profile			Da = 82.9 Csa=0.375		Da = 101.2 Csa=0.348		Da = 1.0 Csa=0.000	
t =	100	yr	t =	1,0	t =	2,0	t =	
$D_a(t)$ =	12,7	mm²/yr	$D_a(t)$ =	1215,2	$D_a(t)$ =	609,1	$D_a(t)$ =	
C_{sa} =	0,462	w/w %	C_{sa} =	0,365	C_{sa} =	0,411	C_{sa} =	
Δx =	5	mm	Δx =	5	Δx =	5	Δx =	

Estimated chloride profile		**erf-sol.**	**Calculated chloride profiles (Mejlbro-Poulsen)**					
x	$C(x,t)$	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$
0	0,462	0,348	0	0,365	0	0,411		
5	0,321	0,339	5	0,252	5	0,285		
10	0,222	0,329	10	0,173	10	0,197		
15	0,153	0,319	15	0,118	15	0,135		
20	0,105	0,309	20	0,081	20	0,092		
25	0,071	0,300	25	0,054	25	0,063		
30	0,048	0,290	30	0,037	30	0,042		
35	0,033	0,281	35	0,024	35	0,028		
40	0,022	0,271	40	0,016	40	0,019		
45	0,015	0,262	45	0,011	45	0,013		
50	0,010	0,253	50	0,007	50	0,008		
55	0,006	0,244	55	0,005	55	0,005		
60	0,004	0,235	60	0,003	60	0,004		
65	0,003	0,226	65	0,002	65	0,002		
70	0,002	0,217	70	0,001	70	0,001		

C_1 = 0,361 D_1 = 1271,8 C_{100} = 0,462 D_{100} = 12,7





Estimation of Chloride Ingress into Concrete

Model developed by Ervin Poulsen and Leif Mejlbro. Programmed by Jens M. Frederiksen.

AEClaboratory		Date: 1997-03-26
Staktoften 20	**Sample identification**	Time: 22:43
DK-2950 Vedbæk	Träslövsläge: H3 (zone Sp)	Init: HES

Input		
Basic constants		
t_{ex} =	0,04	yr
C_i =	0	% mass
w/c =	0,30	[-]
Calculated parameter		
D_{pex} =	155	mm^2/yr
Governing parameters		
α =	0,000	[-]
S =	0,023	$\%mass/mm^{2p}$
S_p =	0,052	%mass
p =	0,464	[-]
k_D =	0,356	[-]

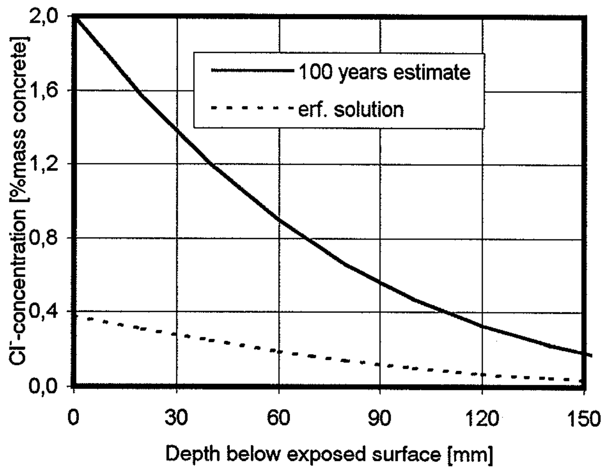
Measured profiles, natural exposure

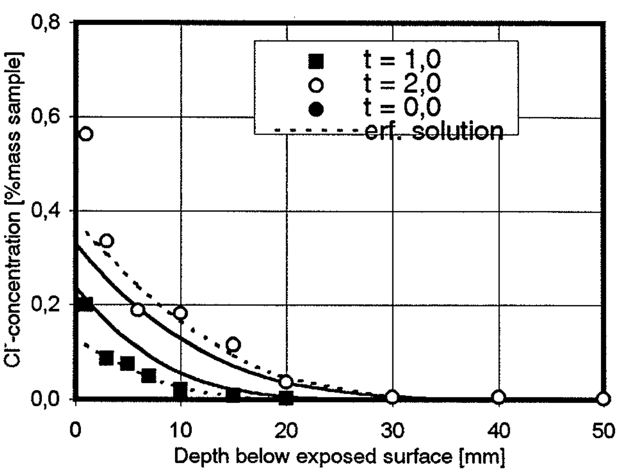
t_{in} [yr] =	1,047	t_{in} [yr] =	2,088	t_{in} [yr] =	
x [mm]	$C(x,t)$ [% mass]	x [mm]	$C(x,t)$ [% mass]	x [mm]	$C(x,t)$ [% mass]
1	0,198	1	0,562		
3	0,086	3	0,335		
5	0,075	6	0,188		
7	0,049	10	0,181		
10	0,021	15	0,114		
15	0,008	20	0,037		
20	0,003	30	0,005		
		40	0,006		
		50	0,003		

Parameters for each chloride profile		Da = 30.9 Csa=0.128		Da = 41.7 Csa=0.373		Da = 1.0 Csa=0.000	
t =	100 yr	t =	1,0	t =	2,0	t =	
$D_a(t)$ =	55,3 mm^2/yr	$D_a(t)$ =	55,3	$D_a(t)$ =	55,3	$D_a(t)$ =	
C_{sa} =	2,000 w/w %	C_{sa} =	0,237	C_{sa} =	0,329	C_{sa} =	
Δx =	20 mm	Δx =	1,75	Δx =	3	Δx =	

Estimated chloride profile		**erf-sol.**	**Calculated chloride profiles (Mejlbro-Poulsen)**					
x	$C(x,t)$	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$
0	2,000	0,373	0	0,237	0	0,329		
20	1,568	0,309	2	0,192	3	0,255		
40	1,202	0,247	4	0,153	6	0,193		
60	0,901	0,191	5	0,119	9	0,142		
80	0,659	0,142	7	0,092	12	0,102		
100	0,470	0,102	9	0,069	15	0,071		
120	0,327	0,070	11	0,051	18	0,048		
140	0,221	0,047	12	0,037	21	0,032		
160	0,145	0,030	14	0,026	24	0,020		
180	0,093	0,018	16	0,018	27	0,013		
200	0,058	0,011	18	0,013	30	0,008		
220	0,035	0,006	19	0,008	33	0,004		
240	0,020	0,003	21	0,005	36	0,002		
260	0,012	0,002	23	0,003	39	0,001		
280	0,006	0,001	25	0,002	42	0,001		

C_1 =	0,232	D_1 =	55,3	C_{100} =	2,000	D_{100} =	55,3





Estimation of Chloride Ingress into Concrete

Model developed by Ervin Poulsen and Leif Mejlbro. Programmed by Jens M. Frederiksen.

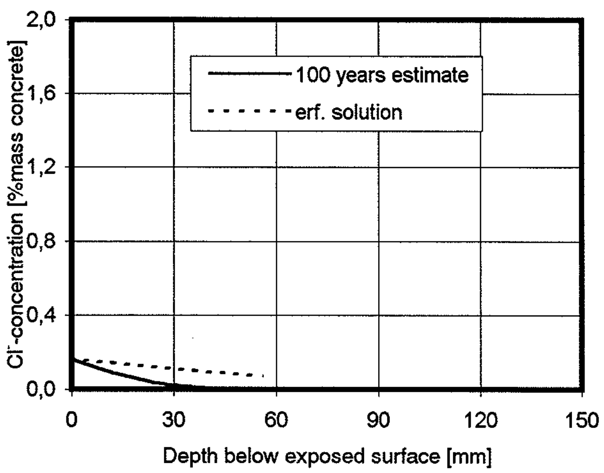
AEClaboratory		Date: 1997-03-26
Staktoften 20	**Sample identification**	Time: 22:43
DK-2950 Vedbæk	Träslövsläge: H3 (zone At)	Init: HES

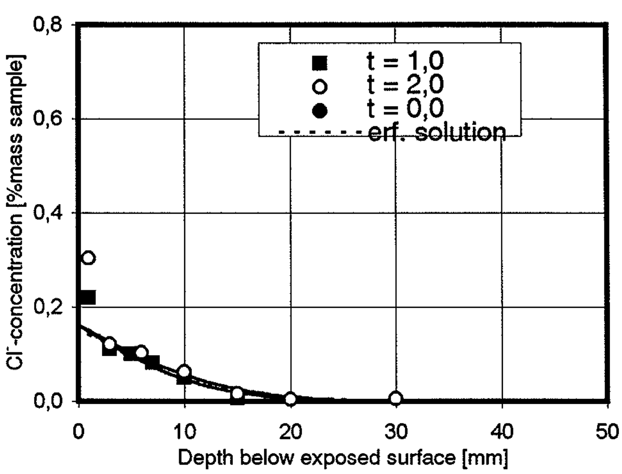
Input			**Measured profiles, natural exposure**					
Basic constants			t_{in} [yr] =	1,047	t_{in} [yr] =	2,088	t_{in} [yr] =	
t_{ex} =	0,04	yr	x	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$
C_i =	0	% mass	[mm]	[% mass]	[mm]	[% mass]	[mm]	[% mass]
w/c =	0,30	[-]	1	0,219	1	0,304		
Calculated parameter			3	0,111	3	0,121		
D_{pex} =	155	mm^2/yr	5	0,101	6	0,104		
Governing parameters			7	0,082	10	0,062		
α =	0,667	[-]	10	0,051	15	0,017		
S =	0,161	%mass/mm^{2p}	15	0,007	20	0,004		
S_p =	0,161	%mass			30	0,005		
p =	0,000	[-]						
k_D =	2,616	[-]						

Parameters for each chloride profile			Da = 47.4	Csa=0.157	Da = 27.0	Csa=0.166	Da = 1.0	Csa=0.000
t =	100	yr	t =	1,0	t =	2,0	t =	
$D_a(t)$ =	2,1	mm^2/yr	$D_a(t)$ =	44,8	$D_a(t)$ =	28,3	$D_a(t)$ =	
C_{sa} =	0,161	w/w %	C_{sa} =	0,161	C_{sa} =	0,161	C_{sa} =	
Δx =	4	mm	Δx =	1,75	Δx =	2	Δx =	

Estimated chloride profile		**erf-sol.**	**Calculated chloride profiles (Mejlbro-Poulsen)**					
x	$C(x,t)$	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$
0	0,161	0,166	0	0,161	0	0,161		
4	0,137	0,158	2	0,138	2	0,138		
8	0,113	0,151	4	0,115	4	0,115		
12	0,091	0,144	5	0,094	6	0,093		
16	0,071	0,137	7	0,075	8	0,074		
20	0,054	0,130	9	0,058	10	0,057		
24	0,040	0,123	11	0,044	12	0,043		
28	0,028	0,116	12	0,032	14	0,031		
32	0,020	0,110	14	0,023	16	0,022		
36	0,013	0,103	16	0,016	18	0,015		
40	0,009	0,097	18	0,011	20	0,010		
44	0,005	0,091	19	0,007	22	0,007		
48	0,003	0,085	21	0,004	24	0,004		
52	0,002	0,079	23	0,003	26	0,003		
56	0,001	0,074	25	0,002	28	0,002		

C_1 =	0,161	D_1 =	46,2	C_{100} =	0,161	D_{100} =	2,1





Estimation of Chloride Ingress into Concrete

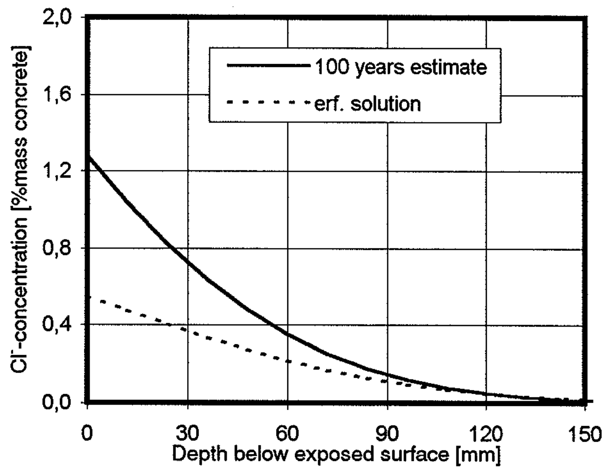
Model developed by Ervin Poulsen and Leif Mejlbro. Programmed by Jens M. Frederiksen.

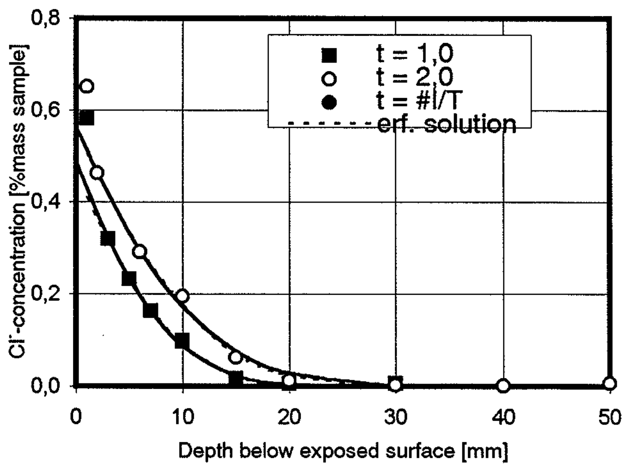
AEClaboratory		Date:	1997-03-24
Staktoften 20	**Sample identification**	Time:	15:37
DK-2950 Vedbæk	Träslövsläge: H1 (zone Su)	Init:	HES

Input			**Measured profiles, natural exposure**					
Basic constants			t_{in} [yr] =	1,047	t_{in} [yr] =	2,016	t_{in} [yr] =	
t_{ex} =	0,04	yr	x	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$
C_i =	0	% mass	[mm]	[% mass]	[mm]	[% mass]	[mm]	[% mass]
w/c =	0,30	[-]	1	0,580	1	0,652		
Calculated parameter			3	0,320	2	0,463		
D_{pex} =	155	mm^2/yr	5	0,232	6	0,292		
Governing parameters			7	0,163	10	0,194		
α =	0,121	[-]	10	0,097	15	0,062		
S =	0,162	$\%mass/mm^{2p}$	15	0,016	20	0,012		
S_p =	0,248	%mass	20	0,006	30	0,003		
p =	0,238	[-]	30	0,006	40	0,002		
k_D =	0,328	[-]			50	0,007		

Parameters for each chloride profile			Da = 29,4 Csa=0,456		Da = 25,0 Csa=0,551		Da = 1,0 Csa=0,000	
t =	100	yr	t =	1,0	t =	2,0	t =	
$D_a(t)$ =	19,7	mm^2/yr	$D_a(t)$ =	34,2	$D_a(t)$ =	31,6	$D_a(t)$ =	
C_{sa} =	1,279	w/w %	C_{sa} =	0,489	C_{sa} =	0,564	C_{sa} =	
Δx =	12	mm	Δx =	1,5	Δx =	2	Δx =	

Estimated chloride profile		**erf-sol.**	**Calculated chloride profiles (Mejlbro-Poulsen)**					
x	$C(x,t)$	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$
0	1,279	0,551	0	0,489	0	0,564		
12	1,038	0,476	1	0,430	1	0,512		
24	0,823	0,404	3	0,323	2	0,464		
36	0,637	0,336	5	0,234	6	0,295		
48	0,480	0,274	7	0,163	10	0,172		
60	0,353	0,218	10	0,087	15	0,077		
72	0,252	0,170	15	0,024	20	0,029		
84	0,175	0,129	20	0,005	30	0,003		
96	0,118	0,096	30	0,000	40	0,000		
108	0,077	0,070	23	0,002	50	0,000		
120	0,049	0,049	23	0,002	30	0,003		
132	0,030	0,034	23	0,002	30	0,003		
144	0,018	0,023	23	0,002	30	0,003		
156	0,010	0,015	23	0,002	30	0,003		
168	0,006	0,010	23	0,002	30	0,003		
C_1 =	0,485	D_1 =	34,4		C_{100} =	1,279	D_{100} =	19,7





Estimation of Chloride Ingress into Concrete

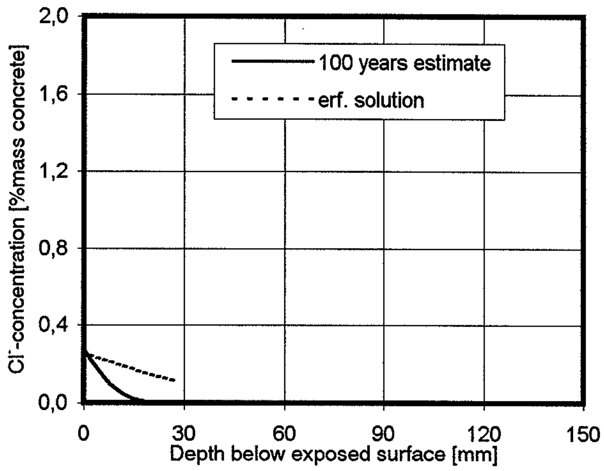
Model developed by Ervin Poulsen and Leif Mejlbro. Programmed by Jens M. Frederiksen.

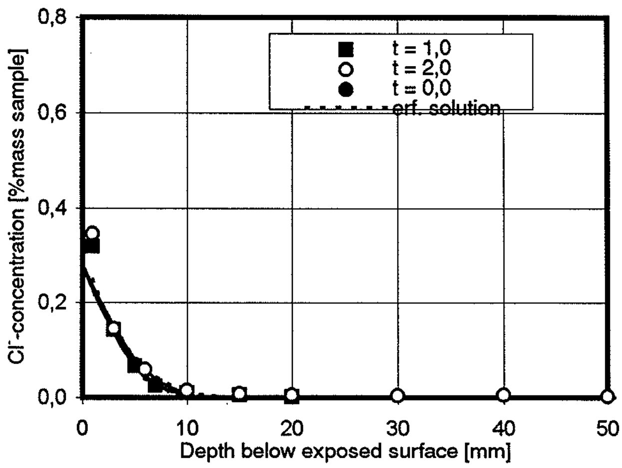
AEClaboratory		Date: 1997-03-24
Staktoften 20	**Sample identification**	Time: 15:41
DK-2950 Vedbæk	Träslövsläge: H1 (zone Sp)	Init: HES

Input			**Measured profiles, natural exposure**					
Basic constants			t_{in} [yr] =	1,047	t_{in} [yr] =	2,027	t_{in} [yr] =	
t_{ex} =	0,04	yr	x	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$
C_i =	0,000	% mass	[mm]	[% mass]	[mm]	[% mass]	[mm]	[% mass]
w/c =	0,30	[-]	1	0,318	1	0,345		
Calculated parameter			3	0,142	3	0,145		
D_{pex} =	155	mm^2/yr	5	0,066	6	0,060		
Governing parameters			7	0,024	10	0,015		
α =	0,710	[-]	10	0,010	15	0,008		
S =	0,281	$\%mass/mm^{2p}$	15	0,006	20	0,005		
S_p =	0,281	%mass	20	0,002	30	0,004		
p =	0,000	[-]			40	0,006		
k_D =	0,617	[-]			50	0,003		

Parameters for each chloride profile			Da = 8,0	Csa=0,310	Da = 6,5	Csa=0,260	Da = 1,0	Csa=0,000
t =	100	yr	t =	1,0	t =	2,0	t =	
$D_a(t)$ =	0,4	mm^2/yr	$D_a(t)$ =	9,2	$D_a(t)$ =	5,7	$D_a(t)$ =	
C_{sa} =	0,281	w/w %	C_{sa} =	0,281	C_{sa} =	0,281	C_{sa} =	
Δx =	2	mm	Δx =	0,75	Δx =	0,75	Δx =	

Estimated chloride profile		**erf-sol.**	**Calculated chloride profiles (Mejlbro-Poulsen)**					
x	$C(x,t)$	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$
0	0,281	0,260	0	0,281	0	0,281		
2	0,228	0,248	1	0,242	1	0,246		
4	0,179	0,237	2	0,204	2	0,212		
6	0,135	0,225	2	0,169	2	0,179		
8	0,097	0,214	3	0,136	3	0,149		
10	0,067	0,203	4	0,108	4	0,121		
12	0,044	0,192	5	0,083	5	0,097		
14	0,028	0,181	5	0,062	5	0,076		
16	0,017	0,171	6	0,046	6	0,059		
18	0,010	0,161	7	0,033	7	0,044		
20	0,005	0,151	8	0,023	8	0,033		
22	0,003	0,141	8	0,016	8	0,024		
24	0,001	0,132	9	0,010	9	0,017		
26	0,001	0,122	10	0,007	10	0,012		
28	0,000	0,114	11	0,004	11	0,008		
C_1 =	0,281	D_1 =	9,5		C_{100} =	0,281	D_{100} =	0,4





Estimation of Chloride Ingress into Concrete

Model developed by Ervin Poulsen and Leif Mejlbro. Programmed by Jens M. Frederiksen.

AEClaboratory
Staktoften 20
DK-2950 Vedbæk

Sample identification
Träslövsläge: H1 (zone At)

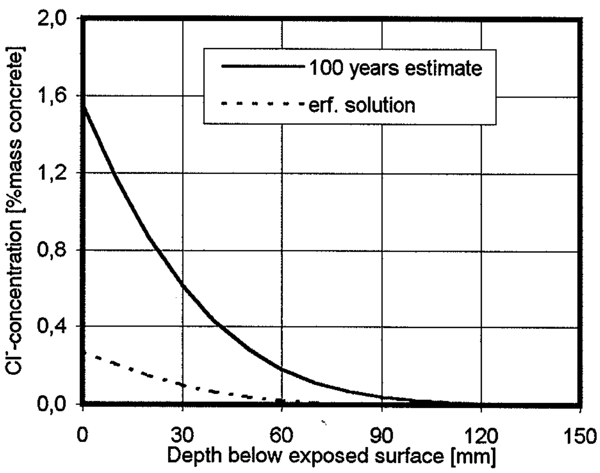
Date: 1997-03-24
Time: 15:46
Init: HES

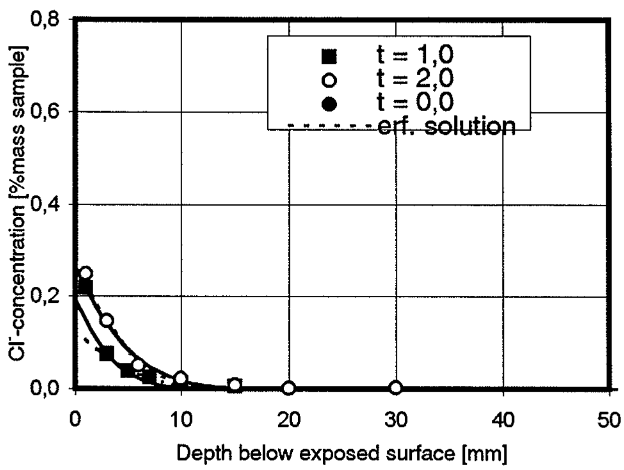
Input			**Measured profiles, natural exposure**					
Basic constants			t_{in} [yr] =	1,047	t_{in} [yr] =	2,027	t_{in} [yr] =	
t_{ex} =	0,04	yr	x	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$
C_i =	0	% mass	[mm]	[% mass]	[mm]	[% mass]	[mm]	[% mass]
w/c =	0,30	[-]	1	0,218	1	0,248		
Calculated parameter			3	0,075	3	0,146		
D_{pex} =	155	mm²/yr	5	0,039	6	0,051		
Governing parameters			7	0,025	10	0,022		
α =	0,000	[-]	10	0,012	15	0,008		
S =	0,020	%mass/mm^{2p}	15	0,005	20	0,002		
S_p =	0,044	%mass			30	0,003		
p =	0,453	[-]						
k_D =	0,068	[-]						

Parameters for each chloride profile			Da = 14,4 Csa=0,126		Da = 5,9 Csa=0,269		Da = 1,0 Csa=0,000	
t =	100	yr	t =	1,0	t =	2,0	t =	
$D_a(t)$ =	10,6	mm²/yr	$D_a(t)$ =	10,6	$D_a(t)$ =	10,6	$D_a(t)$ =	
C_{sa} =	1,553	w/w %	C_{sa} =	0,194	C_{sa} =	0,264	C_{sa} =	
Δx =	10	mm	Δx =	1	Δx =	2	Δx =	

Estimated chloride profile		**erf-sol.**	**Calculated chloride profiles (Mejlbro-Poulsen)**					
x	$C(x,t)$	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$
0	1,553	0,269	0	0,194	0	0,264		
10	1,175	0,207	1	0,147	2	0,176		
20	0,864	0,151	2	0,108	4	0,111		
30	0,616	0,103	3	0,077	6	0,065		
40	0,425	0,066	4	0,053	8	0,036		
50	0,284	0,039	5	0,036	10	0,018		
60	0,183	0,022	6	0,023	12	0,009		
70	0,114	0,011	7	0,014	14	0,004		
80	0,068	0,005	8	0,009	16	0,002		
90	0,039	0,002	9	0,005	18	0,001		
100	0,022	0,001	10	0,003	20	0,000		
110	0,012	0,000	11	0,001	22	0,000		
120	0,006	0,000	12	0,001	24	0,000		
130	0,003	0,000	13	0,000	26	0,000		
140	0,001	0,000	14	0,000	28	0,000		

C_1 = 0,190 D_1 = 10,6 C_{100} = 1,553 D_{100} = 10,6





Estimation of Chloride Ingress into Concrete

Model developed by Ervin Poulsen and Leif Mejlbro. Programmed by Jens M. Frederiksen.

AEClaboratory
Staktoften 20
DK-2950 Vedbæk

Date: 1997-03-24
Time: 15:48
Init: HES

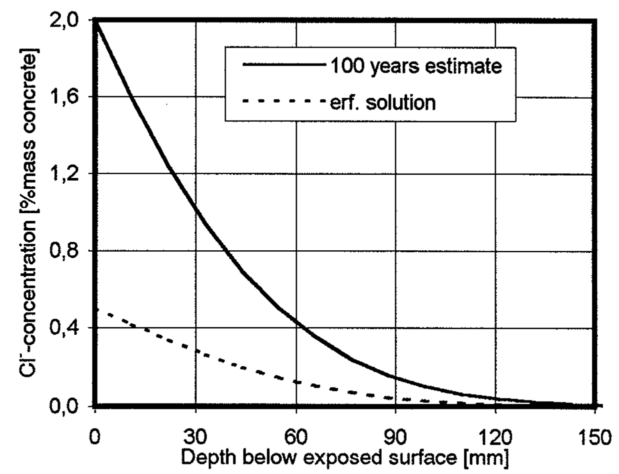
Sample identification
Träslövsläge: H2 (zone Su)

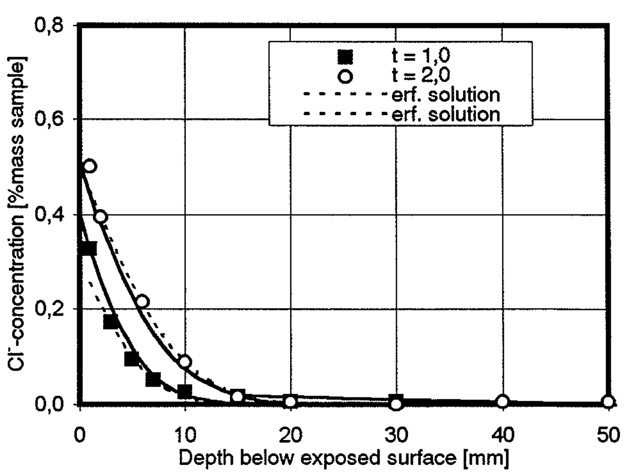
Input			**Measured profiles, natural exposure**					
Basic constants			t_{in} [yr] =	1,047	t_{in} [yr] =	2,027	t_{in} [yr] =	
t_{ex} =	0,04	yr	x	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$
C_i =	0	% mass	[mm]	[% mass]	[mm]	[% mass]	[mm]	[% mass]
w/c =	0,30	[-]	1	0,326	1	0,500		
Calculated parameter			3	0,172	2	0,394		
D_{pex} =	155	mm^2/yr	5	0,094	6	0,214		
Governing parameters			7	0,051	10	0,089		
α =	0,000	[-]	10	0,025	15	0,016		
S =	0,069	$\%mass/mm^{2p}$	15	0,016	20	0,006		
S_p =	0,129	%mass	20	0,005	30	0,000		
p =	0,348	[-]	30	0,006	40	0,005		
k_D =	0,105	[-]			50	0,005		

Parameters for each chloride profile			Da = 13,4	Csa=0,299	Da = 13,9	Csa=0,502	Da = 1,0	Csa=0,000
t =	100	yr	t =	1,0	t =	2,0	t =	
$D_a(t)$ =	16,3	mm^2/yr	$D_a(t)$ =	16,3	$D_a(t)$ =	16,3	$D_a(t)$ =	
C_{sa} =	2,000	w/w %	C_{sa} =	0,403	C_{sa} =	0,511	C_{sa} =	
Δx =	11	mm	Δx =	1	Δx =	1	Δx =	

Estimated chloride profile		**erf-sol.**	**Calculated chloride profiles (Mejlbro-Poulsen)**					
x	$C(x,t)$	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$
0	2,000	0,502	0	0,403	0	0,511		
11	1,591	0,419	1	0,328	1	0,442		
22	1,237	0,339	3	0,205	2	0,379		
33	0,938	0,267	5	0,118	6	0,185		
44	0,694	0,203	7	0,062	10	0,076		
55	0,500	0,149	10	0,020	15	0,019		
66	0,351	0,106	15	0,002	20	0,003		
77	0,239	0,072	20	0,000	30	0,000		
88	0,158	0,048	30	0,000	40	0,000		
99	0,102	0,030	15	0,002	50	0,000		
110	0,064	0,018	15	0,002	15	0,019		
121	0,038	0,011	15	0,002	15	0,019		
132	0,023	0,006	15	0,002	15	0,019		
143	0,013	0,003	15	0,002	15	0,019		
154	0,007	0,002	15	0,002	15	0,019		

C_1 = 0,397 D_1 = 16,3 C_{100} = 2,000 D_{100} = 16,3





Estimation of Chloride Ingress into Concrete

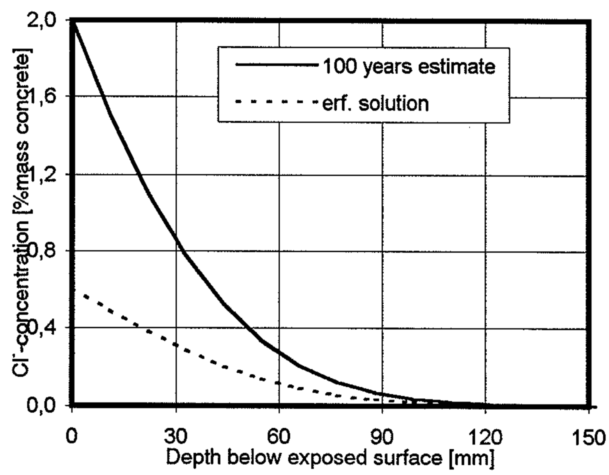
Model developed by Ervin Poulsen and Leif Mejlbro. Programmed by Jens M. Frederiksen.

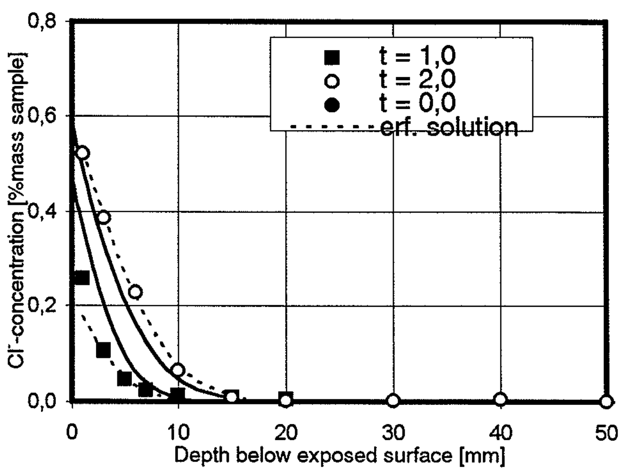
AEClaboratory		Date:	1997-03-24
Staktoften 20	**Sample identification**	Time:	16:00
DK-2950 Vedbæk	Träslövsläge: H2 (zone Sp)	Init:	HES

Input			**Measured profiles, natural exposure**					
Basic constants			t_{in} [yr] =	1,047	t_{in} [yr] =	2,027	t_{in} [yr] =	
t_{ex} =	0,04	yr	x	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$
C_i =	0	% mass	[mm]	[% mass]	[mm]	[% mass]	[mm]	[% mass]
w/c =	0,30	[-]	1	0,257	1	0,522		
Calculated parameter			3	0,106	3	0,386		
D_{pex} =	155	mm^2/yr	5	0,047	6	0,228		
Governing parameters			7	0,024	10	0,066		
α =	0,000	[-]	10	0,013	15	0,009		
S =	0,097	%mass/mm^{2p}	15	0,009	20	0,003		
S_p =	0,170	%mass	20	0,006	30	0,003		
p =	0,313	[-]			40	0,005		
k_D =	0,068	[-]			50	0,002		

Parameters for each chloride profile			Da = 9,2	Csa=0,213	Da = 10,7	Csa=0,605	Da = 1,0	Csa=0,000
t =	100	yr	t =	1,0	t =	2,0	t =	
$D_a(t)$ =	10,6	mm^2/yr	$D_a(t)$ =	10,6	$D_a(t)$ =	10,6	$D_a(t)$ =	
C_{sa} =	2,000	w/w %	C_{sa} =	0,474	C_{sa} =	0,586	C_{sa} =	
Δx =	11	mm	Δx =	1	Δx =	2	Δx =	

Estimated chloride profile		**erf-sol.**	**Calculated chloride profiles (Mejlbro-Poulsen)**					
x	$C(x,t)$	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$
0	2,000	0,605	0	0,474	0	0,586		
11	1,511	0,491	1	0,368	1	0,492		
22	1,102	0,384	3	0,204	3	0,330		
33	0,773	0,288	5	0,099	6	0,161		
44	0,521	0,207	7	0,042	10	0,049		
55	0,337	0,142	10	0,009	15	0,007		
66	0,208	0,093	15	0,000	20	0,001		
77	0,123	0,058	20	0,000	30	0,000		
88	0,069	0,035	15	0,000	40	0,000		
99	0,037	0,020	15	0,000	50	0,000		
110	0,019	0,011	15	0,000	30	0,000		
121	0,009	0,005	15	0,000	30	0,000		
132	0,004	0,003	15	0,000	30	0,000		
143	0,002	0,001	15	0,000	30	0,000		
154	0,001	0,001	15	0,000	30	0,000		
C_1 =	0,467	D_1 =	10,6		C_{100} =	2,000	D_{100} =	10,6





Estimation of Chloride Ingress into Concrete

Model developed by Ervin Poulsen and Leif Mejlbro. Programmed by Jens M. Frederiksen.

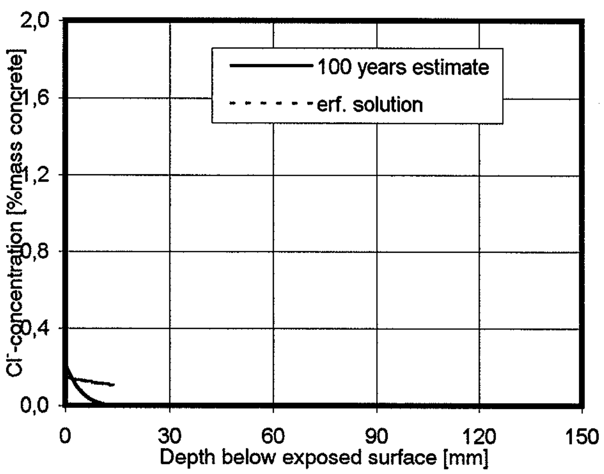
AEClaboratory		Date: 1997-03-24
Staktoften 20	**Sample identification**	Time: 15:57
DK-2950 Vedbæk	Träslövsläge: H2 (zone At)	Init: HES

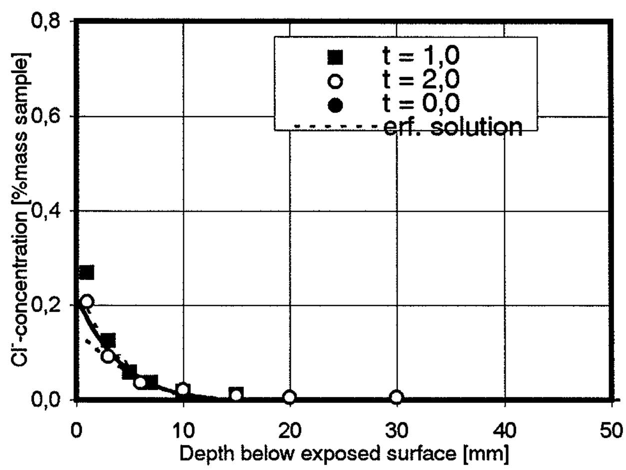
Input			**Measured profiles, natural exposure**					
Basic constants			t_{in} [yr] =	1,047	t_{in} [yr] =	2,027	t_{in} [yr] =	
t_{ex} =	0,04	yr	x	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$
C_i =	0,000	% mass	[mm]	[% mass]	[mm]	[% mass]	[mm]	[% mass]
w/c =	0,30	[-]	1	0,268	1	0,206		
Calculated parameter			3	0,124	3	0,092		
D_{pex} =	155	mm²/yr	5	0,058	6	0,036		
Governing parameters			7	0,036	10	0,021		
α =	1,000	[-]	10	0,018	15	0,009		
S =	0,044	%mass/mm^{2p}	15	0,011	20	0,005		
S_p =	0,219	%mass			30	0,005		
p =	0,904	[-]						
k_D =	4,298	[-]						

Parameters for each chloride profile			Da = 11,7	Csa=0,223	Da = 8,8	Csa=0,145	Da = 1,0	Csa=0,000
t =	100	yr	t =	1,0	t =	2,0	t =	
$D_a(t)$ =	0,3	mm²/yr	$D_a(t)$ =	24,5	$D_a(t)$ =	12,6	$D_a(t)$ =	
C_{sa} =	0,219	w/w %	C_{sa} =	0,212	C_{sa} =	0,215	C_{sa} =	
Δx =	1	mm	Δx =	1	Δx =	1	Δx =	

Estimated chloride profile		**erf-sol.**	**Calculated chloride profiles (Mejlbro-Poulsen)**					
x	$C(x,t)$	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$
0	0,219	0,145	0	0,212	0	0,215		
1	0,176	0,142	1	0,169	1	0,172		
2	0,139	0,140	2	0,134	2	0,136		
3	0,109	0,137	3	0,104	3	0,107		
4	0,085	0,134	4	0,080	4	0,083		
5	0,065	0,131	5	0,061	5	0,063		
6	0,049	0,129	6	0,046	6	0,047		
7	0,037	0,126	7	0,034	7	0,035		
8	0,027	0,123	8	0,025	8	0,026		
9	0,020	0,121	9	0,018	9	0,019		
10	0,014	0,118	10	0,013	10	0,013		
11	0,010	0,115	11	0,009	11	0,009		
12	0,007	0,112	12	0,006	12	0,007		
13	0,005	0,110	13	0,004	13	0,004		
14	0,003	0,107	14	0,003	14	0,003		

C_1 =	0,211	D_1 =	25,6	C_{100} =	0,219	D_{100} =	0,3





Estimation of Chloride Ingress into Concrete

Model developed by Ervin Poulsen and Leif Mejlbro. Programmed by Jens M. Frederiksen.

AEClaboratory		Date:	1997-03-26
Staktoften 20	**Sample identification**	Time:	22:48
DK-2950 Vedbæk	Träslövsläge: H8 (zone Su)	Init:	HES

Input		
Basic constants		
t_{ex} =	0,04	yr
C_i =	0	% mass
w/c =	0,30	[-]
Calculated parameter		
D_{pex} =	155	mm^2/yr
Governing parameters		
α =	1,000	[-]
S =	0,414	$\%mass/mm^{2p}$
S_p =	0,414	%mass
p =	0,000	[-]
k_D =	12,282	[-]

Measured profiles, natural exposure

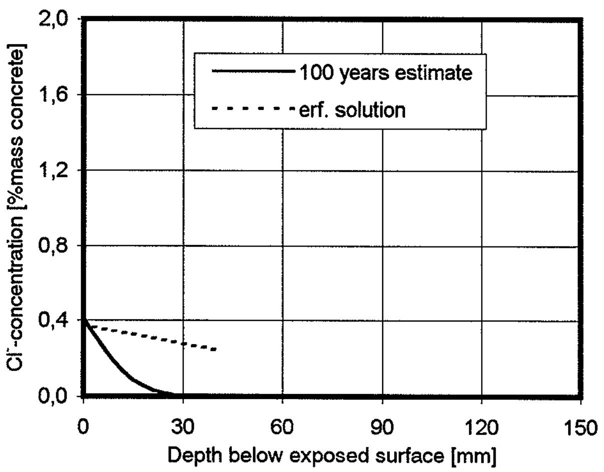
t_{in} [yr] =	1,047	t_{in} [yr] =	2,088	t_{in} [yr] =	
x [mm]	$C(x,t)$ [% mass]	x [mm]	$C(x,t)$ [% mass]	x [mm]	$C(x,t)$ [% mass]
1	0,587	1	0,517		
3	0,361	3	0,318		
5	0,258	6	0,203		
7	0,252	10	0,205		
10	0,201	15	0,103		
15	0,065	20	0,013		
20	0,011	30	0,001		
30	0,001	40	0,001		
		50	0,002		

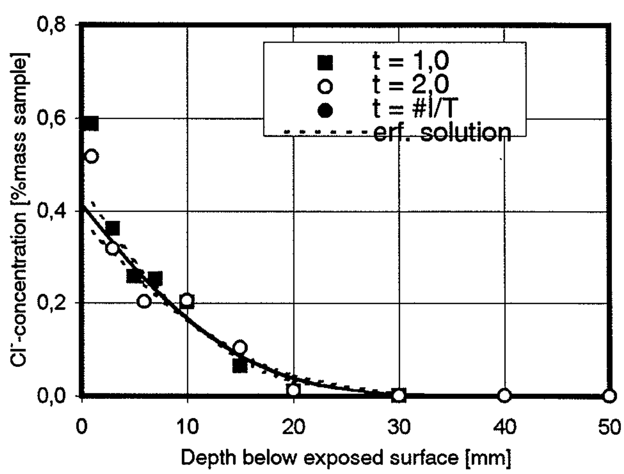
Parameters for each chloride profile			Da = 62,0 Csa=0,447		Da = 40,3 Csa=0,377		Da = 1,0 Csa=0,000	
t =	100	yr	t =	1,0	t =	2,0	t =	
$D_a(t)$ =	0,7	mm^2/yr	$D_a(t)$ =	70,0	$D_a(t)$ =	35,1	$D_a(t)$ =	
C_{sa} =	0,414	w/w %	C_{sa} =	0,414	C_{sa} =	0,414	C_{sa} =	
Δx =	3	mm	Δx =	3	Δx =	3	Δx =	

Estimated chloride profile / **erf-sol.** / **Calculated chloride profiles (Mejlbro-Poulsen)**

x	$C(x,t)$	$C(x,t)$ erf-sol.	x	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$
0	0,414	0,377	0	0,414	0	0,414		
3	0,333	0,367	3	0,332	3	0,333		
6	0,257	0,357	6	0,254	6	0,256		
9	0,189	0,347	9	0,186	9	0,188		
12	0,133	0,337	12	0,129	12	0,131		
15	0,089	0,327	15	0,086	15	0,087		
18	0,057	0,317	18	0,054	18	0,055		
21	0,034	0,307	21	0,032	21	0,033		
24	0,020	0,298	24	0,018	24	0,019		
27	0,011	0,288	27	0,010	27	0,010		
30	0,005	0,279	30	0,005	30	0,005		
33	0,003	0,269	33	0,002	33	0,002		
36	0,001	0,260	36	0,001	36	0,001		
39	0,001	0,251	39	0,000	39	0,000		
42	0,000	0,241	42	0,000	42	0,000		

C_1 =	0,414	D_1 =	73,2	C_{100} =	0,414	D_{100} =	0,7





Estimation of Chloride Ingress into Concrete

Model developed by Ervin Poulsen and Leif Mejlbro. Programmed by Jens M. Frederiksen.

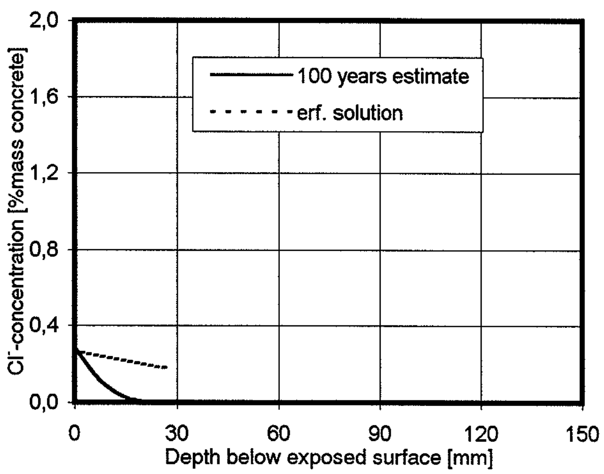
AEClaboratory		Date: 1997-03-26
Staktoften 20	**Sample identification**	Time: 22:47
DK-2950 Vedbæk	Träslövsläge: H8 (zone Sp)	Init: HES

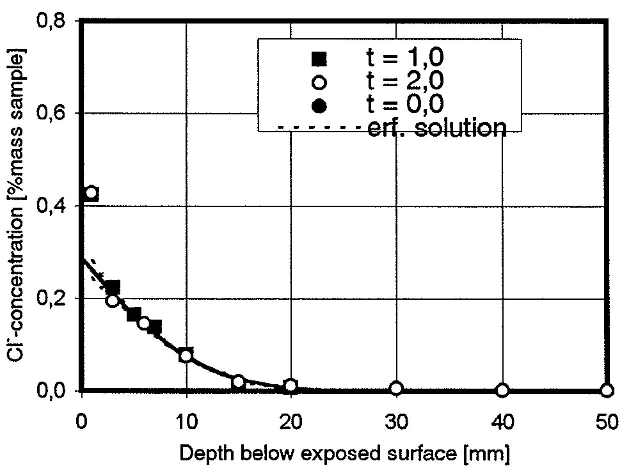
Input			**Measured profiles, natural exposure**					
Basic constants			t_{in} [yr] =	1,047	t_{in} [yr] =	2,088	t_{in} [yr] =	
t_{ex} =	0,04	yr	x	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$
C_i =	0	% mass	[mm]	[% mass]	[mm]	[% mass]	[mm]	[% mass]
w/c =	0,30	[-]	1	0,423	1	0,428		
Calculated parameter			3	0,223	3	0,194		
D_{pex} =	155	mm²/yr	5	0,164	6	0,145		
Governing parameters			7	0,137	10	0,075		
α =	1,000	[-]	10	0,077	15	0,020		
S =	0,288	%mass/mm^{2p}	15	0,011	20	0,011		
S_p =	0,288	%mass	20	0,007	30	0,005		
p =	0,000	[-]			40	0,002		
k_D =	6,771	[-]			50	0,001		

Parameters for each chloride profile			Da = 35,7	Csa=0,308	Da = 21,0	Csa=0,266	Da = 1,0	Csa=0,000
t =	100	yr	t =	1,0	t =	2,0	t =	
$D_a(t)$ =	0,4	mm²/yr	$D_a(t)$ =	38,6	$D_a(t)$ =	19,3	$D_a(t)$ =	
C_{sa} =	0,288	w/w %	C_{sa} =	0,288	C_{sa} =	0,288	C_{sa} =	
Δx =	2	mm	Δx =	1,5	Δx =	2	Δx =	

Estimated chloride profile		**erf-sol.**	**Calculated chloride profiles (Mejlbro-Poulsen)**					
x	$C(x,t)$	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$
0	0,288	0,266	0	0,288	0	0,288		
2	0,237	0,259	2	0,249	2	0,237		
4	0,189	0,253	3	0,211	4	0,188		
6	0,145	0,246	5	0,176	6	0,144		
8	0,108	0,240	6	0,143	8	0,106		
10	0,077	0,233	8	0,114	10	0,075		
12	0,052	0,227	9	0,089	12	0,051		
14	0,034	0,220	11	0,067	14	0,033		
16	0,022	0,214	12	0,050	16	0,021		
18	0,013	0,208	14	0,036	18	0,012		
20	0,007	0,201	15	0,026	20	0,007		
22	0,004	0,195	17	0,018	22	0,004		
24	0,002	0,189	18	0,012	24	0,002		
26	0,001	0,183	20	0,008	26	0,001		
28	0,001	0,177	21	0,005	28	0,000		

C_1 =	0,288	D_1 =	40,4	C_{100} =	0,288	D_{100} =	0,4





Estimation of Chloride Ingress into Concrete

Model developed by Ervin Poulsen and Leif Mejlbro. Programmed by Jens M. Frederiksen.

AEClaboratory
Staktoften 20
DK-2950 Vedbæk

Sample identification	
Träslövsläge:	H8 (zone At)

Date: 1997-03-26
Time: 22:46
Init: HES

Input

Basic constants

t_{ex} =	0,04	yr
C_i =	0,000	% mass
w/c =	0,30	[-]

Calculated parameter

D_{pex} =	155	mm^2/yr

Governing parameters

α =	0,000	[-]
S =	0,063	$\%mass/mm^{2p}$
S_p =	0,098	%mass
p =	0,243	[-]
k_D =	0,156	[-]

Measured profiles, natural exposure

t_{in} [yr] =	1,047	t_{in} [yr] =	2,088	t_{in} [yr] =	
x [mm]	$C(x,t)$ [% mass]	x [mm]	$C(x,t)$ [% mass]	x [mm]	$C(x,t)$ [% mass]
1	0,224	1	0,380		
3	0,128	3	0,179		
5	0,087	6	0,132		
7	0,061	10	0,058		
10	0,020	15	0,000		
15	0,001	20	0,000		
		30	0,001		

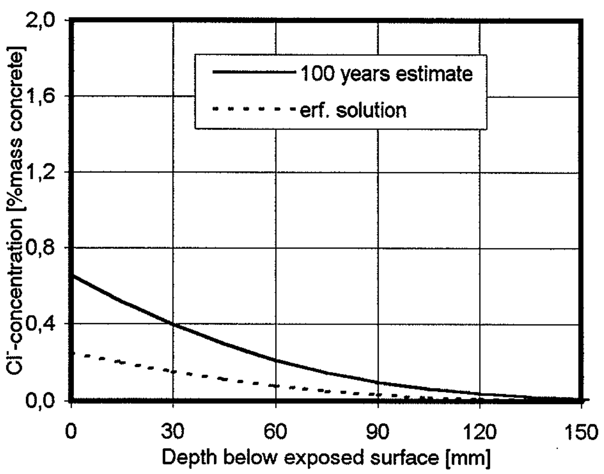
Parameters for each chloride profile

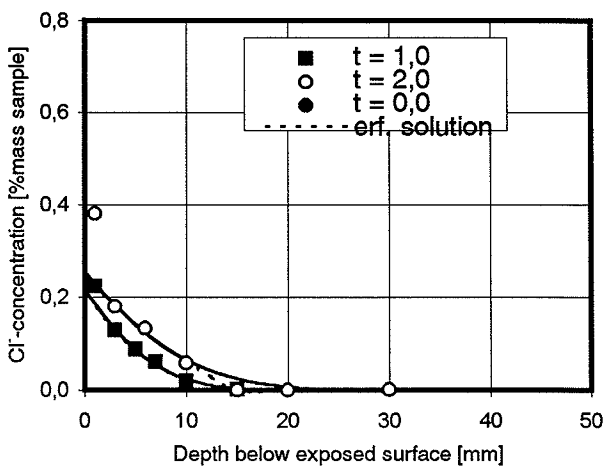
			Da = 20,5 Csa=0,201		Da = 18,9 Csa=0,249		Da = 1,0 Csa=0,000	
t =	100	yr	t =	1,0	t =	2,0	t =	
$D_a(t)$ =	24,2	mm^2/yr	$D_a(t)$ =	24,2	$D_a(t)$ =	24,2	$D_a(t)$ =	
C_{sa} =	0,660	w/w %	C_{sa} =	0,216	C_{sa} =	0,257	C_{sa} =	
Δx =	15	mm	Δx =	1,5	Δx =	2	Δx =	

Estimated chloride profile / Calculated chloride profiles (Mejlbro-Poulsen)

Estimated chloride profile x	$C(x,t)$	erf-sol. $C(x,t)$	x	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$
0	0,660	0,249	0	0,216	0	0,257		
15	0,520	0,201	2	0,170	2	0,206		
30	0,398	0,156	3	0,130	4	0,161		
45	0,295	0,116	5	0,097	6	0,122		
60	0,212	0,082	6	0,070	8	0,090		
75	0,147	0,055	8	0,048	10	0,065		
90	0,098	0,036	9	0,032	12	0,045		
105	0,063	0,022	11	0,021	14	0,031		
120	0,039	0,013	12	0,013	16	0,020		
135	0,024	0,007	14	0,008	18	0,013		
150	0,014	0,004	15	0,005	20	0,008		
165	0,007	0,002	17	0,003	22	0,005		
180	0,004	0,001	18	0,001	24	0,003		
195	0,002	0,000	20	0,001	26	0,001		
210	0,001	0,000	21	0,000	28	0,001		

C_1 = 0,213 D_1 = 24,2 C_{100} = 0,660 D_{100} = 24,2





Estimation of Chloride Ingress into Concrete

Model developed by Ervin Poulsen and Leif Mejlbro. Programmed by Jens M. Frederiksen.

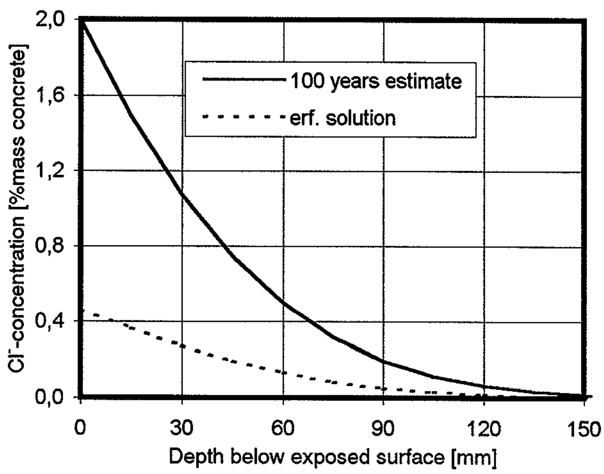
AEClaboratory		Date: 1997-03-26
Staktoften 20	**Sample identification**	Time: 13:12
DK-2950 Vedbæk	Träslövsläge: H5 (zone Su)	Init: HES

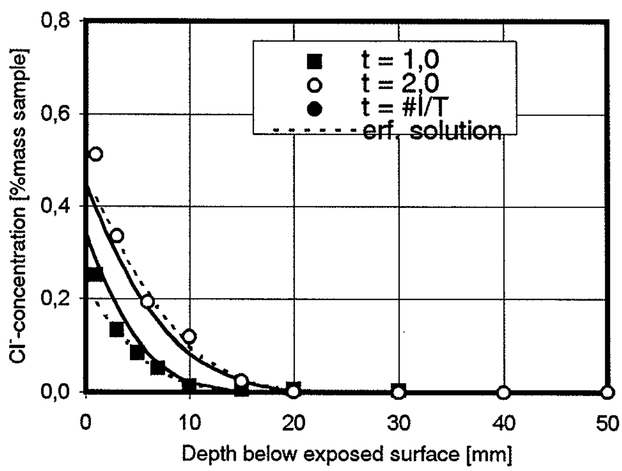
Input			**Measured profiles, natural exposure**					
Basic constants			t_{in} [yr] =	1,047	t_{in} [yr] =	2,074	t_{in} [yr] =	
t_{ex} =	0,04	yr	x	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$
C_i =	0	% mass	[mm]	[% mass]	[mm]	[% mass]	[mm]	[% mass]
w/c =	0,25	[-]	1	0,251	1	0,512		
Calculated parameter			3	0,132	3	0,335		
D_{pex} =	90	mm²/yr	5	0,085	6	0,193		
Governing parameters			7	0,053	10	0,118		
α =	0,000	[-]	10	0,014	15	0,025		
S =	0,061	%mass/mm^{2p}	15	0,006	20	0,001		
S_p =	0,098	%mass	20	0,007	30	0,000		
p =	0,383	[-]	30	0,004	40	0,000		
k_D =	0,222	[-]			50	0,002		

Parameters for each chloride profile			Da = 16,8	Csa=0,218	Da = 16,2	Csa=0,461	Da = 1,0	Csa=0,000
t =	100	yr	t =	1,0	t =	2,0	t =	
$D_a(t)$ =	19,9	mm²/yr	$D_a(t)$ =	19,9	$D_a(t)$ =	19,9	$D_a(t)$ =	
C_{sa} =	2,000	w/w %	C_{sa} =	0,344	C_{sa} =	0,450	C_{sa} =	
Δx =	15	mm	Δx =	1,5	Δx =	2	Δx =	

Estimated chloride profile		**erf-sol.**	**Calculated chloride profiles (Mejlbro-Poulsen)**					
x	$C(x,t)$	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$
0	2,000	0,461	0	0,344	0	0,450		
15	1,493	0,365	1	0,284	1	0,394		
30	1,076	0,275	3	0,185	3	0,296		
45	0,747	0,197	5	0,113	6	0,181		
60	0,498	0,134	7	0,065	10	0,083		
75	0,319	0,086	10	0,024	15	0,026		
90	0,196	0,052	15	0,003	20	0,006		
105	0,115	0,030	20	0,000	30	0,000		
120	0,064	0,016	30	0,000	40	0,000		
135	0,035	0,008	23	0,000	50	0,000		
150	0,018	0,004	23	0,000	30	0,000		
165	0,009	0,002	23	0,000	30	0,000		
180	0,004	0,001	23	0,000	30	0,000		
195	0,002	0,000	23	0,000	30	0,000		
210	0,001	0,000	23	0,000	30	0,000		

C_1 =	0,338	D_1 =	19,9	C_{100} =	2,000	D_{100} =	19,9





Estimation of Chloride Ingress into Concrete

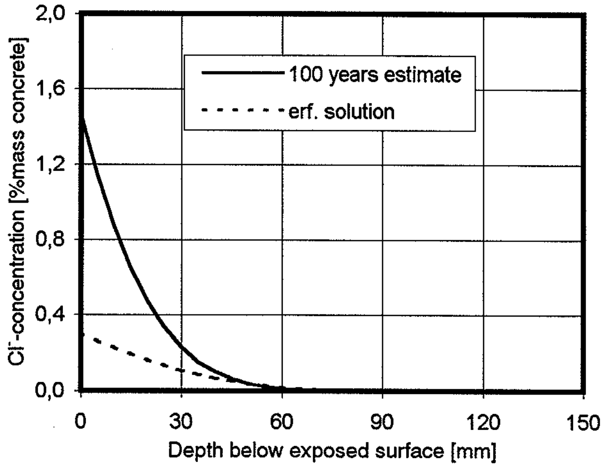
Model developed by Ervin Poulsen and Leif Mejlbro. Programmed by Jens M. Frederiksen.

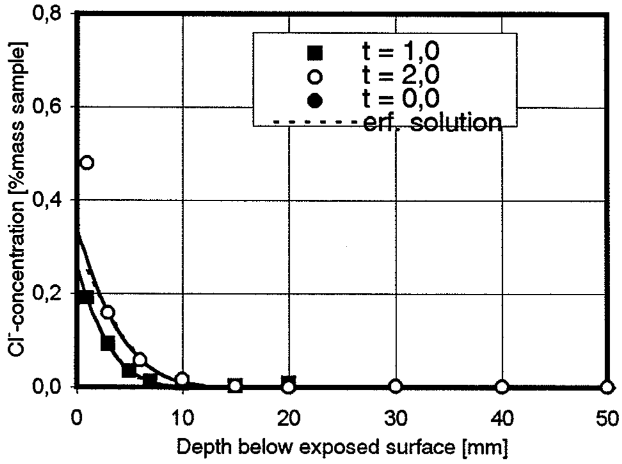
AEClaboratory		Date: 1997-03-26
Staktoften 20	**Sample identification**	Time: 13:10
DK-2950 Vedbæk	Träslövsläge: H5 (zone Sp)	Init: HES

Input			Measured profiles, natural exposure					
Basic constants			t_{in} [yr] =	1,047	t_{in} [yr] =	2,074	t_{in} [yr] =	
t_{ex} =	0,04	yr	x	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$
C_i =	0	% mass	[mm]	[% mass]	[mm]	[% mass]	[mm]	[% mass]
w/c =	0,25	[-]	1	0,191	1	0,479		
Calculated parameter			3	0,092	3	0,158		
D_{pex} =	90	mm^2/yr	5	0,034	6	0,058		
Governing parameters			7	0,012	10	0,017		
α =	0,204	[-]	10	0,008	15	0,003		
S =	0,043	%mass/mm^{2p}	15	0,003	20	0,000		
S_p =	0,076	%mass	20	0,008	30	0,003		
p =	0,472	[-]			40	0,001		
k_D =	0,186	[-]			50	0,001		

Parameters for each chloride profile			Da = 6,1	Csa=0,233	Da = 5,6	Csa=0,297	Da = 1,0	Csa=0,000
t =	100	yr	t =	1,0	t =	2,0	t =	
$D_a(t)$ =	3,4	mm^2/yr	$D_a(t)$ =	8,5	$D_a(t)$ =	7,4	$D_a(t)$ =	
C_{sa} =	1,467	w/w %	C_{sa} =	0,260	C_{sa} =	0,339	C_{sa} =	
Δx =	5	mm	Δx =	1	Δx =	1,5	Δx =	

Estimated chloride profile		erf-sol.	Calculated chloride profiles (Mejlbro-Poulsen)					
x	$C(x,t)$	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$
0	1,467	0,297	0	0,260	0	0,339		
5	1,144	0,262	1	0,190	2	0,237		
10	0,872	0,227	2	0,133	3	0,158		
15	0,649	0,194	3	0,090	5	0,100		
20	0,471	0,163	4	0,059	6	0,060		
25	0,333	0,135	5	0,037	8	0,034		
30	0,229	0,109	6	0,022	9	0,018		
35	0,154	0,087	7	0,013	11	0,009		
40	0,100	0,068	8	0,007	12	0,004		
45	0,063	0,053	9	0,004	14	0,002		
50	0,039	0,040	10	0,002	15	0,001		
55	0,023	0,029	11	0,001	17	0,000		
60	0,013	0,021	12	0,000	18	0,000		
65	0,007	0,015	13	0,000	20	0,000		
70	0,004	0,011	14	0,000	21	0,000		
C_1 =	0,255	D_1 =	8,6		C_{100} =	1,467	D_{100} =	3,4





Estimation of Chloride Ingress into Concrete

Model developed by Ervin Poulsen and Leif Mejlbro. Programmed by Jens M. Frederiksen.

AEClaboratory		Date: 1997-03-26
Staktoften 20	**Sample identification**	Time: 13:05
DK-2950 Vedbæk	Träslövsläge: H5 (zone At)	Init: HES

Input		
Basic constants		
t_{ex} =	0,04	yr
C_i =	0	% mass
w/c =	0,25	[-]
Calculated parameter		
D_{pex} =	90	mm²/yr
Governing parameters		
α =	0,985	[-]
S =	0,000	%mass/mm^{2P}
S_p =	0,171	%mass
p =	12,180	[-]
k_D =	44,901	[-]

Measured profiles, natural exposure

t_{in} [yr] =	1,047	t_{in} [yr] =	2,074	t_{in} [yr] =	
x [mm]	$C(x,t)$ [% mass]	x [mm]	$C(x,t)$ [% mass]	x [mm]	$C(x,t)$ [% mass]
1	0,273	1	0,327		
3	0,085	3	0,123		
5	0,041	6	0,046		
7	0,030	10	0,018		
10	0,020	15	0,003		
15	0,005	20	0,002		
		30	0,004		

Parameters for each chloride profile			Da = 16,8	Csa=0,131	Da = 6,1	Csa=0,221	Da = 1,0	Csa=0,000
t =	100	yr	t =	1,0	t =	2,0	t =	
$D_a(t)$ =	1,7	mm²/yr	$D_a(t)$ =	154,9	$D_a(t)$ =	79,0	$D_a(t)$ =	
C_{sa} =	0,708	w/w %	C_{sa} =	0,197	C_{sa} =	0,281	C_{sa} =	
Δx =	2	mm	Δx =	1	Δx =	1	Δx =	

Estimated chloride profile		**erf-sol.**	**Calculated chloride profiles (Mejlbro-Poulsen)**					
x	$C(x,t)$	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$	x	$C(x,t)$
0	0,708	0,221	0	0,197	0	0,280		
2	0,413	0,211	1	0,149	1	0,212		
4	0,240	0,201	3	0,084	3	0,121		
6	0,138	0,191	5	0,047	6	0,051		
8	0,079	0,182	7	0,026	10	0,016		
10	0,045	0,172	10	0,011	15	0,004		
12	0,026	0,162	15	0,002	20	0,001		
14	0,014	0,153	15	0,002	30	0,000		
16	0,008	0,144	15	0,002	15	0,004		
18	0,004	0,135	15	0,002	15	0,004		
20	0,002	0,126	15	0,002	15	0,004		
22	0,001	0,117	15	0,002	15	0,004		
24	0,001	0,109	15	0,002	15	0,004		
26	0,000	0,102	15	0,002	15	0,004		
28	0,000	0,094	15	0,002	15	0,004		

C_1 =	0,192	D_1 =	162,0	C_{100} =	0,708	D_{100} =	1,7