CHLORIDE INGRESS IN CONCRETE BLOCKS AT THE RØDBYHAVN MARINE EXPOSURE SITE – STATUS AFTER 5 YEARS

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Abstract

This paper presents new results from a long-running study following the chloride ingress in concrete blocks exposed at the marine exposure site located at Rødbyhavn harbour in Denmark. The site was established in 2010 as part of the preparatory work for the planned Fehmarnbelt fixed link between Denmark and Germany.

Chloride profiles have previously been measured on cores extracted from the blocks after 0.5 and 2 years of exposure to seawater – and now after 5 years. The studied blocks represent 15 different concrete mixes produced using a variety of binder types. The chloride ingress in the blocks have been investigated for both submerged and splash zone exposure conditions.

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. Results from the Rødbyhavn exposure site are also compared to chloride data from the field exposure site in Träslövsläge, Sweden.

Based on the findings from Rødbyhavn and chloride data from the literature, a simplified chloride penetration model for long-term marine exposure is proposed and discussed.

Keywords: Concrete durability, chloride ingress, field exposure, marine environment, modelling.

1. INTRODUCTION

Availability of reliable data from long-running investigations of field-exposed concrete is very important for a number of reasons. For instance, the durability design of large concrete structures typically involves the use of models to predict the service life of the given structure. Such models must be validated against long-term data from field-exposed concrete in order to demonstrate their applicability for the type of concrete and exposure environment of the given structure. Also, data from long-running studies of field-exposed concrete is one of the primary keys to improve our knowledge on concrete durability, e.g. the resistance against chloride ingress for concrete in marine environments.

In 2010 Femern A/S established a marine field exposure site in the harbour of Rødbyhavn as part of the preparatory work for the coming Fehmarnbelt Fixed Link between Denmark and Germany [1]. A total of 15 large concrete blocks with different concrete mix designs have been exposed to seawater at the exposure site since 2010, and measurement of chloride penetration in the blocks has been performed after 0.5, 2 and 5 years of exposure.

This paper gives an update on the measured chloride penetration data from the exposure site with an emphasis on the most recent data obtained after 5 years exposure. Based on the presented data from Rødbyhavn, and other chloride data from the literature, a simplified chloride penetration model is also proposed and discussed.

2. EXPERIMENTAL

2.1 Design and production of concrete blocks

The 15 large concrete block exposed at the marine exposure site in Rødbyhavn were produced with dimensions of 2 x 1 x 0.2 m (H x W x D). The 15 different mix designs for the blocks are presented in Table 1 in terms of the nominal composition of constituent materials. The mix designs were composed by various combinations of three different cements and three different mineral additions. The cements are: Low alkali sulphate resistant Portland cement CEM I 42.5 N – SR5 EA, Rapid hardening ordinary Portland cement CEM I 52.5 N, and blast furnace cement CEM III/B 42.5 N (slag cement). The mineral additions are: Fly ash, silica fume slurry, and ground granulated blast furnace slag. The nominal eqv. w/c-ratio are 0.40 for all concretes except for concrete H and I, which have eqv. w/c-ratios of 0.45 and 0.35, respectively. Further details regarding the design and production of the concrete blocks can be found in Ref. [1] and [2].

2.2 Exposure and sampling

The 15 concrete blocks were exposed to seawater at the field exposure site in Rødbyhavn at a maturity of 43-49 days. The blocks are placed partly immersed in seawater with the upper 70 cm above normal water level. The chloride content of the seawater is approx. 0.7% chloride [3] and the annual temperature variations of the seawater are typically between -1ºC and 20ºC. After 5 years of exposure, two Ø100 mm cores were drilled from each concrete block for determination of chloride (and calcium profiles), i.e. one core from the submerged zone and one core from the splash zone.

2.3 Profile grinding and chloride analysis

Two chloride profiles were determined for each of the extracted cores: One profile from the west and one profile from the east facing side of the cores. The 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 determined according to the procedure given in DS 423.28, which is similar to NT BUILD 208 [4]. The chloride contents were measured using potentiometric titration rather than Volhard titration. The measured chloride profiles were subsequently corrected for potential variations in paste content as a function of profile depth. This was done by using measured calcium profiles (not shown) in conjunction with the chloride profiles.

3. RESULTS

3.1 Chloride profiles

Fig. 1 displays the chloride profiles measured after 5 years exposure in the submerged zone for a selection of five representative concrete types: A (100% SPRC), B (85% SRPC + 15% FA), E (96% SRPC + 4% SF), F (84% SRPC + 12% FA + 4% SF), and K (100% slag cement). For comparison, the chloride profiles measured after 0.5 and 2 years are also plotted for these concretes. Furthermore, Fig. 1 also includes a diagram where the 5-year profiles for the five representative concretes are plotted together. A complete collection of all the chloride profiles measured for concretes A-O after 0.5, 2 and 5 years can be found on the website www.expertcentre.dk [1], including profiles both from submerged zone and splash zone. For all profiles, a significant decrease in chloride content is observed in the outermost 2-5 mm.

It is noted that the 2-year profile for Concrete A generally shows chloride concentrations, which are lower than the measured chloride profile after 0.5 years. We have no explanation for this unexpected result, and we question the reliability of the 2-years profile. Consequently, the 2-year data for Concrete A has been excluded in the following. It is also noted that the 0.5 years chloride profile for Concrete B shows an isolated peak at an ingress depth of 6 mm, which we interpret as a consequence of a significant deviation from the "normal" ratio between the amount of aggregates and cement paste in the concrete. This interpretation is supported by the appearance of a significant negative peak at a depth of 6 mm in the calcium profile measured on the same concrete core from Concrete B that was used for measuring the chloride profile.

3.2 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 concrete types (A-O) at the Rødbyhavn exposure site according to the procedure given in NT Build 443 [5]. This was achieved by fitting the error-function solution to Fick 2nd law of diffusion to the measured chloride contents by means of a non-linear regression analysis in accordance with the method of least squares fit. 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. As an example, the fitted curves are shown along with the measured chloride profiles for Concrete E in Fig. 2.

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

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

In equation (1) C_r is a reference chloride concentration, which was set to a standard value of 0.05 wt% (of concrete). Calculated values of D_a, C_s and K_{Cr} are given in Table 2 for five representative types of concrete (A, B, E, F, and K) from the Rødbyhavn exposure site. A collection of calculated values of D_a, C_s and K_{Cr} for all concrete types (A-O) can be found on www.expertcentre.dk [1]. A pronounced decrease of D_a is generally observed for all the five concrete types during the first five years of exposure, whereas C_s generally increases somewhat for all the five concrete types during the same exposure period.

Table 1: Mix design for concrete blocks. The activity factors used to calculate the equivalent w/c-ratios are 2.0 for silica fume and 0.5 for fly ash.

		Concrete ID:	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**
Powder composition wt%	Low alkali SR cement	CEM I 42.5 N	100	85	75	75	96	84	84	84
	Rapid hardening cement	CEM 1 52.5 N								
	Slag cement	CEM III/B 42.5 N								
	Fly ash	EN 450-1 N		15	25	25		12	12	12
	Silica fume	50 %-wt slurry					4	4	4	4
	GG blast furnace slag	EN 15167-1								
Concrete composition	Cement	kg/m^3	365	322	300	336	340	300	310	276
	Fly ash	kg/m^3		57	100	112		43	44	39
	Silica fume, solid matter	kg/m^3					14	14	15	13
	GGBFS	kg/m^3								
	Water content	l/m^3	146	140	140	157	147	140	145	145
	Aggregate 0/2	kg/m^3	695	671	642	678	695	677	731	700
	Aggregate 4/8	kg/m^3	377	374	367	349	377	377	386	380
	Aggregate 8/16	kg/m^3	266	270	271	704	266	272	266	268
	Aggregate 16/22	kg/m^3	529	538	541		529	543	530	534
	Air entraining agent	kg/m^3	1.7	1.7	2.3	4.0	0.7	1.6	0.0	1.5
	Superplasticizer	kg/m^3	2.8	2.3	2.2	2.9	2.7	2.9	3.82.	2.6
	Eqv. w/c ratio	-	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.45

		Concrete ID:	**I**	**J**	**K**	**L**	**M**	**N**	**O**
Powder composition wt%	Low alkali SR cement	CEM I 42.5 N	84	84					96
	Cement	CEM 1 52.5 N						30	
	Slag cement	CEM III/B 42.5 N			100	100	100		
	Fly ash	EN 450-1 N	12	12					
	Silica fume	50 %-wt slurry	4	4					4
	GG blast furnace slag	EN 15167-1						70	
Concrete composition	Cement	kg/m^3	330	350	360	375	410	108	340
	Fly ash	kg/m^3	47	50					
	Silica fume, solid matter	kg/m^3	16	17					14
	GGBFS	kg/m^3						252	
	Water content	l/m^3	135	163	144	150	164	144	147
	Aggregate 0/2	kg/m^3	671	687	689	702	686	689	695
	Aggregate 4/8	kg/m^3	374	354	373	381	353	374	377
	Aggregate 8/16	kg/m^3	270	713	263	269	712	263	266
	Aggregate 16/22	kg/m^3	538		525	535		525	529
	Air entraining agent	kg/m^3	2.3	2.2	0.8	0.0	1-6	1.0	0.0
	Superplasticizer	kg/m^3	3.6	3.4	2.3	2.6	2.9	2.9	3.7
	Eqv. w/c ratio	-	0.35	0.40	0.40	0.40	0.40	0.40	0.40

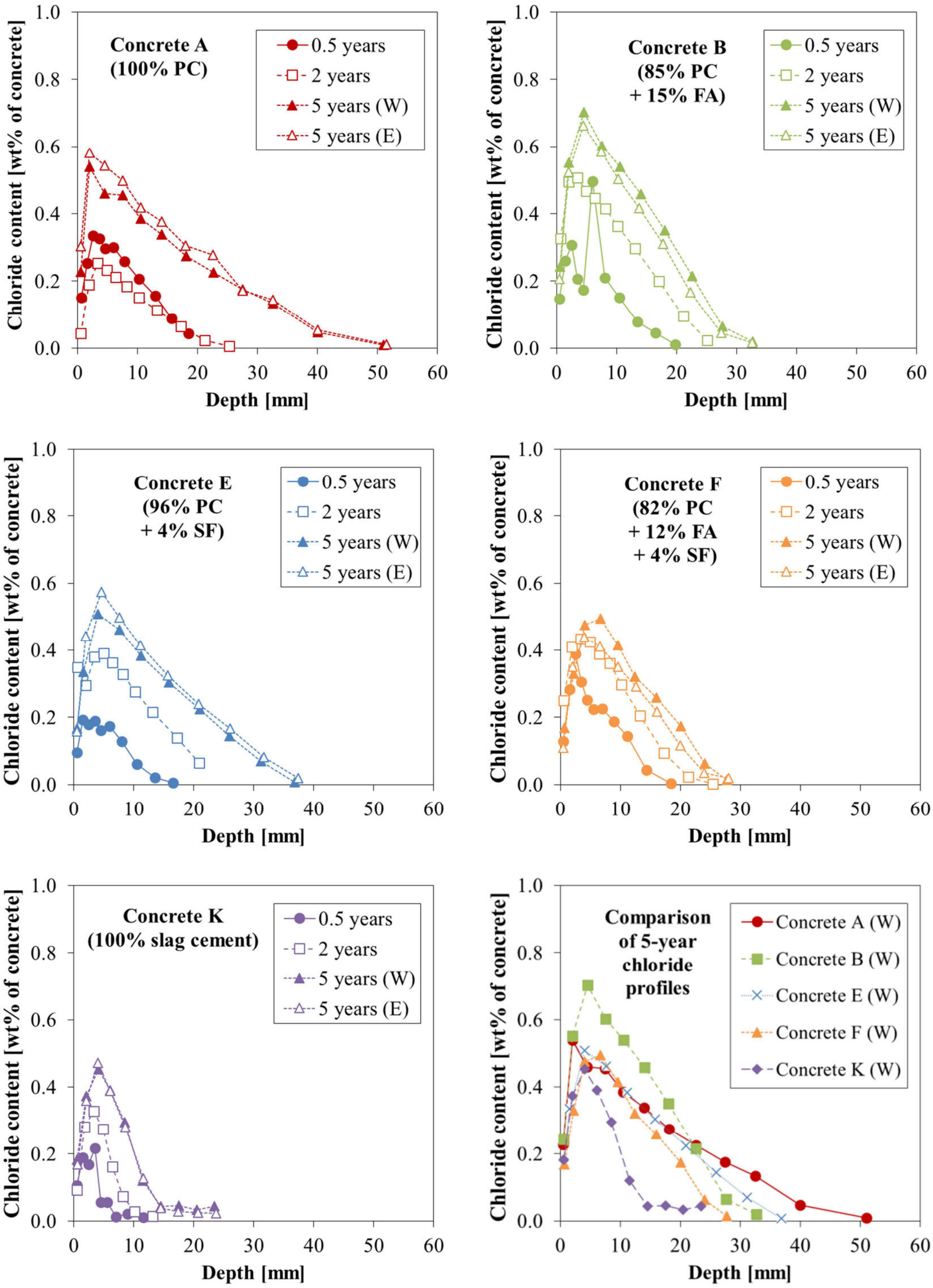

Figure 1: Chloride profiles measured on cores drilled from the permanently submerged part of concrete blocks at the Rødbyhavn marine exposure site after 0.5, 2 and 5 years of exposure. Two profiles were determined for each of the extracted cores after 5 years: One profile from the west (W) and one profile from the east (E) facing side of the cores.

In Fig. 3, the 5-year values of D_a and C_s for five representative concrete types are compared to similar data determined from chloride profiles measured after 0.5 and 2 years of exposure at the Rødbyhavn exposure site.

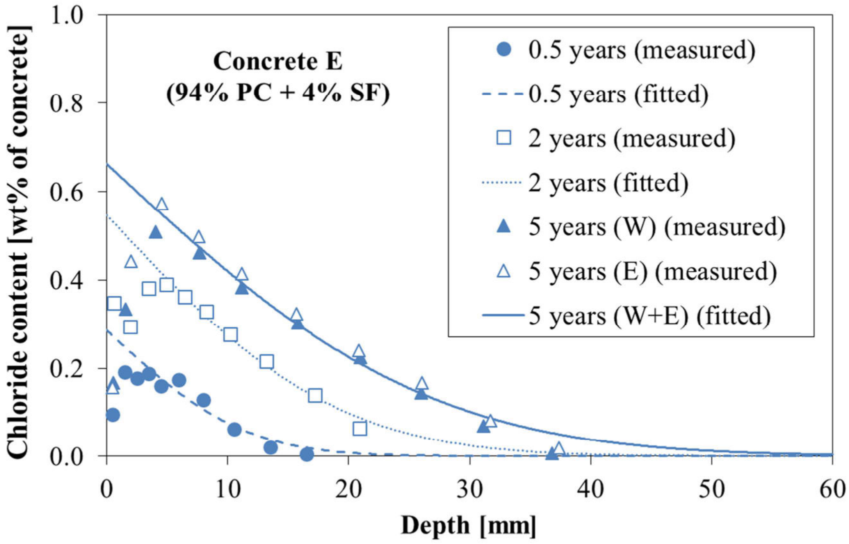

Figure 2: Measured chloride profiles for concrete E in the submerged zone plotted along with calculated profiles obtained by fitting the error-function solution to Fick's 2[nd] law of diffusion to the measured profiles.

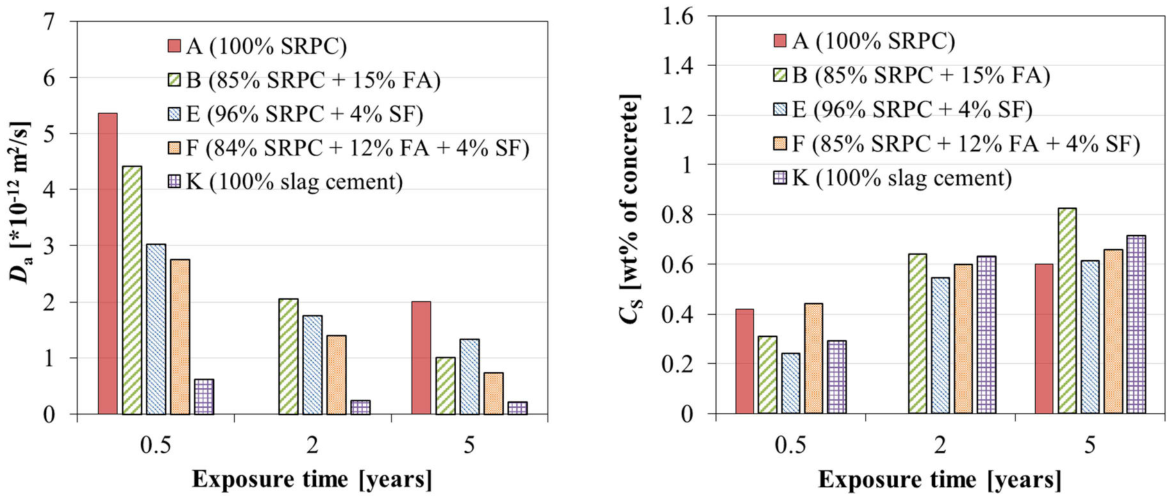

Figure 3: Achieved chloride diffusion coefficients (D_a) (*left*) and surface chloride concentrations (C_s) (*right*) after 5 years marine exposure for five representative concrete types (A, B, E, F, and K) from the field exposure site in Rødbyhavn, Denmark. Values for D_a and C_s were obtained from chloride profiles measured on cores drilled from the submerged zone of the exposed concrete blocks. Similar data determined after 0.5 and 2 years of exposure [2] are shown as well for comparison.

4. DISCUSSION

4.1 Influence of binder type on chloride ingress

The data presented in Fig. 1, Fig. 3 and Table 2 demonstrates that the resistance against chloride ingress for the investigated types of concrete is strongly influenced by the binder composition used in the concrete mix. For example, the chloride profiles in Fig. 1 show that the chloride ingress is significantly lower in Concrete K with slag cement compared to the ingress observed for all the other concrete types. The same tendency is also reflected in the very low values of D_a observed for Concrete K (Fig. 3). The presented data generally suggest that the investigated binder types may be ranked in the following order in terms of their ability to ensure a high resistance against chloride ingress: (1) slag cement, (2) blends of Portland cement + fly ash + silica fume (3) Portland cement + fly ash blends, (4) Portland cement + silica fume blends, and (5) pure Portland cement. The improved resistance against chloride ingress as a result of using mineral addition such as slag, fly ash or silica fume has previously been confirmed in numerous studies (e.g. [2] and [6]).

4.2 Simplified model for chloride ingress in concrete structures

In a previous investigation dealing with the chlorid ingress in a number of Danish concrete bridges in marine environment it was observed that the values for achieved chloride diffusion coefficient (D_a) and surface chloride concentration (C_s) appear to become more or less constant for exposure times beyond 5 to 10 years [7]. These findings led to the suggestion of a relatively simple model for chloride ingress into concrete, which is based on a linear correlation between the ingress depth (x_{cr}) of a given reference chloride concentration (cr) and the square root of exposure time:

$$x_{cr} = a_{cr} \cdot \sqrt{t} + b_{cr} \tag{2}$$

where a_{cr} is a factor of proportionality and b_{cr} is the intercept with the y-axis in a plot of x_{cr} against the square root of exposure time (t). The value of a_{cr} is an expression of the rate of chloride ingress of the reference chloride concentration (cr), while the value of b_{cr} is interpreted as a result of a “fast” initial ingress of chloride during the first few months (or years) after the first exposure to the marine environment. Hydration reaction will typically still occur during this early period, which means that the permeability of concrete will be somewhat higher compared to the same concrete in a more mature state. The initial penetration depth (b_{cr}) could also partly be a consequence of initial capillary suction of seawater at the time of the first exposure to a submerged marine environment. Therefore, b_{cr} will most likely be different for the same concrete depending of the maturity, as well as the moisture content in the concrete, at the time of the first exposure to seawater.

Equation (2) can be rearranged for t:

$$t = \left(\frac{x_{cr} - b_{cr}}{a_{cr}} \right)^2 \tag{3}$$

In principle, this equation can be utilized to estimate the time until initiation of reinforcement corrosion in a concrete structure, i.e. the duration of the initiation phase, which is sometimes used as a definition of the service life of a concrete structure. Such an estimation can be obtained 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 (cr) at a level equal to the threshold value for initiation of chloride-induced reinforcement corrosion for the given concrete.

Table 2: Initial chloride concentration in the concrete (C_i), chloride concentration at the concrete surface (C_s), achieved chloride diffusion coefficient (D_a) and penetration parameter $K_{0.05}$ determined for the 15 concrete types (A-O) at the marine exposure site in Rødbyhavn, Denmark after 5 years of exposure. Parameters were determined for both submerged zone (SUB) and splash zone (SPL), and for each combination of concrete type and exposure environment, two sets of parameters were determined: One set calculated from each of the chloride profiles measured on the west and east facing side of the extracted cores. Similar parameters determined after 0.5 and 2 years exposure can be found in Ref. [2].

Concrete ID	**Exposure environment**	**C_i [wt% of concr.]**	**C_S [wt% of concr.]**		**D_a [*10^{-12} m^2/s]**		**$K_{0.05}$ [mm/years$^{0.5}$]**	
			West	East	West	East	West	East
A	SUB	0.012	0.57	0.63	2.02	2.01	21	21
	SPL	0.012	0.65	0.63	1.94	2.07	21	21
B	SUB	0.012	0.84	0.81	1.08	0.93	16	15
	SPL	0.012	0.86	1.00	1.02	1.14	16	18
C	SUB	0.011	0.89	0.81	0.75	0.84	14	14
	SPL	0.011	0.83	0.83	0.98	0.99	16	16
D	SUB	0.013	0.95	0.83	0.60	0.28	13	8
	SPL	0.013	0.94	0.95	0.84	0.71	15	14
E	SUB	0.012	0.58	0.65	1.33	1.32	17	17
	SPL	0.012	0.66	0.70	1.53	1.69	19	20
F	SUB	0.014	0.77	0.55	0.70	0.77	13	13
	SPL	0.014	0.72	0.72	0.80	0.78	14	14
G	SUB	0.010	0.67	0.63	0.66	0.56	12	11
	SPL	0.010	0.65	0.69	0.83	0.76	13	13
H	SUB	0.012	0.65	0.65	1.07	0.80	15	13
	SPL	0.012	0.69	0.67	1.17	1.21	17	17
I	SUB	0.011	0.68	0.72	0.63	0.63	12	12
	SPL	0.011	0.73	0.73	0.71	0.65	13	12
J	SUB	0.010	0.80	0.76	0.74	0.80	13	14
	SPL	0.010	0.99	0.99	0.73	0.68	14	13
K	SUB	0.021	0.70	0.73	0.22	0.21	7.6	7.4
	SPL	0.021	0.66	0.60	0.21	0.20	7.3	7.0
L	SUB	0.020	0.67	0.65	0.19	0.15	6.8	6.1
	SPL	0.020	0.69	0.71	0.22	0.21	7.4	7.3
M	SUB	0.023	0.82	0.66	0.20	0.20	7.5	7.2
	SPL	0.023	0.82	0.86	0.25	0.22	8.4	7.9
N	SUB	0.012	0.53	0.36	0.19	0.20	6.4	5.7
	SPL	0.012	0.80	0.87	0.19	0.26	6.8	8.2
O	SUB	0.011	0.48	0.58	1.01	1.19	14	16
	SPL	0.011	0.59	0.63	1.41	2.02	17	21

The suggested model for chloride ingress was initially derived from an analysis of (1) data from the abovementioned investigation of chloride ingress in a number of Danish coast bridges [7], and (2) data from 20 years marine exposure of concrete slabs in a Swedish field exposure site [6]. In Fig. 4, measured chloride data from Rødbyhavn is used to further examine the validity of the proposed ingress model. This is done by plotting the penetration depth ($x_{0.05}$) of 0.05 wt% chloride concentration against the square root of exposure time for five of the investigated concrete types (A, B, E, F, and K). For each exposure time (0.5, 2 and 5 years), the values of $x_{0.05}$ were determined by linear interpolation between the two data points of each measured chloride profile being closest to 0.05 wt% chloride. It is generally observed that the data for each concrete type plots more or less along a straight line, thus supporting the linear correlation between $x_{0.05}$ and $t^{½}$ implied in Equation (2). A linear regression analysis has been performed on the data set of each of the five concrete types presented in Fig. 4, and the resulting regression lines are plotted here as well. The scale of the x-axis lines is set to 10 years$^{0.5}$ (= 100 years), which means that the penetration depths ($x_{0.05}$) after e.g. 100 years can be estimate directly in the plot by reading the value on the y-axis for each regression line at x = 10 years$^{0.5}$. The regression lines indicates that $x_{0.05}$ after 100 years exposure will be approx. 163 mm, 87 mm, 148 mm, 74 mm, and 58 mm for Concrete A, B, E, F, and K, respectively.

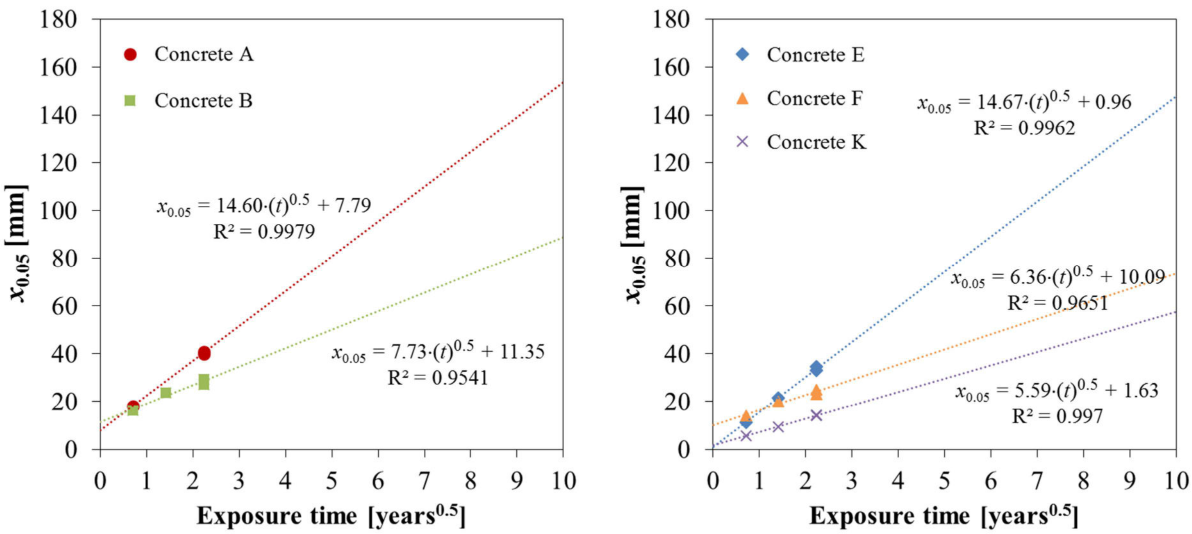

Figure 4: Penetration depth of 0.05 wt% chloride concentration ($x_{0.05}$) in submerged exposure conditions as a function of the square root of exposure time. The plots includes data for five selected concrete types (A, B, E, F, and K) from the Rødbyhavn marine exposure site. For each concrete type a linear regression analysis has been performed on the plotted data and the results are displayed as the dotted lines. The correlation coefficient (R^2) from each regression analysis is also shown along with the optimised parameters ($a_{0.05}$ and $b_{0.05}$) inserted in the equation $x_{0.05} = a_{0.05}\cdot(t)^{0.5} + b_{0.05}$.

The validity of using the calculated regression lines in Fig. 4 as models for estimating the chloride ingress in comparable concrete types from other locations has been examined by a comparison with chloride ingress data from concrete slabs exposed at the marine exposure site in Träslövsläge, Sweden [6,8]. In Fig. 5, the regression lines for concrete A, B, E, and F is plotted together with extracted data sets of $x_{0.05}$ for five selected concrete types (2-40, H8, H4, 10-40, and 12-35) from Träslövsläge. The selected concrete types have compositions that are comparable to either Concrete A, B, E, or F, and the values of $x_{0.05}$ were determined from measured chloride profiles by linear interpolation between the two data points of each chloride profile being closest to 0.05 wt% chloride.

Generally, each data set of $x_{0.05}$ for the Träslövsläge concretes plots very close to the relevant regression line from the analysis of the Rødbyhavn chloride data. Specifically, the $x_{0.05}$ values for Concrete 2-40 (100% PC) plots along the regression line for Concrete A (100% PC), the $x_{0.05}$ values for Concrete H8 (80% PC + 20% fly ash) plots close to the regression line for Concrete B (85% PC + 15% fly ash), and the $x_{0.05}$ values for Concrete 10-40 (78.5% PC + 17% fly ash + 4.5% silica fume) and Concrete 12-35 (85% PC + 10% fly ash + 5% silica fume) plots close to the regression line for Concrete F (84% PC + 12% fly ash + 4% silica fume). An exception is the $x_{0.05}$ values for Concrete H4 (95% PC + 5% silica fume), which for some unknown reason show a less convincing compliance with the regression line for Concrete E (96% PC + 4% silica fume).

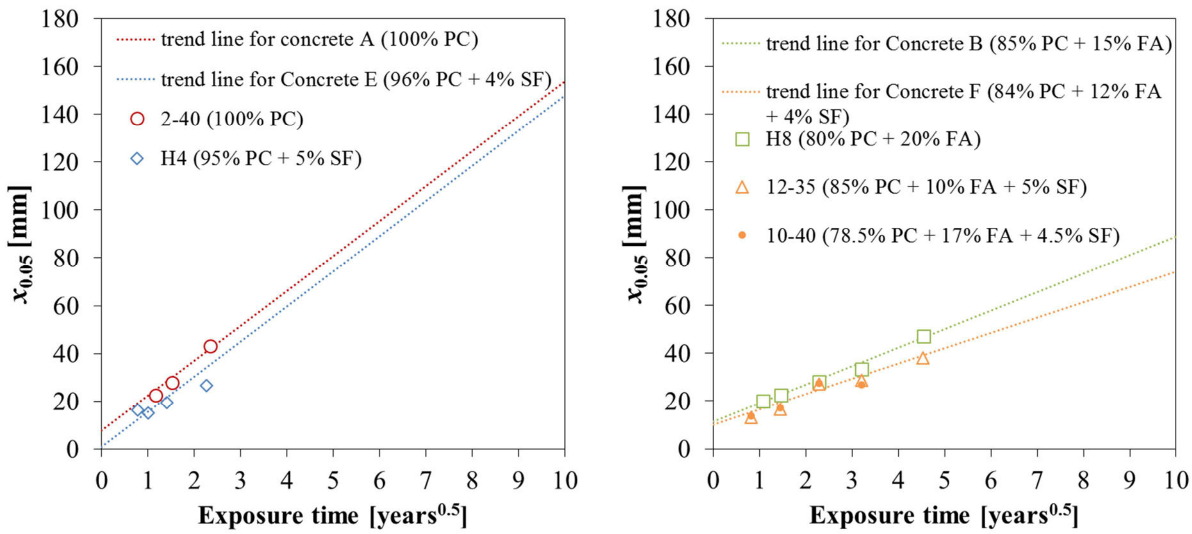

Figure 5: Penetration depth of 0.05 wt% chloride concentration ($x_{0.05}$) in submerged exposure conditions as a function of the square root of exposure time. The plots includes data for five selected concrete types (2-40, H4, H8, 12-35, and 10-40) from the marine exposure site in Träslövsläge, Sweden [6,8]. The calculated regression lines for Concrete A, B, E, and F from the marine exposure site in Rødbyhavn are included for comparison.

A linear regression analysis has also been performed on the data set of $x_{0.05}$ for each of the selected concrete types from Träslövsläge, and the optimised parameters ($a_{0.05}$ and $b_{0.05}$) from the analyses are given in Table 3 along with the optimised parameters from the linear regression analyses of the chloride data for Concrete A, B, E, F, and K. It is generally observed that the concretes from Rødbyhavn and Träslövsläge with comparable binder compositions have rather similar values for $a_{0.05}$ and $b_{0.05}$. Again, an exception is the two concretes with a binder of Portland cement + silica fume (E (Rødbyhavn) and H4 (Träslövsläge)), which show somewhat diverse values for $a_{0.05}$ (15 mm/years$^{0.5}$ vs. 8 mm/years$^{0.5}$) and $b_{0.05}$ (1 mm vs. 9 mm). The reason for this discrepancy is unknown at this point. Furthermore, validation against reliable long-term field data is generally still needed to calibrate and further develop the suggested chloride ingress model.

Table 3: 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. 4 and selected chloride data from the marine exposure site in Träslövsläge, Sweden [6,8]. SRPC = sulphate-resistant Portland cement, OPC = ordinary Portland cement, FA = fly ash, SF = silica fume. *Calculated assuming an efficiency factor of 2.0 and 0.5 for silica fume and fly ash, respectively. **Calculated assuming an efficiency factor of 1.0 and 0.3 for silica fume and fly ash, respectively [6,8].

Concrete ID	**Binder**	**Eqv. w/c-ratio**	**$a_{0.05}$ [mm/year$^{0.5}$]**	**$b_{0.05}$ [mm]**
A (Rødbyhavn)	100% SRPC	0.40	14.60	7.79
2-40 (Träslövsläge)	100% OPC	0.40	17.60	1.81
B (Rødbyhavn)	85% SRPC + 15% FA	0.40*	7.73	11.35
H8 (Träslövsläge)	80% SRPC + 20% FA	0.30**	4.65	11.05
E (Rødbyhavn)	96% SRPC + 4% SF	0.40*	14.67	0.96
H4 (Träslövsläge)	95% SRPC + 5% SF	0.40**	7.61	8.99
F (Rødbyhavn)	84% SRPC + 12% FA + 4% SF	0.40*	6.36	10.09
10-40 (Träslövsläge)	78.5% SRPC + 17% FA + 4.5% SF	0.40**	6.18	9.32
12-35 (Träslövsläge)	85% SRPC + 10% FA + 5% SF	0.35**	7.10	7.60
K (Rødbyhavn)	100% slag cement	0.40	5.59	1.63

5. CONCLUSIONS

The following conclusion can be drawn from the investigation of the most recent chloride ingress data from the marine exposure site in Rødbyhavn, Danmark and from a comparison with relevant chloride data from the field exposure site in Träslövsläge, Sweden:

- Among the studied concrete types from Rødbyhavn, the highest resistance against chloride ingress is observed for Concrete K with a binder of slag cement.
- Intermediate resistance against chloride ingress is observed for concrete types with binders consisting of Portland cement in combination with fly ash and/or silica fume.
- Lowest resistance against chloride ingress is observed for Concrete A with a binder of 100% Portland cement.
- Analysis of chloride data from submerged concretes at the exposure sites in Rødbyhavn and Träslövsläge support the validity of a proposed model for estimation of chloride ingress in concrete structures that is based on a simple square root of time dependency.

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