CHLORIDE INGRESS IN OLD DANISH BRIDGES

Søren Lundsted Poulsen, Henrik Erndahl Sørensen
Danish Technological Institute, Taastrup, Denmark

ABSTRACT

The ingress of chloride into three Danish bridges located in marine environments has been studied by means of chloride profiles measured on concrete cores from submerged conditions. The sample materials represent three different concrete types and exposure times ranging from 30 to 34 years. Chloride transport parameters such as the achieved chloride diffusion coefficient (D_a), surface chloride concentration (C_s) and the penetration parameter K_{Cr} were determined by fitting the error function solution to Fick's 2nd law to the measured profiles. Comparison with data from earlier investigations shows that D_a and C_s are almost constant for exposure times beyond ten years. The findings from the old Danish bridges are also compared to data from 20 years marine exposure of concrete slabs in a Swedish field exposure site, and the possibility to apply a simplified chloride penetration model for long term marine exposure is discussed.

INTRODUCTION

It is well-known that the ingress of chloride in concrete structures exposed to seawater can lead to initiation of reinforcement corrosion, provided that a certain critical chloride concentration is exceeded at the depth of the reinforcement [1,2]. The duration of the period before the critical chloride concentration is reached depends on a wide variety of parameters, e.g. the thickness of the concrete cover, the exposure conditions, the permeability of the concrete, the chloride binding capacity of the concrete binder, the conditions at the concrete-steel interface, etc.

In the beginning of the 1970's Collepardi et al. [3,4] introduced the use of the error function solution to Fick's second law as a mathematical model for the ingress of chloride into marine concrete structures:

$$C(x,t) = C_i - (C_s - C_i) \cdot erf \cdot \left(\frac{x}{\sqrt{4 \cdot D \cdot t}} \right) \qquad (1)$$

where C(x,t) is the chloride concentration at depth x at time t, C_i is the initial (background) chloride concentration, C_s is the chloride concentration at the exposed concrete surface, D is the chloride diffusion coefficient, and *erf* is the error function. In this approach, the parameters D and C_s are assumed to be constants. However, on the basis of results from the laboratory and from field exposure it was later established that both D and C_s should be considered as time-dependent parameters [5-9].
In most of the service life models used nowadays for predicting the ingress of chloride into concrete the time dependency of D is included. This is typically done by employing a power function which expresses the time dependency of the diffusivity through a so-called age factor (α). In this way, a certain time-dependent decline of D can be included when attempting to predict/calculate the ingress of chloride in concrete.

This paper presents the results of an investigation of the chloride ingress into a series of Danish coast bridges and the studied materials represent marine exposure times in the range from about 30 to 34 years. In addition, data from a series of earlier studies of chloride ingress into concrete in marine environments is also presented in the paper and used for comparison with the new data from the old Danish bridges.

EXPERIMENTAL

Sampling

A series of Ø100 mm concrete cores have been drilled and collected from three Danish coast bridges with the primary purpose of studying the long-term durability of concrete exposed to a marine environment (Fig. 1-3). Four concrete cores were taken from each bridge, two of these cores were used to measure detailed chloride ingress profiles, and all cores were taken from a constantly submerged position on the concrete structures in order to ensure that the exposure conditions were as constant and comparable as possible.

The studied bridges include the Vejle Fjord Bridge, the Alssund Bridge and the Farø Bridges. In addition, chloride profiles from earlier investigations undertaken by the Danish Road Directorate on the Vejle Fjord Bridge and the Farø Bridges are included in the results presented here as well. Accordingly, the chloride profiles presented in this paper cover a range of exposure times from approximately 11 to 34 years.

Furthermore, data from an (on-going) investigation of the chloride ingress into concrete slabs exposed for up to 20 years at the marine field exposure site at Träslövsläge in Sweden has been employed to compare the obtained data for the three bridges with some data representing younger exposure time [17]. The presented data from Träslövsläge were obtained on concrete cores taken from both submerged and atmospheric exposure conditions.

Mixing proportions for the concrete of the three bridges, as well as six selected concrete types from the Träslövsläge field exposure site, are given in Table 1.

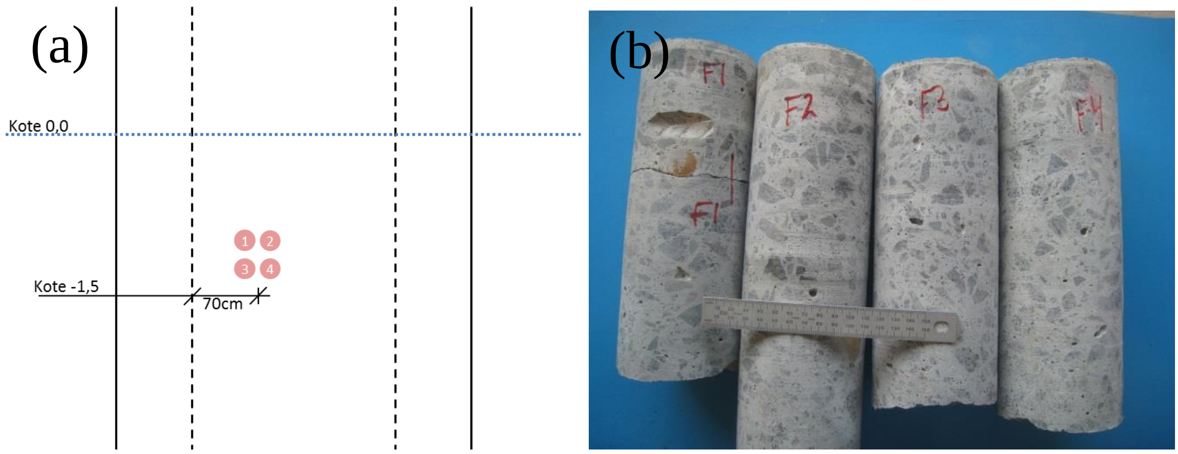

Figure 1 – Sampling of drilled concrete cores from the Farø Bridges: (a) Sketch of sampling location on pillar SF7 (south side) and (b) drilled concrete cores F1, F2, F3, and F4 from pillar SF7.

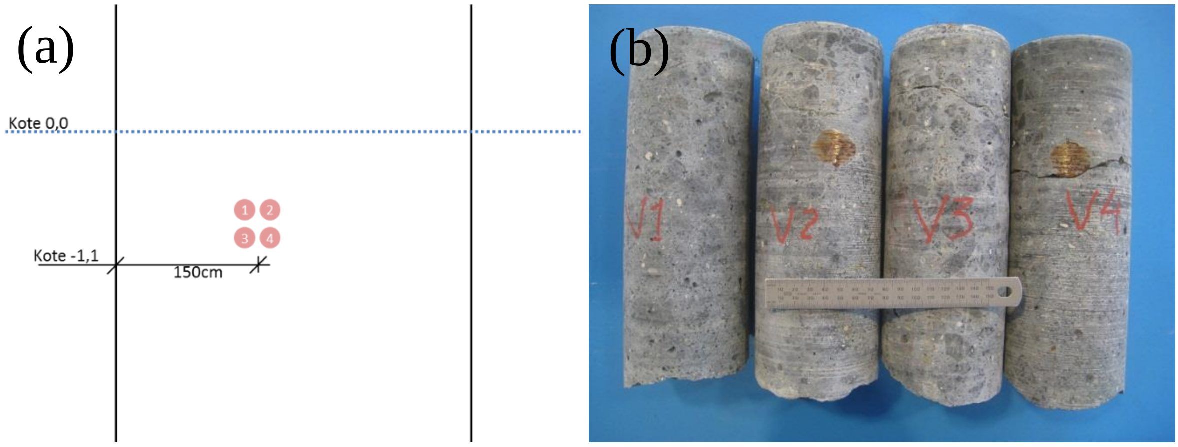

Figure 2 – Sampling of drilled concrete cores from the Vejle Fjord Bridge: (a) sketch of sampling location on pillar 8 (south side) and (b) drilled concrete cores V1, V2, V3, and V4 from pillar 8.

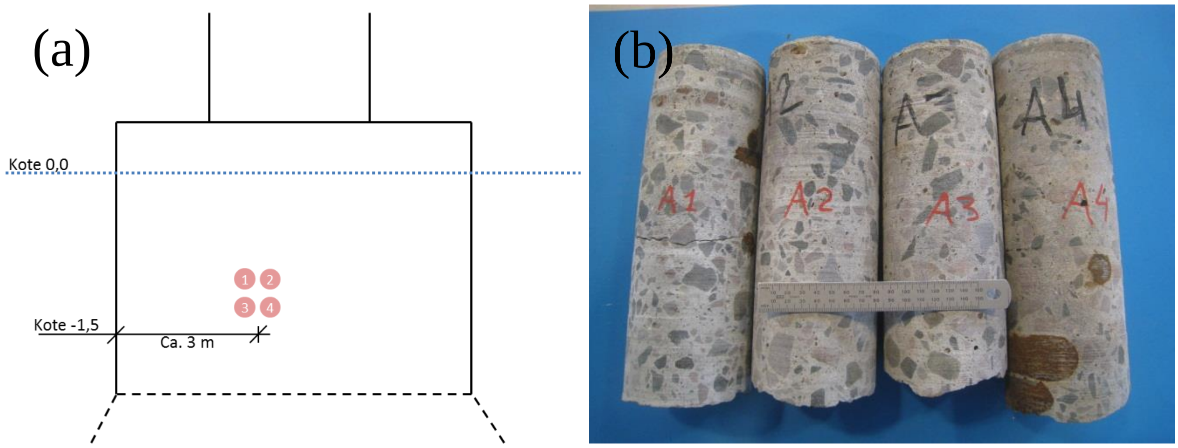

Figure 3 – Sampling of drilled concrete cores from the Alssund Bridge: (a) Sketch of sampling location on pillar 6 (west side), and (b) drilled concrete cores A1, A2, A3, and A4 from pillar 6.

Profile grinding and chloride analysis

Chloride profiles were measured by grinding off material in layers parallel to the exposed surface of the drilled concrete cores. The chloride content of each layer was subsequently measured according to the procedure given in DS 423.28, which is similar to NT BUILD 208 [10]. A list of the samples used for measuring of chloride profiles is shown in Table 2 along with information about exposure time, year of sampling and level of sample drilling.

Some of the measured chloride profiles were corrected for potential variations in paste content as a function of profile depth. This was done for the samples where calcium profiles had been measured in conjunction with the chloride profiles. The corrections were achieved by multiplying the measured chloride concentration at penetration depth *x* with the ratio Ca_x/Ca_{avg}, where Ca_x is the calcium content measured at depth *x* and Ca_{avg} is an average of all the calcium measurements from profile depths > approx. 18 mm.

*Table 1 – Mixing proportions for the concretes of the three investigated Danish bridges as well as for six of the concrete types exposed at the marine field exposure site in Träslövsläge, Sweden [17]. AEA = Air entraining agent, SRPC = sulphate resistant Portland cement, OPC = ordinary Portland cement, FA = fly ash, SF = silica fume. *Calculated assuming an efficiency factor of 1.0 and 0.3 for silica fume and fly ash, respectively. ? = data not available.*

Bridge/ sample ID	**Binder type**	**Binder [kg/m^3]**	**Water [kg/m^3]**	**Water/ binder ratio**	**Total aggregate [kg/m^3]**	**Super-plasticizer [wt% of binder]**	**AEA [wt% of binder]**	**Air content [%]**
Vejle Fjord Bridge	100% slag cement	400	180	0.45	1720	?	?	?
Alssund Bridge	100% SRPC	335	135	0.40	1870	?	0.04	?
Farø Bridges	77% SRPC + 23% FA	430	150	0.42*	1683	1.5	0.03	?
1-35 (Träslövsläge)	100% SRPC	450	158	0.35	1678	1.0	0.041	6.0
1-40 (Träslövsläge)	100% SRPC	420	168	0.40	1679	0.8	0.03	6.2
2-50 (Träslövsläge)	100% OPC	390	195	0.50	1640	-	0.026	5.8
3-35 (Träslövsläge)	95% SRPC + 5% SF	450	158	0.35*	1669	1.2	0.08	5.8
H8 (Träslövsläge)	80% SRPC + 20% FA	616	159	0.30*	1545	2.8	-	3.0
12-35 (Träslövsläge)	85% SRPC + 10% FA + 5% SF	450	146	0.35*	1698	1.87	0.055	6.4

Table 2 – List of concrete samples (drilled cores) used for determination of chloride profiles.

Bridge	**Sample ID**	**Time of exposure to seawater [years]**	**Year of sampling**	**Level of sample drilling relative to the water surface [m]**
Vejle Fjord Bridge	V2, V4	34	2012	-1.1
	D1*, D4*	17	1995	-1.1
Alssund Bridge	A2, A4	31	2012	-1.5
Farø Bridges	F1, F4	30	2012	-1.5
	K1*, K2*	22	2004	-1.5
	K1*, K2*, K3*	11	1992	-1.5

**Samples D1, D4, K1 (2004), K2 (2004), K1 (1992), K2 (1992), K3 (1992) were examined in earlier investigations undertaken by the Danish Road Directorate. Unpublished data.*

RESULTS

Chloride profiles

The measured chloride profiles for the old Danish bridges are displayed in Fig. 4-6 along with calculated profiles determined by fitting equation (1) to the measured data. For the Vejle Fjord Bridge profiles have been measured after 17 and 34 years of chloride exposure (Fig. 4). The data for the youngest exposure time is from unpublished results in an earlier investigation. At both exposure times the maximum chloride content is roughly 0.6 wt% (of concrete). However, the profiles measured after 34 years have shifted somewhat deeper into the concrete compared to the ones determined after 17 years. For all profiles a significant decrease in chloride content is observed in the outermost 10 mm.

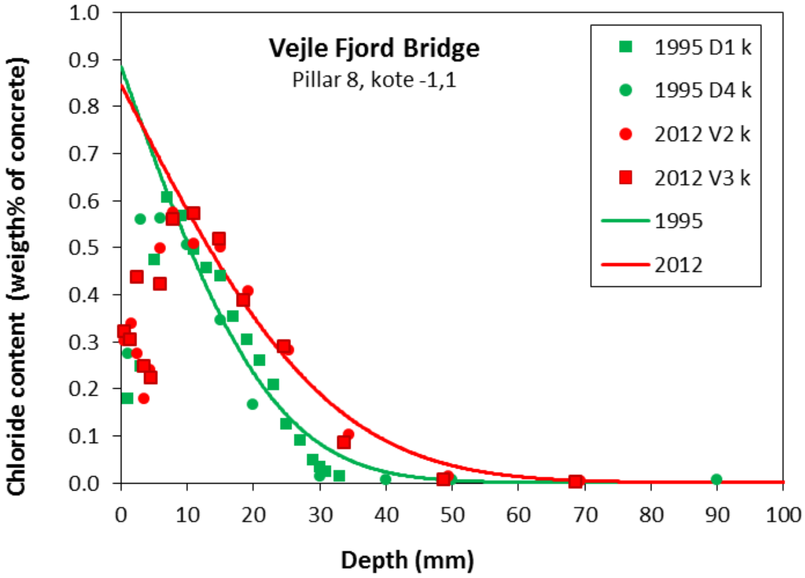

Figure 4 – Chloride profiles measured on drilled concrete cores from the Vejle Fjord Bridge (Pillar 8, kote -1.1 m) after 17 (green symbols) and 34 years (red symbols) of exposure. The two solid curves are calculated profiles obtained by fitting equation (1) (see text) to the measured chloride contents after 17 and 34 years of exposure to seawater, respectively. The 'k' in the legends indicates that the profiles have been corrected for variations in the paste content as a function of profile depth. The profiles representing 17 years of exposure are originating from an earlier investigation undertaken by the Danish Road Directorate.

Two chloride profiles were measured for the Alssund Bridge after 31 years of exposure to seawater (Fig. 5). The chloride content is generally somewhat higher for core A4 compared to A2 with maximum contents (wt% of concrete) for the two profiles of 0.55 and 0.4, respectively. For both profiles the chloride content is almost reduced to the background level at a penetration depth of 90 mm and a significant drop is observed in the outermost 10 mm.

The profiles presented for the Farø Bridges in Fig. 6 represents three different exposure times, namely 11, 22, and 30 years. The data from 11 and 22 years exposure are from unpublished results in earlier investigations. For the two youngest exposure times the maximum chloride content ranges from approx. 0.7 to 0.8 (wt% of concrete), whereas the two profiles measured after 30 years displays lower maximum chloride contents of approx. 0.45. However, at penetration depths above approx. 40 mm these profiles generally show higher concentration than the younger ones. For all the presented profiles a significant drop in chloride content is observed in the outermost 10-15 mm.

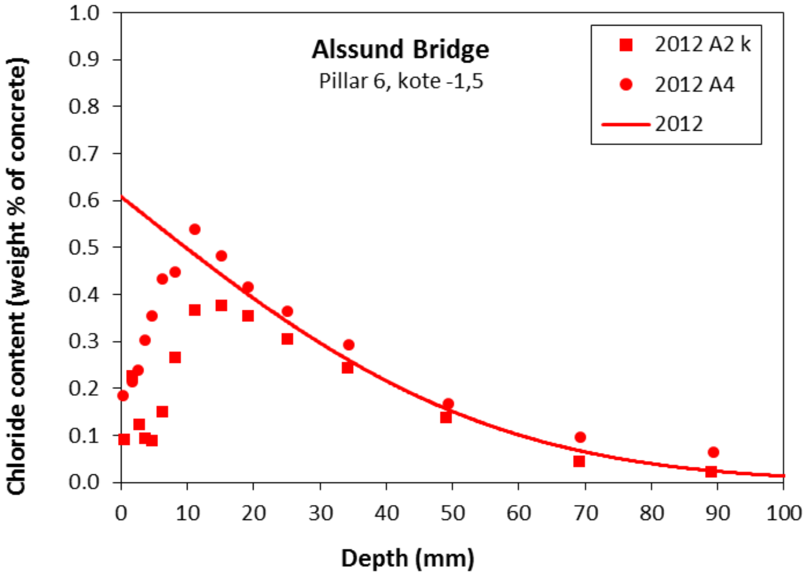

Figure 5 – Chloride profiles measured on two drilled concrete cores from the Alssund Bridge (Pillar 6, kote – 1.5 m) after 31 years of exposure to seawater. The solid curve is a calculated profile obtained by fitting equation (1) (see text) to the measured chloride contents. A 'k' in the legends indicates that the profiles have been corrected for variations in the paste content as a function of profile depth.

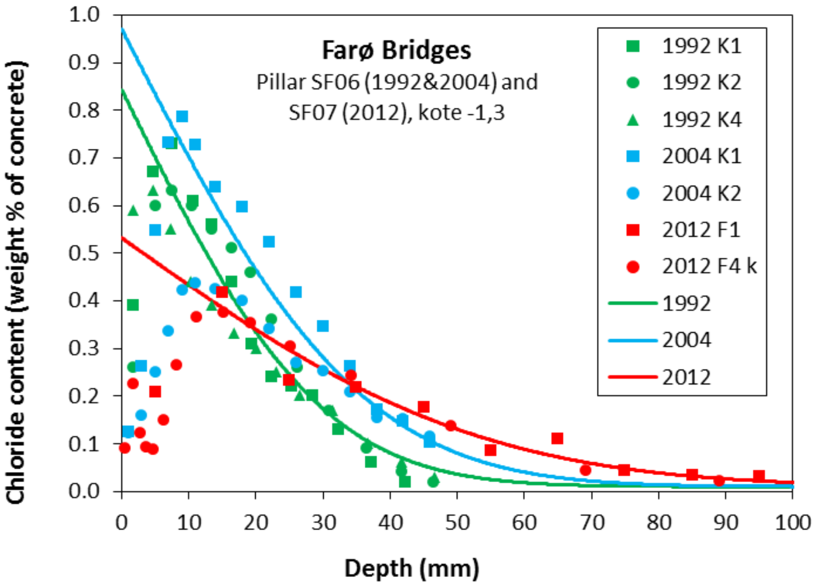

Figure 6 – Chloride profiles measured on drilled concrete cores from the Farø Bridge (Pillar SF6 and SF7). The profiles were obtained after 11, 22, 30 years of exposure to seawater and are displayed with green, blue and red symbols, respectively. The solid curves are calculated profiles obtained by fitting equation (1) (see text) to the measured chloride profiles. The 'k' in the legends indicates that the profile for core 2012 F4 has been corrected for variations in the paste content as a function of profile depth. All profiles for exposure times of 11 and 22 years are originating from earlier investigations carried out by the Danish Road Directorate.

Chloride penetration parameters

Values for the calculated chloride concentration at the exposed concrete surface (C_s) and the achieved chloride diffusion coefficient (D_a) have been calculated for all the investigated bridges according to the procedure given in NT Build 443 [11], i.e. by fitting equation (1) to the measured chloride contents by means of a non-linear regression analysis in accordance with the method of least squares fit. In the cases of the Vejle Fjord Bridge and the Farø Bridges values for C_s and D_a were determined separately for each of the investigated exposure times. Generally, a number of points of the chloride profiles nearest to the concrete surface were omitted in the regression analyses, i.e. all points between the concrete surface and the point representing the highest measured chloride content were not included in the fitting procedure. The fitted curves are shown along with the chloride profiles in Fig. 4-6.

The penetration parameter K_{Cr} (also named the "first year penetration") was determined for the measured profiles according to equation (2):

$$K_{Cr} = 2\sqrt{D_a} \cdot \text{erf}^{-1}\left(\frac{C_s - C_r}{C_s - C_i}\right) \quad (2)$$

In equation (2) C_r is a reference chloride concentration, which was set to a standard value of 0.05 wt% (of concrete). Results from the calculation of D_a, C_s and K_{Cr} are given in Table 3, and Fig. 7 displays D_a and C_s as a function of exposure time.

Table 3 – Exposure time, achieved chloride diffusion coefficient (D_a), chloride concentration at the concrete surface (C_s), initial chloride concentration of the concrete (C_i) and penetration parameter $K_{0.05}$ for concrete samples collected from three Danish coast bridges. The values of D_a, C_s and C_i were determined by fitting equation (1) to the measured chloride profiles. $K_{0.05}$ was calculated according to equation (2). The data for the Vejle Fjord Bridge at 17 years and the Farø Briges at 10.7 and 22.4 years were obtained from chloride profiles determined in earlier investigations undertaken by the Danish Road Directorate.

Bridge	**Exposure time [years]**	**D_a [$*10^{-12}$ m²/s]**	**C_s [wt% of concr.]**	**C_i [wt% of concr.]**	**$K_{0.05}$ [mm/year^{½}]**
Vejle Fjord Bridge	34	0.28	0.85	0.001	8.0
	17	0.30	0.89	0.001	8.3
Alssund Bridge	31	0.95	0.61	0.001	13.5
Farø Bridges	30	0.92	0.53	0.010	13.5
	22.4	0.55	0.97	0.010	12.0
	10.7	0.80	0.84	0.010	14.0

DISCUSSION

Influence of binder type on chloride ingress

Among the investigated bridges the highest resistance against chloride ingress is observed for the Vejle Fjord Bridge, i.e. the values of D_a and K_{Cr} is significantly lower for this bridge as compared to the other bridges (see Table 3). This is explained by the fact that the examined part of the Vejle Fjord Bridge is constructed with a concrete based on a slag cement. The use of slag cement has previously been reported to result in a refinement of the pore structure of the cement paste, as well as enhancement of the chloride binding capacity, thus leading to a higher resistance of the concrete against ingress of chloride ions [12,13].

Somewhat lower resistance against chloride ingress is observed for the Alssund Bridge and the Farø Bridges, which represents constructions made with concrete binders of 100% low-alkali sulphate-resistant Portland cement and low-alkali sulphate-resistant Portland cement + 23% fly ash, respectively. Generally, these two bridges show rather comparable values for D_a and K_{Cr}.

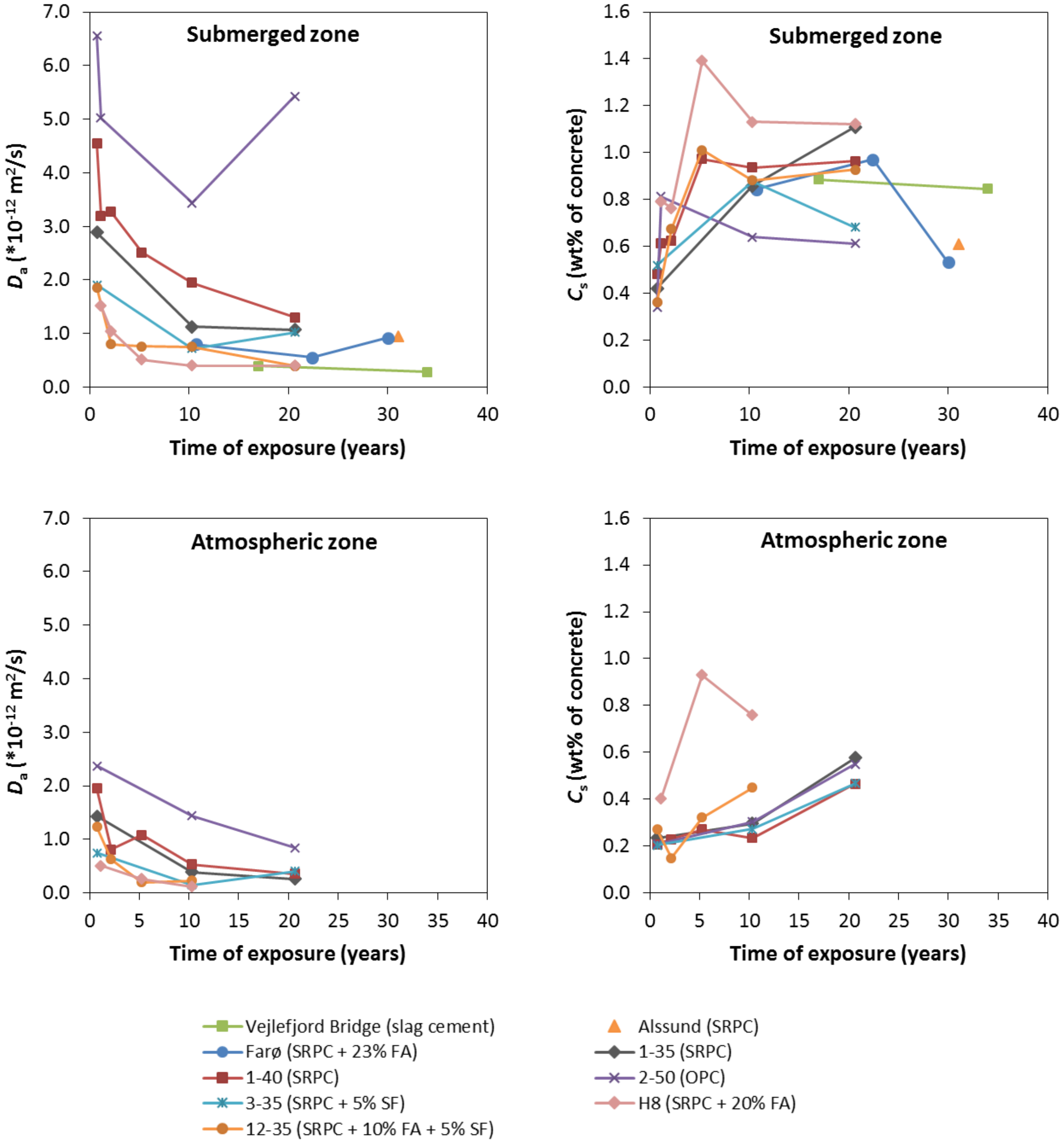

Figure 7 – Achieved chloride diffusion coefficients (D_a) and chloride concentrations at the exposed concrete surface (C_s) as a function of exposure time. D_a and C_s were determined by fitting of equation (1) to chloride profiles measured on concrete cores taken from three Danish coast bridges. Additional data from a study of the chloride ingress in a series of concrete slabs exposed at submerged and atmospheric conditions at the marine field exposure site in Träslövsläge, Sweden [17] are included in the figure for comparison. Binder compositions for the concretes are given in parenthesis in the legend, where SRPC = sulphate-resistant Portland cement, OPC = ordinary Portland cement, FA = fly ash and SF = silica fume.

Time-dependency of the achieved chloride diffusion coefficient (D_a)

The ingress of chloride ions into concrete structures exposed in marine environments is generally considered as the decisive parameter for initiation of reinforcement corrosion. Therefore, all the models used nowadays for predicting the service life of marine reinforced concrete structures include a model for the ingress of chloride. In such ingress models the chloride diffusivity is usually treated as a time-dependent parameter, i.e. the chloride diffusion coefficient decreases as a function of exposure time [14-16]. This gradual decay of the diffusion coefficient is achieved by employing a power function, which expresses the time dependency of the diffusivity through a so-called age factor. The implementation of such an age factor in the majority of service life models for chloride ingress is based on observations in a number of studies that the chloride diffusion coefficient decreases as a function of exposure time [5-7]. However, the results presented in this paper indicate that – at least for some concrete structures – the time-dependency of the diffusivity may recede to an insignificant level and become more or less constant after prolonged chloride exposure.

In Fig. 7 it is seen that the value of D_a is almost identical for the Vejle Fjord Bridge after 17 and 34 years of chloride exposure. The three values of D_a derived from the samples taken from the Farø Bridges after 11, 22 and 30 years of exposure varies between $0.55*10^{-12}$ and $0.92*10^{-12}$ m^2/s, and it is noted that D_a does not appear to decrease as a function of time. These data suggest that the usually assumed decay of the chloride diffusion coefficient as a function of exposure time either does not apply or is insignificant for these two bridges when the exposure time has exceeded ten years. Obviously, in the early exposure ages, when the ongoing hydration still contributes to the development of a more dense microstructure, the value of D_a is expected to have exhibited a more time-dependent nature.

Fig. 7 also includes some selected data from another (on-going) research project dealing with chloride ingress in concrete [17]. This project involves a comprehensive series of concrete slabs with various compositions, which are exposed at the marine field exposure site at Träslövsläge in Sweden. Three different exposure conditions are studied in the project: Submerged, splash and atmospheric zone. At the time of writing chloride profiles have been measured for these slabs after approx. 0.5, 1, 2, 5, 10, and 20 years of exposure and the obtained profiles have subsequently been used for curve-fitting to ingress models based on Fick's second law in order to determine parameters such as D_a and C_s. The selected data plotted in Fig. 7 represents D_a and C_s for six types of concretes with different binders and water/binder ratios from 0.30 to 0.50. Only results for concretes exposed to submerged and atmospheric conditions are represented in Fig. 7, since the data available for splash zone conditions were rather limited at exposure times above 5 years. Details about binder composition and concrete mixing proportions are given in Table 1. The concretes labelled 1-40 (100% Portland cement) and H8 (80% Portland cement + 20% fly ash) were selected for comparison with the results from the Danish bridges since they have binder compositions resembling the concrete from the Alssund and the Farø Bridges. In order to investigate the possible effect of w/c-ratio on the development of D_a and C_s over time, two further concretes (1-35 (w/c = 0.35) and 2-50 (w/c = 0.50)) with binders of pure Portland cement were also included in Fig. 7 besides concrete 1-40 (w/c = 0.40). The Träslövsläge concretes identified as 3-35 (95% Portland cement + 5% silica fume) and 12-35 (85% Portland cement + 10% fly ash + 5% silica fume) were chosen due to their close similarity in binder composition compared to the concrete types that have been used for the Great Belt Bridge and the Øresund Bridge, both major concrete constructions in the Danish infrastructure.

A significant decrease of D_a is observed during the first 5 to 10 years of exposure for all of the Träslövsläge concrete types from submerged conditions, but hereafter the values of D_a become more or less constant for most of the concretes. An exception is concrete 2-50 for which a marked and surprising increase in D_a is observed from 10 to 20 years, and also concrete 1-40 deviates slightly with a continued decrease of the D_a value during this period. An explanation for this deviating behaviour is not available, but it should be noted that concretes 2-50 and 1-40 were produced with pure cements and with water/binder ratios of 0.50 and 0.40, respectively, whereas the remaining Träslövsläge concretes in

Fig. 7 all have water/binder ratios of 0.35 or below. However, the general tendency of D_a becoming almost constant or showing a less marked decrease at exposure times above 5 to 10 years corresponds well with our results from the Danish bridges.

D_a and C_s obtained from Träslövsläge concretes exposed at marine atmospheric conditions are also included in Fig. 7. A pronounced decrease in D_a values are observed during the first 10 years of exposure for all the concretes. But hereafter the decrease rate diminishes to an almost insignificant level, i.e. the D_a values appear to reach an almost constant level after 10 years of exposure. However, concrete 2-50 deviates from this behaviour since the D_a value for this concrete clearly continues to decrease in the period from 10 to 20 years, which is contradicting the observation in the submerged condition. But overall, the same general receding decrease of D_a to an almost constant level after prolonged exposure times is observed for both submerged and atmospheric exposure conditions.

A possible explanation of the late decrease in D_a values for concrete 1-40 (mainly in submerged condition) and 2-50 (in the atmospheric condition) might be, that it is a consequence of the higher permeability compared to the other displayed Träslövsläge concretes. Due to this high permeability (which is reflected in the rather high initial D_a values measured at the first testing period) the chloride ingress during the early exposure will be high due to possible high capillary suction and low resistance against chloride penetration. As the D_a value represent an average diffusion coefficient for the entire exposure period an initial high chloride content in the outer part of the concrete is expected to influence the calculated D_a values for longer time than for concretes less pronounced initial chloride ingress.

Time-dependency of the chloride concentration at the concrete surface (C_s)

Fig. 7 also shows the calculated chloride concentration at the exposed concrete surface (C_s) as a function of the exposure time for the three studied bridges, where the chloride concentrations are expressed as wt% of concrete. In the case of the Farø Bridges, C_s increases slightly from 0.84 after 11 years to 0.97 after 22 years, which is in accordance with earlier studies, where the surface chloride concentration has been observed to increase as a function of exposure time for concrete exposed to seawater [8,9,17]. However, a significant decrease to 0.53 at 30 years is also observed for the Farø Bridges. This rather unexpected and pronounced drop in chloride surface concentration can possibly be explained by the fact that the concrete cores collected after 30 years of exposure were taken from a different pillar than the cores collected after 11 and 22 years.

For the Vejle Fjord Bridge C_s appears to be more or less constant with almost identical values of 0.89 after 17 years and 0.85 after 34 years. This observation might be a consequence of the Vejle Fjord Bridge having reached a high maturity, where the time-dependency of C_s has diminished to an insignificant level.

In Fig. 7 the surface chloride concentration C_s from the six concrete types from Träslövsläge is plotted along with the data from the Danish bridges for comparison. A clear and gradual increase in C_s is observed for all types during the first five years of exposure in submerged conditions, but hereafter the value of C_s appears to become constant or it decreases slightly. An exception from this behaviour is seen for concrete 1-35, in which case C_s continues to increase also after 10 years. However, the tendency with almost constant C_s beyond 5 years of submerged exposure has generally been observed for all the various concrete types at the marine exposure station at Träslövsläge (not shown here), which is in good agreement with absence of a well-defined time dependency of the C_s values for the three studied bridges.

Fig. 7 also displays C_s values obtained from Träslövsläge concretes exposed in marine atmospheric conditions. In contrast to the corresponding data from submerged conditions, the C_s values generally continue to increase for the entire observed exposure period, even with a slightly accelerated increase from 10 to 20 years. An exception is concrete H8, in which case C_s drops distinctly in the period from 5 to 10 years. Unfortunately, data for 20 years exposure was not available for this concrete.

Prediction of service life for concrete structures from K_{Cr}

Having calculated the penetration parameter K_{Cr} makes it possible, when C_s and D_a can be considered as not time-dependent, to estimate the penetration depth (x_{Cr}) of a reference chloride concentration (*Cr*) with time (*t*):

$$x_{Cr} = K_{Cr} \cdot \sqrt{t} \tag{3}$$

Equation (3) implies a linear relationship between x_{Cr} and with K_{Cr} being a factor of proportionallity.

In Fig. 8 the penetration depth ($x_{0.05}$) of 0.05 wt% chloride concentration has been plotted in each measured chloride profile as a function of the square root of exposure time for the three investigated bridges as well as for the six selected Träslövsläge concretes from the submerged zone. The figure also includes a similar plot representing the Träslövsläge concretes in the atmospheric zone. In this figure, it is generally observed that the data for each concrete type plots more or less along a straight line, thus indicating a linear correlation between $x_{0.05}$ and $\sqrt{t}$ as implied in equation (3). This is the case for both the submerged and the atmospheric zone. It is also noted, that the chloride ingress is generally lower in the atmospheric zone compared to the submerged zone.

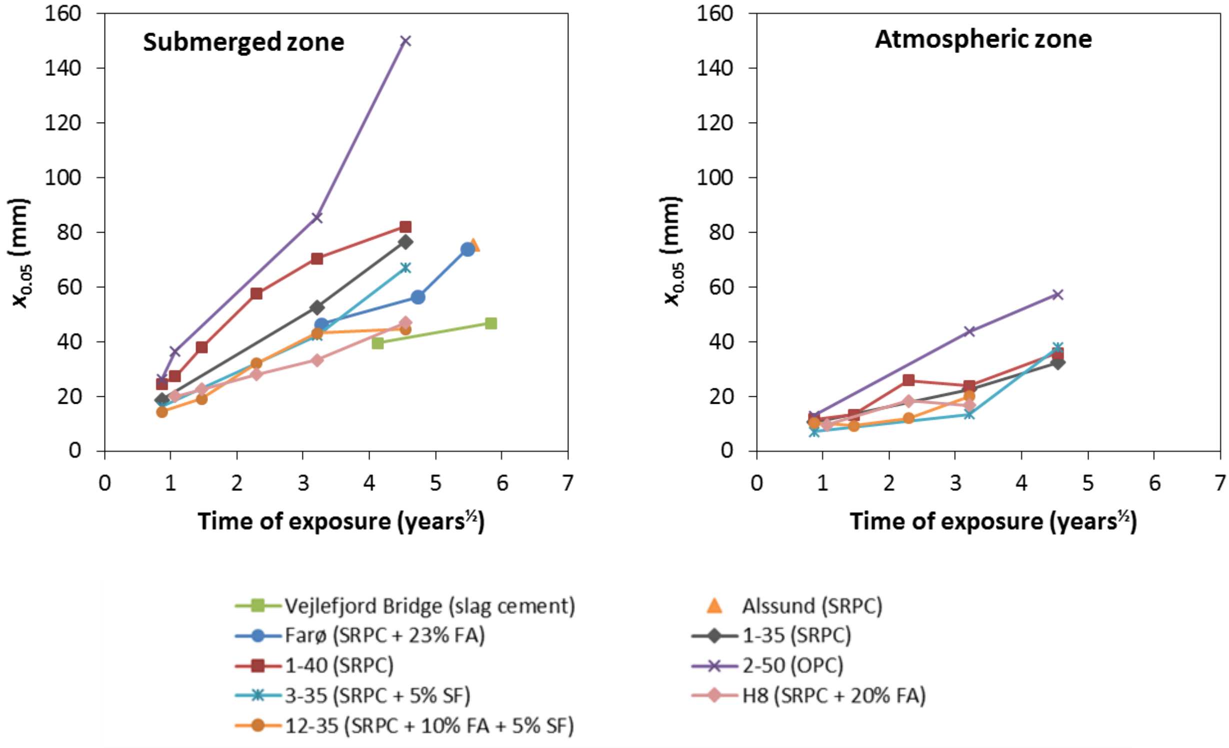

Figure 8 – Penetration depth of the 0.05 wt% chloride concentration ($x_{0.05}$) as a function of the square root of exposure time for submerged and atmospheric conditions. The values of $x_{0.05}$ were calculated from the curve fit for each measured chloride profile. The figure includes data for three Danish coast bridges as well as data from the marine field exposure site in Träslövsläge, Sweden [17]. Binder compositions for the concretes are given in parenthesis in the legend, where SRPC = sulphate-resistant Portland cement, FA = fly ash and SF = silica fume.

The observations of a linear correlation between $x_{0.05}$ and $\sqrt{t}$ indicate that the parameters D_a and C_s, which are time-dependent especially at young ages, are somewhat inter-correlated when they are calculated from the curve-fitting procedure. If these two parameters are combined into the parameter K_{Cr} according to equation (2), the time-dependency of this parameter is generally less pronounced. However, as indicated by the data presented in Fig. 7 this time-dependency of D_a and C_s is rapidly reduced as a function of exposure time, except in the case of C_s values from atmospheric exposure conditions where the calculated surface concentrations apparently continue to increase also after 10 years. The observed accelerated increase in $x_{0.05}$ for the Farø Bridges at 30 years can most likely be ascribed to the fact that the concrete cores representing this exposure age were drilled from another pillar than the ones collected at younger exposure times. An accelerated increase in $x_{0.05}$ is also observed for concrete 2-50 from 10 to 20 years, which is difficult to explain as mentioned earlier in the discussion of D_a values. It could perhaps be a result of complications caused by double-sided penetration of chloride into the concrete slabs (100 mm thick) after prolonged exposure. It is reported in ref. [17] that for some of the slabs at the Träslövsläge marine exposure station, prolonged double-sided chloride penetration has resulted in cases where the chloride content near the centre of the slabs is composed of chloride contributions coming from both sides of the slabs.

According to equation (3) a data trend plotted in graphs like the ones in Fig. 8 should have an origin at the point (0,0). However, it is noted that an extension of the data trends for the different concrete types towards the beginning of the exposure period results in intercepts of the y-axis at values > 0 mm. The existence of this initial penetration depth (here denoted as b_{cr}) is not finally explained and validated, but it could be the result of a fast initial ingress of chloride during the first few months (or years) after the first exposure to the marine environment. Typically, hydration reactions will still occur within the concrete during this period, which means that the concrete will not have reached the same degree of resistance against chloride ingress compared to the same concrete in a more mature state. The initial penetration depth (b_{cr}) could also be partly due to capillary suction of seawater at the time of first exposure to a submerged marine environment. Consequently, the parameter b_{cr} will most likely show different values for the same concrete depending on the maturity, as well as the moisture content in the concrete, at time of the first chloride exposure.

Based on the data shown in Fig. 8, we tentatively suggest that a linear regression analysis performed on the type of data presented in two graphs can be used as a basis for predicting the future ingress of a certain reference chloride concentration (C_r) in concrete exposed to a submerged or an atmospheric marine environment. Such a linear regression analysis will yield an equation of the type:

$$x_{cr} = a_{cr} \cdot \sqrt{t} + b_{cr} \quad (4)$$

where a_{cr} is a parameter with no time-dependency and b_{cr} is the intercept of the y-axis. In the special case, where b_{cr} is zero, the parameter a_{cr} can be regarded as being equal to the penetration parameter K_{cr}, i.e. equation (4) is essentially reduced to equation (3).

Rearranging equation (4) for t gives:

$$t = \left(\frac{x_{cr} - b_{cr}}{a_{cr}} \right)^2 \quad (5)$$

This equation can be used to predict the duration of the period before initiation of reinforcement corrosion, i.e. the initiation phase which is sometimes defined as the service life of a concrete construction. Such a prediction can be made by equating the value of x_{cr} with the thickness of the concrete cover above the reinforcing steel and by setting the reference chloride concentration (C_r) at a level equal to the threshold value for initiation of reinforcement corrosion for the given concrete.

Linear regression analysis have been performed on the data set of each concrete types presented in Fig. 8, except for the Alssund Bridge and the Vejlefjord Bridge in which cases a regression analysis did not make sense, since only one and two data point were available for the analysis, respectively. The resulting regression lines are plotted in Fig. 9 along with the data upon which the regression analyses were performed. The optimized parameters ($a_{0.05}$ and $b_{0.05}$) from the analyses are given in Table 4. It is observed in Fig. 9 that the ingress of chloride is faster in the case of concretes with binders of pure Portland cement as compared to the concrete types with binders containing fly ash and/or silica fume. As an example, equation (4) has been filled out for concrete 1-35 with optimized parameter from the regression analysis (see Table 4):

$$x_{0.05} = a_{0.05} \cdot \sqrt{t} + b_{0.05} = 16 \text{ mm/year}^{0.5} \cdot \sqrt{t} \ + \ 4 \text{ mm} \qquad (7)$$

Such an equation can be utilized to calculate the penetration depth of the 0.05 wt% chloride concentration front ($x_{0.05}$) at any desired exposure time for this particular concrete, e.g. after 100 years of exposure:

$$x_{0.05}(100 \text{ years}) = 16 \text{ mm/year}^{0.5} \cdot \sqrt{100 \text{ years}} \ + \ 4 \text{ mm} = 164 \text{ mm} \qquad (8)$$

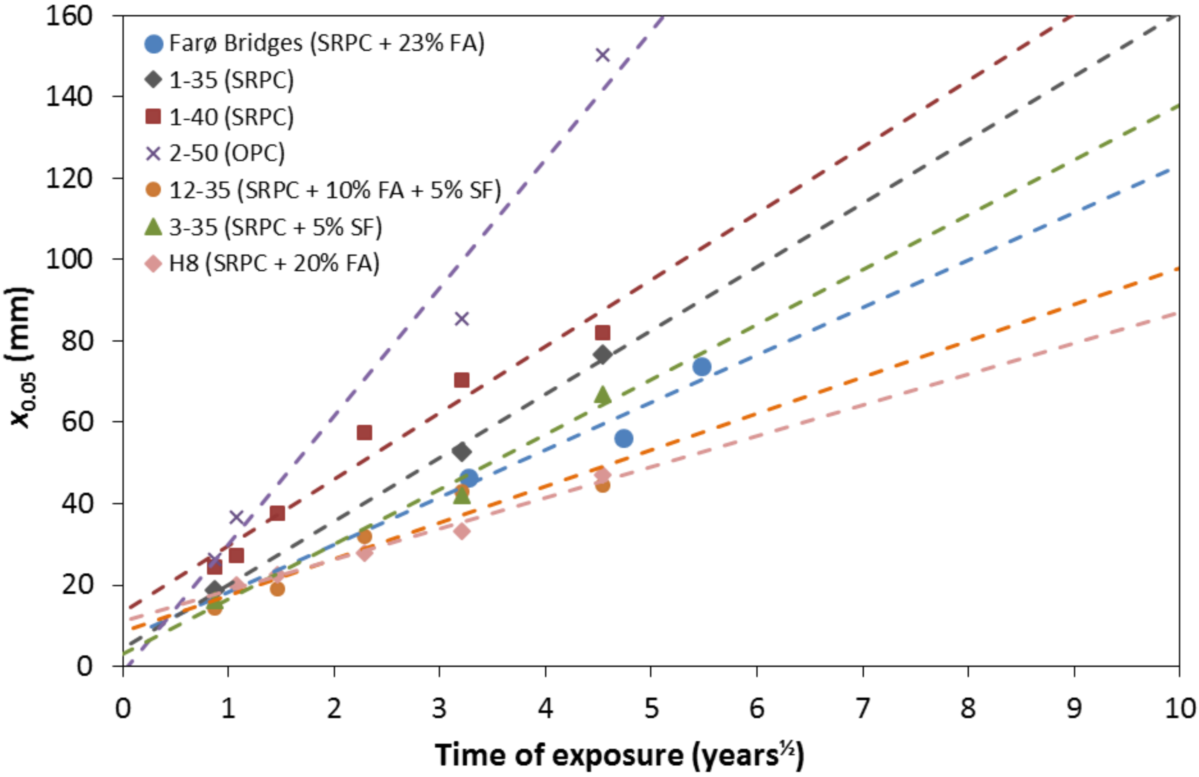

Figure 9 – Penetration depth of 0.05 wt% chloride concentration ($x_{0.05}$) in submerged exposure conditions as a function of the square root of exposure time. The plot includes data for the Farø Bridges as well as for six concrete types from the marine exposure station in Träslövsläge, Sweden [17]. For each concrete type a linear regression analysis has been performed on the plotted data and the results are displayed in the figure as broken lines. The slope of the lines corresponds to the ingress parameter $a_{0.05}$ and the intercept with y-axis gives the parameter $b_{0.05}$ of the equation $x_{0.05} = a_{0.05} \cdot \sqrt{t} + b_{0.05}$ *(see text for further explanation).*

*Table 4 – Penetration parameters $a_{0.05}$ and $b_{0.05}$ for concretes exposed in submerged marine environment (see text for further explanation). The parameters were obtained by linear regression analyses performed on the data plotted in Fig. 9. SRPC = sulphate-resistant Portland cement, OPC = ordinary Portland cement, FA = fly ash, SF = silica fume. *Calculated assuming an efficiency factor of 1.0 and 0.3 for silica fume and fly ash, respectively.*

Bridge/Concrete ID	Binder	Water/binder ratio	$a_{0.05}$ [mm/year$^{0.5}$]	$b_{0.05}$ [mm]
Farø Bridges	77% SRPC + 23% FA	0.42*	12	7
1-35 (Träslövsläge)	100% SRPC	0.35	16	4
1-40 (Träslövsläge)	100% SRPC	0.40	16	13
2-50 (Träslövsläge)	100% OPC	0.50	32	-2
3-35 (Träslövsläge)	95% SRPC + 5% SF	0.35*	13	3
12-35 (Träslövsläge)	80% SRPC + 20% FA	0.30*	9	8
H8 (Träslövsläge)	85% SRPC + 10% FA + 5% SF	0.35*	8	11

If the penetration depth has been estimated according to the above-mentioned method for a given reference chloride concentration (C_r) it is rather simple to recalculate to a penetration depth for another chloride concentration if the corresponding C_s value is known and if the inner part of the chloride profile fits the error-function solution given in eq. (1).

We realize that the data presented in Fig. 8 and Fig. 9 represents a rather sparse basis for proposing the abovementioned method for service life predictions. But should future data for the chloride ingress in the Träslövslage concretes plot as a clear continuation of the linear trends it will strongly support our simple procedure for estimating the service life of concrete structures.

CONCLUSIONS

The following conclusions can be drawn from the study of the chloride ingress in samples from three Danish concrete bridges in marine environments and form the comparison with chloride ingress data from earlier investigations:

- The highest resistance to chloride ingress is observed for the bridge constructed with a concrete based on slag cement.
- Intermediate resistance against chloride penetration is observed for the two bridges with binders of 100% Portland cement and Portland blended with 23% fly ash, respectively.
- Apparent chloride diffusion coefficients (D_a) are observed to be more or less independent of time for chloride exposure times beyond ten years.
- For exposure times above 17 years the surface chloride concentration (C_s) appears to be almost constant for the bridge constructed with a concrete based on slag cement.
- The presented analysis indicates that the service life of marine concrete structures can be predicted from a simple model based on a square root of time dependency. However, reliable field exposure data is need as input for the model. The approach appears to be applicable for concrete exposed in a marine environment in both the submerged and the atmospheric zone.
- Additional reliable data from long-term field exposure to chlorides are needed in order to calibrate and further develop the suggested model.

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