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CONCRETE EXPERTCENTRE

In cooperation with the Danish Road Directorate

Vejdirektoratet

New model for chloride penetration into concrete ?

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Investigation of marine bridges in 2012


Vejle Fjord bridge 1975-80


Alssund bridge 1978-81


Faroe bridges 1980-85

Survey vessel

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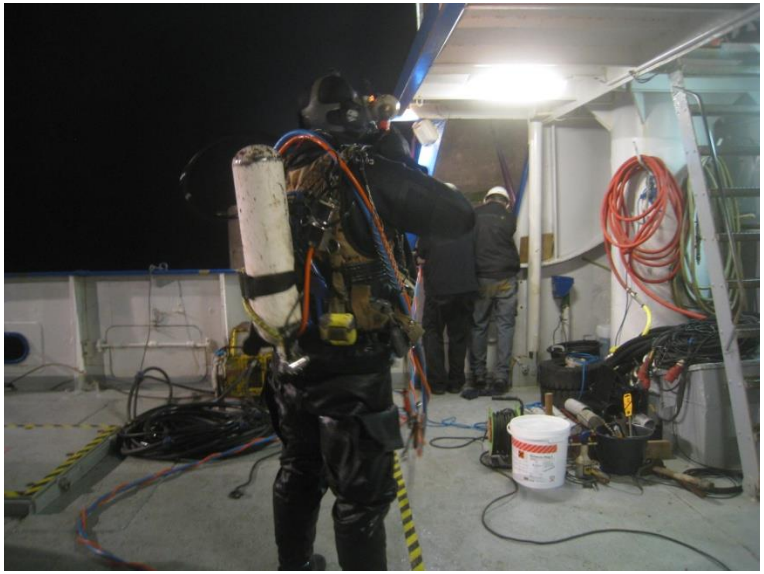
Core drilling below water level



Extracted concrete cores

Sample No.	Bridge	Year of construction	Kote [m]	Sampling date	Exposure time	Binder type
V1-V4	Vejle Fjord bridge	1975-1980	-1,0	18-01-2012	≈ 34 yr	400 kg slag cement (Aquafirm) 180 kg water (w/c = 0,45)
A1-A4	Alssund bridge	1978-1981	-1,5	17-01-2012	≈ 31 yr	380 kg ALS cement (AaP) 150 kg water (w/c = 0,39)
F1-F4	Faroe bridges	1980-1985	-1,5	03-02-2012	≈ 30 yr	330 kg Low alkali cement (AaP) 100 kg FA from Danaske 150 kg water (eq. w/c =0,42)

Eq. w/c-ratio marked with red has been calculated assuming an efficiency factor of 0.3 for fly ash (others 0.5)

Cores from Vejle Fjord bridge

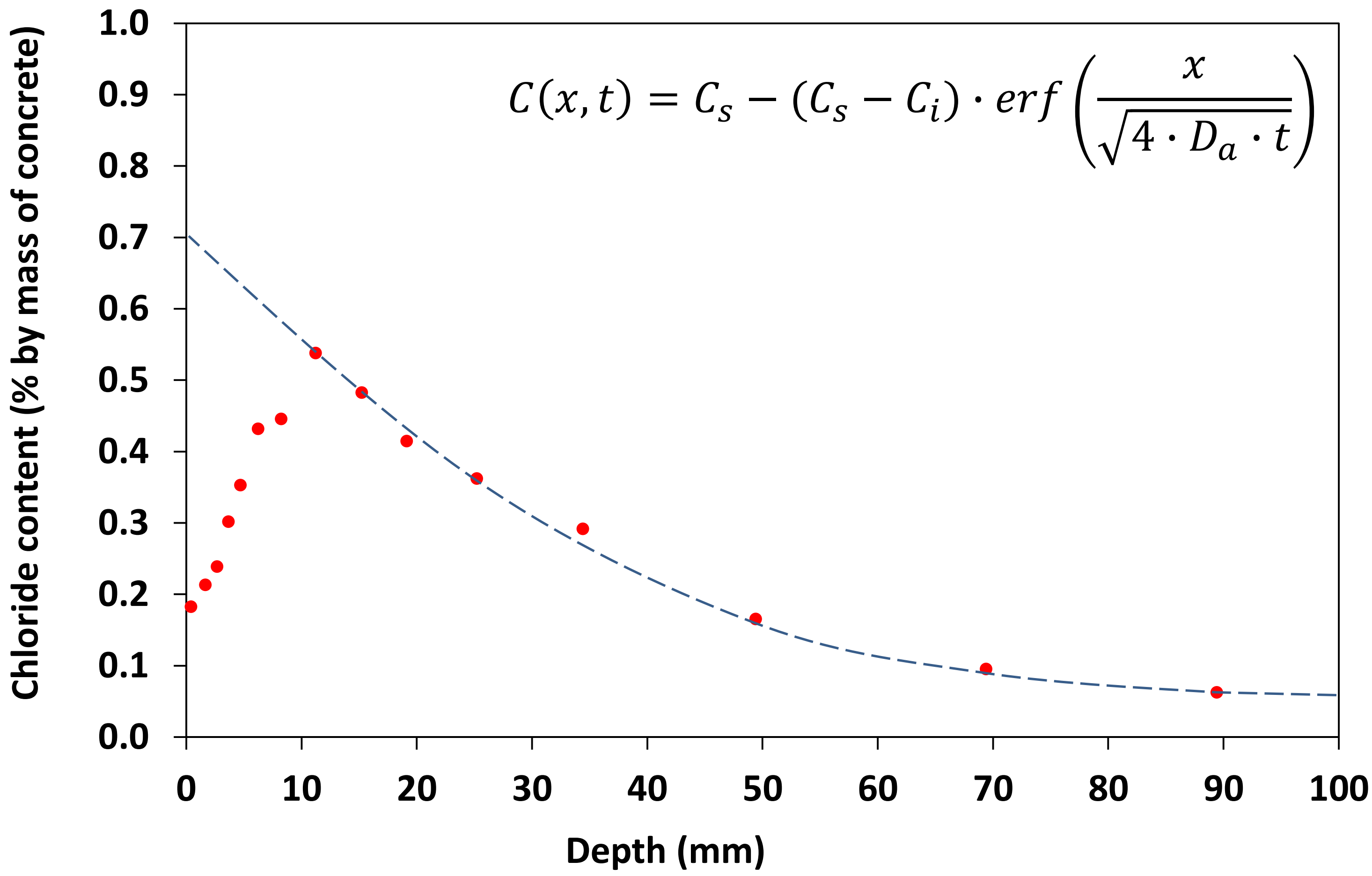
Cores from Alssund bridge

Cores from Faroe bridges

Chloride analyses

Chloride penetration model – curve fitting

The error function solution to Fick's 2nd law of diffusion for a semi-infinite medium



Chloride penetration model – penetration parameter

Rearrangement of the error function solution
to Ficks 2nd law of diffusion for a semi-infinite medium

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

By rearranging we get: $x = 2\sqrt{D_a} \cdot erf^{-1}\left(\frac{C_s - C(x,t)}{C_s - C_i}\right) \cdot \sqrt{t}$

Which can be written as: $x_{C_r} = K_{C_r} \cdot \sqrt{t}$

when : $K_{C_r} = 2\sqrt{D_a} \cdot erf^{-1}\left(\frac{C_s - C_r}{C_s - C_i}\right)$ and $C_r = C(x,t)$

K_{C_r} is a constant, when D_a and C_s are constants
K_{C_r} is named the "penetration parameter" or the "first year penetration" when given in mm/$\sqrt{\text{year}}$

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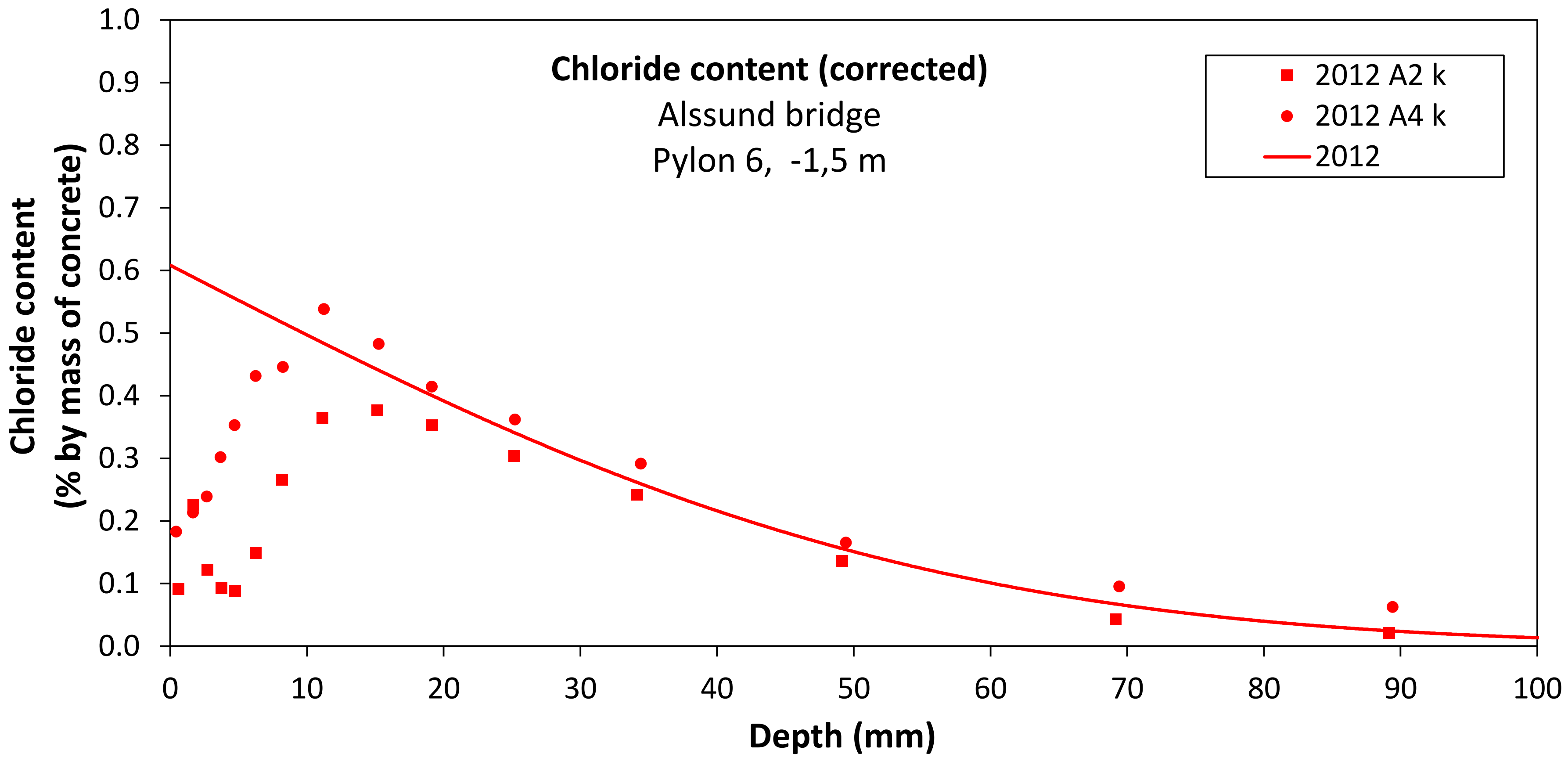
Alssund bridge – chloride penetration parameters



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

$$K_{0,05} = 2\sqrt{D_a} \cdot erf^{-1}\left(\frac{C_s - 0,05}{C_s - C_i}\right)$$

Year	2012	Unit
Exp.time	31	Yr
D_a	0.95	$x10^{-12}$ m^2/s
C_s	0.608	%Cl by mass of CO
C_i	0.001	%Cl by mass of CO
$K_{0,05}$	13.5	mm/yr½

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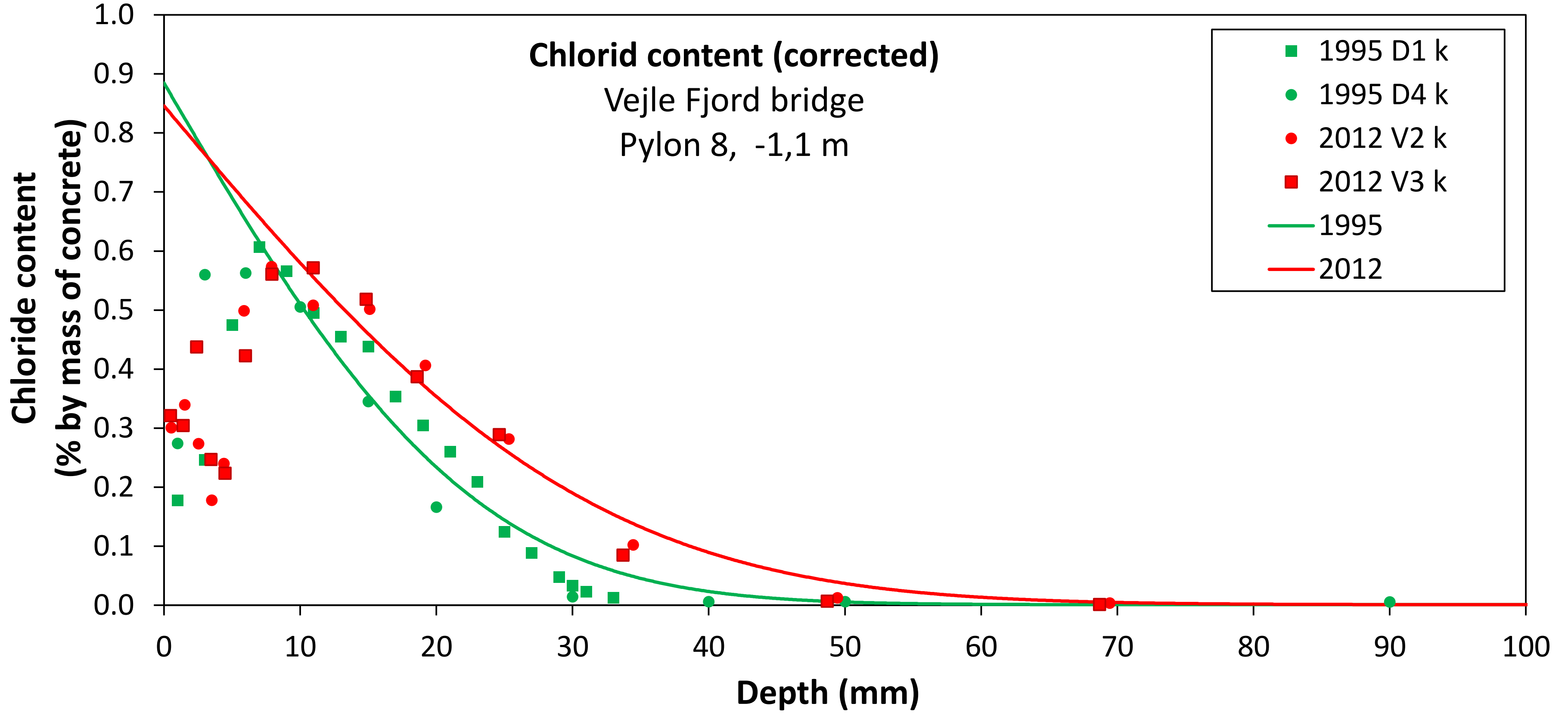
Vejle Fjord bridge – chloride penetration parameters



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

$$K_{0,05} = 2\sqrt{D_a} \cdot erf^{-1}\left(\frac{C_s - 0{,}05}{C_s - C_i}\right)$$

Year	1995	2012	Unit
Exp.time	17	34	Yr
D_a	0.30	0.28	x10^{-12} m^2/s
C_s	0.885	0.846	%Cl by mass of CO
C_i	0.001	0.001	%Cl by mass of CO
$K_{0,05}$	8,3	8.0	mm/yr^{½}

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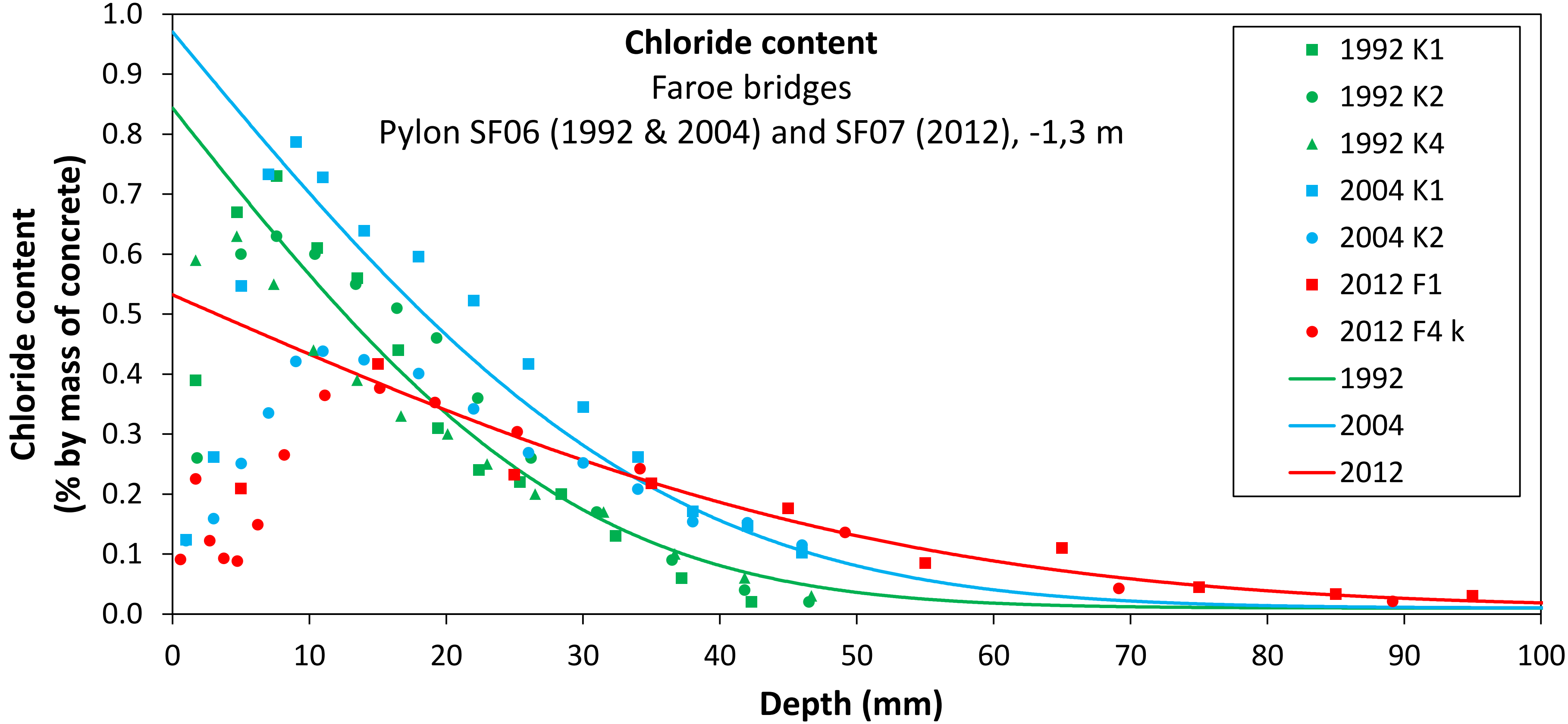
Faroe bridges – chloride penetration parameters



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

$$K_{0,05} = 2\sqrt{D_a} \cdot erf^{-1}\left(\frac{C_s - 0,05}{C_s - C_i}\right)$$

Year	1992	2004	2012	Unit
Exp.time	10.7	22.4	30	Yr
D_a	0.80	0.55	0.92	$x10^{-12}$ m^2/s
C_s	0.844	0.971	0.532	%Cl by mass of CO
C_i	0.010	0.010	0.010	%Cl by mass of CO
$K_{0,05}$	14.0	12.0	13.5	mm/yr^{½}

Chloride penetration parameters – 3 bridges

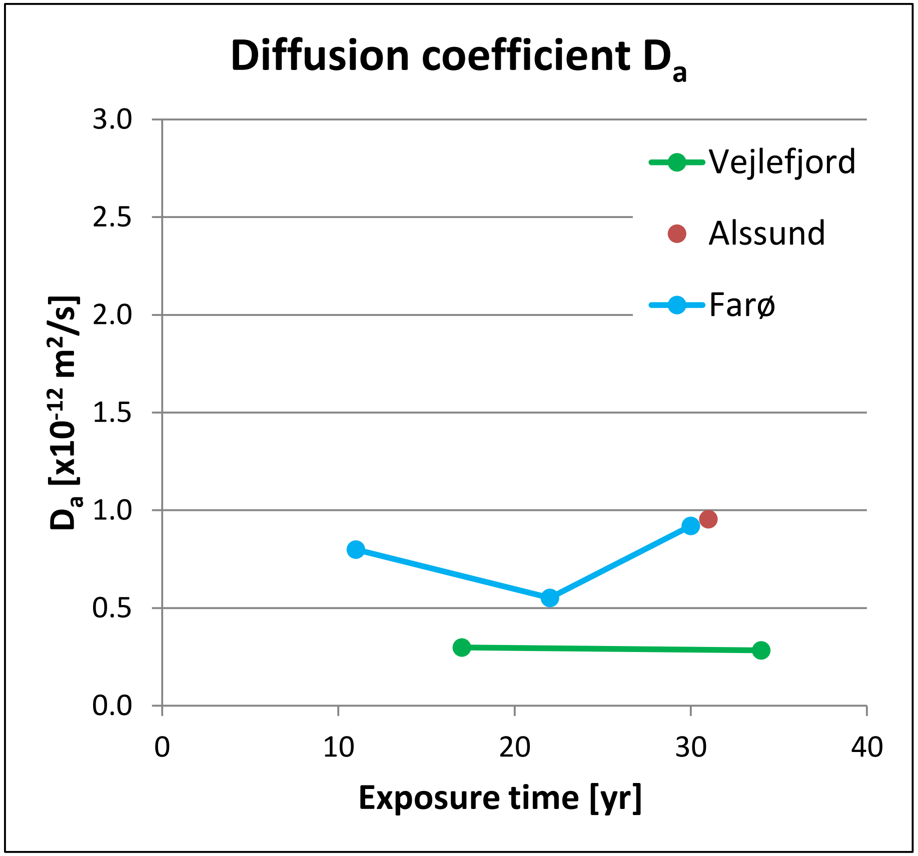
Bridge	Exposure time [years]	D_a [$*10^{-12}$ m^2/s]	C_s [wt% of conc.]	C_i [wt% of conc.]	$K_{0.05}$ [mm/year½]
Vejle Fjord Bridge	17	0.30	0.89	0.001	8.3
	34	0.28	0.85	0.001	8.0
Alssund Bridge	31	0.95	0.61	0.001	13.5
Farø Bridges	11	0.80	0.84	0.010	14.0
	24	0.55	0.97	0.010	12.0
	30	0.92	0.53	0.010	13.5

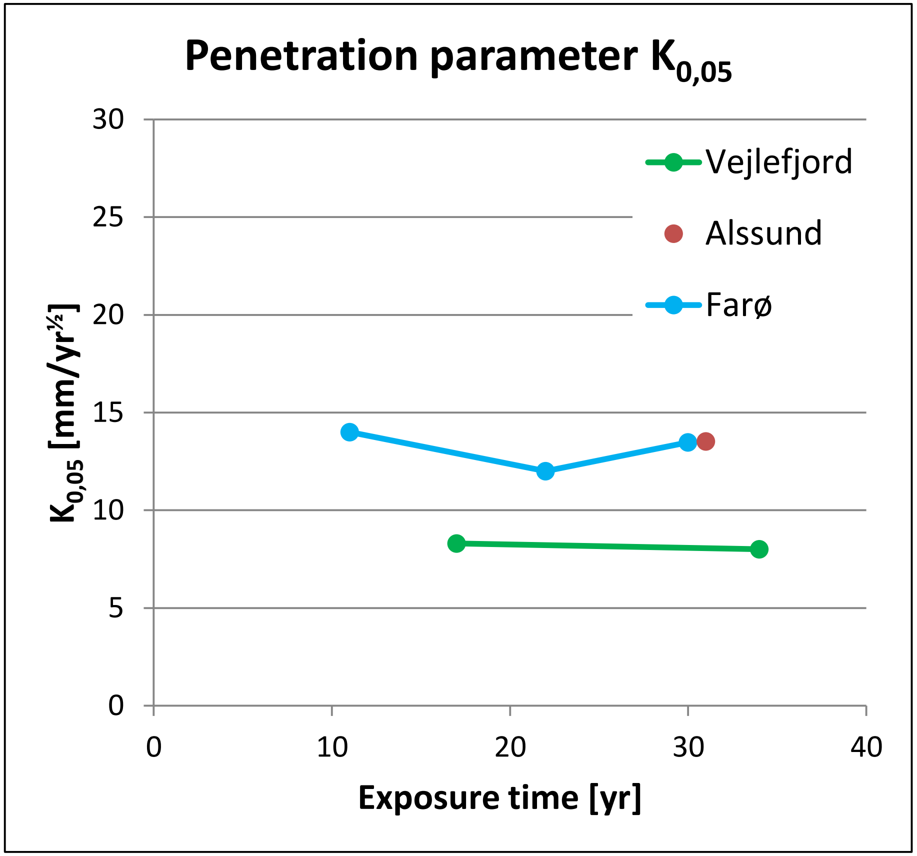
Data marked with blue is calculated on chloride profiles from earlier investigations

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

$$K_{0,05} = 2\sqrt{D_a} \cdot erf^{-1}\left(\frac{C_s - 0{,}05}{C_s - C_i}\right)$$

Chloride penetration parameters – 3 bridges





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

$$K_{0,05} = 2\sqrt{D_a} \cdot erf^{-1}\left(\frac{C_s - 0{,}05}{C_s - C_i}\right)$$

It is not evident, that a time dependent apperent diffusion coefficient, e.g.:

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

is observed after long time marine exposure of the concrete in the submerged part of the bridges

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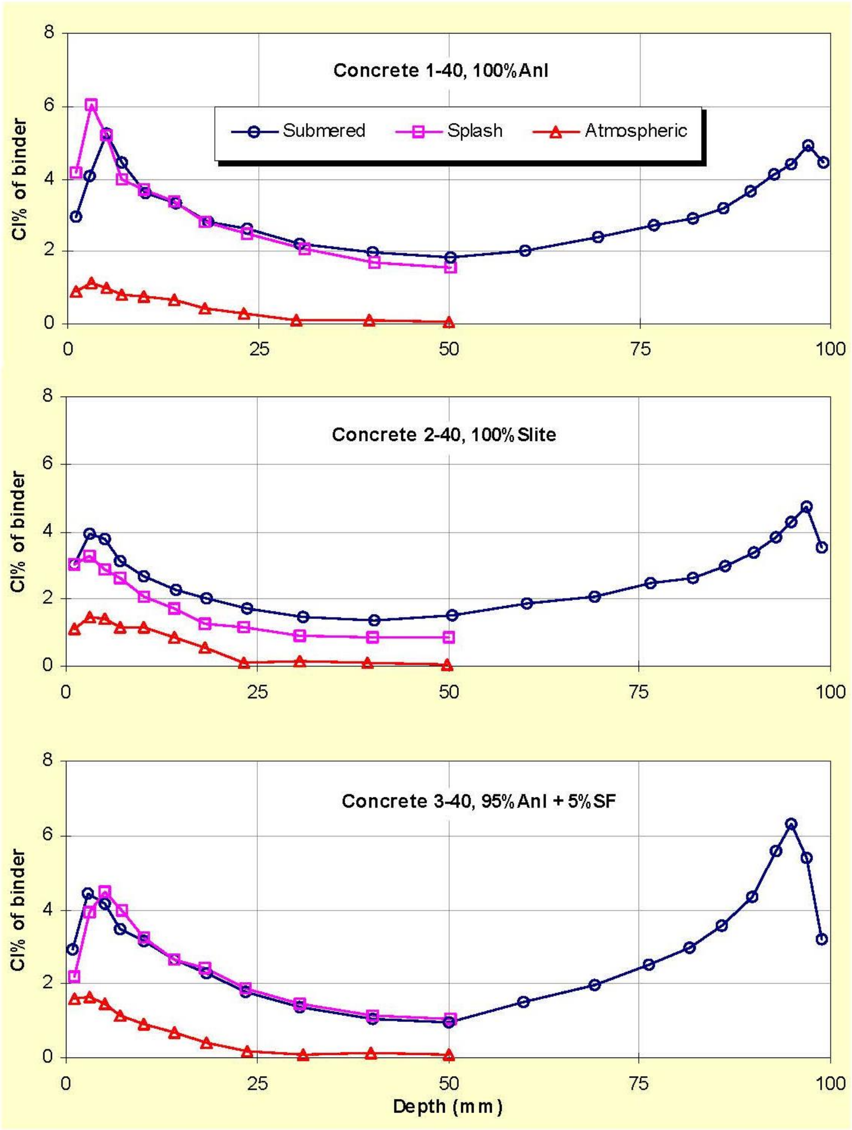
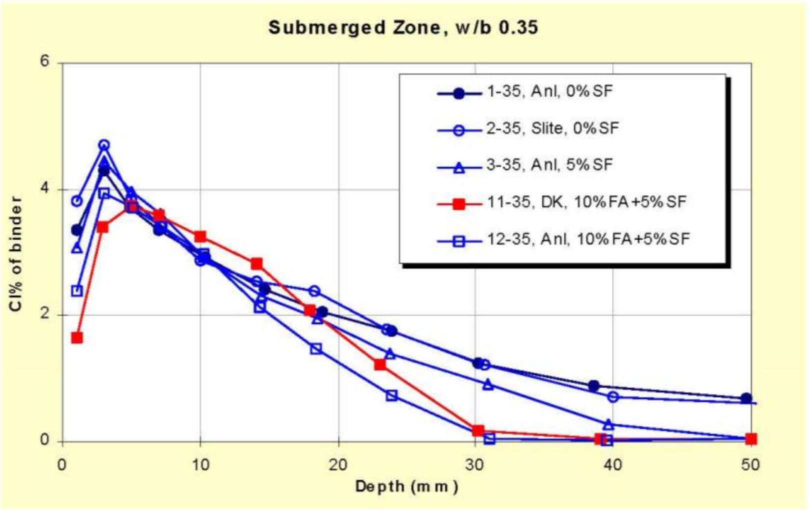
Marine field exposure site in Träslövsläge, Sweden

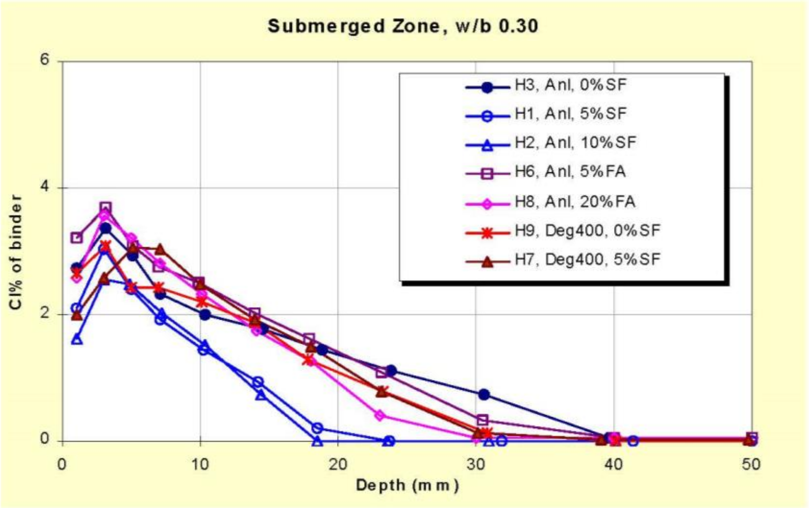
Träslövsläge data from: Boubitsas, D.; Tang, L,; Utgenannt, P., "Chloride Ingress in Concrete Exposed to Marine Environment – Field data up to 20 years exposure", SBUF, Final draft rapport: 2014-02-14, 137p.

Marine exposure of approx. 40 different concrete types starting in 1991.

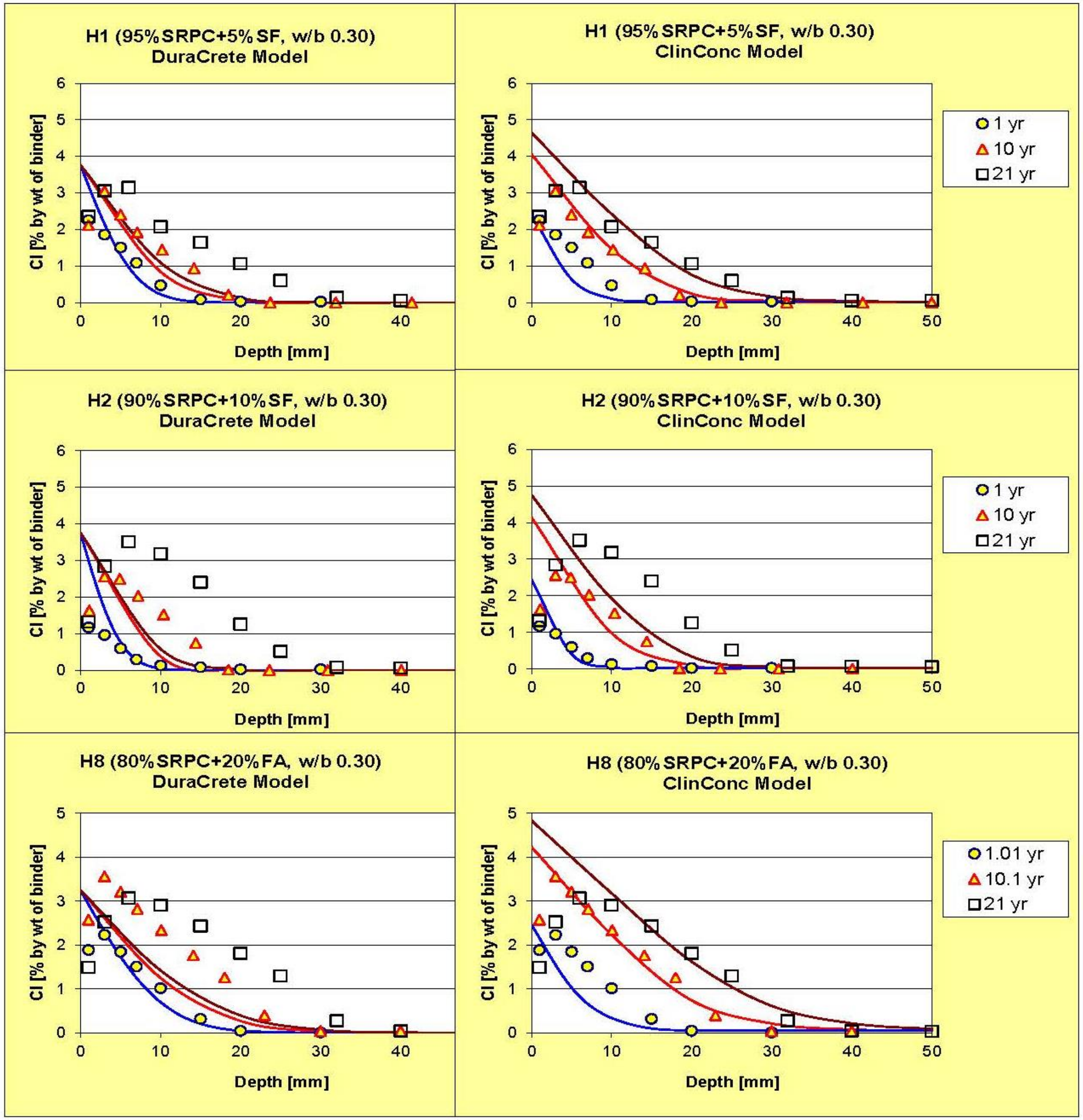
Results from Träslövsläge – 10 years exposure







Results from Träslövsläge – 20 years subm. exposure



Results from Träslövsläge – exposure time dependency

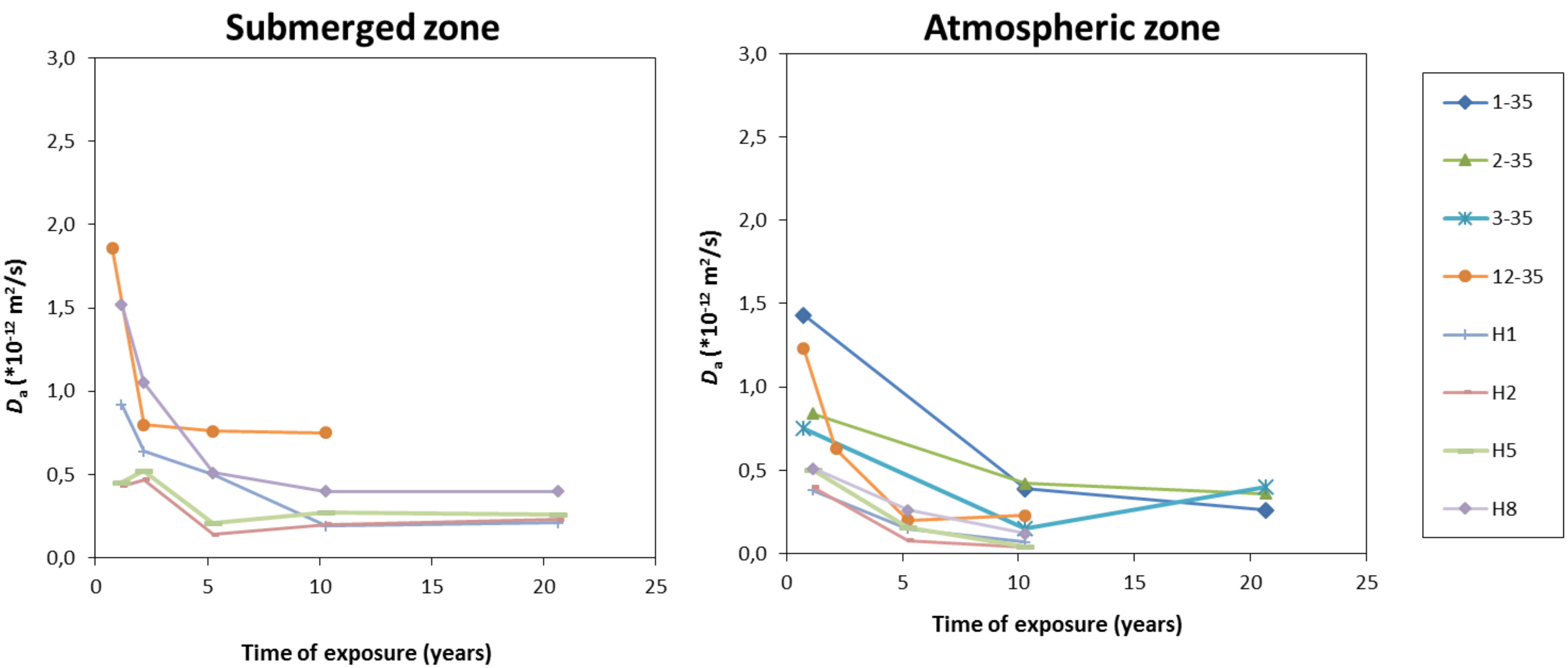
Binder types and sampling ages

ID	w/b ratio	Binder type	Binder (kg/m³)	Sampling age (years)
Träslövsläge 2-35	0.35	100% OPC	450 kg CE	1, 10, 20
Träslövsläge 1-35	0.35	100% SRPC	450 kg CE	0.75, 10, 20
Träslövsläge H8	0.35	80% SRPC + 20% FA	493 kg CE + 123 kg FA	1, 2, 5, 10, 20
Träslövsläge 3-35	0.35	95% SRPC + 5% SF	428 kg CE + 22 kg SF	0.75, 10, 20
Träslövsläge H1	0.30	95% SRPC + 5% SF	475 kg CE + 25 kg SF	1, 2, 5, 10, 20
Träslövsläge H5	0.25	95% SRPC + 5% SF	523 kg CE + 28 kg SF	1, 2, 5, 10, 20
Träslövsläge H2	0.30	90% SRPC + 10% SF	450 kg CE + 50 kg SF	1, 2, 5, 10, 20
Träslövsläge 12-35	0.30	85% SRPC + 10% FA + 5% SF	383 kg CE + 45 kg FA + 22 kg SF	0.75, 2, 5, 10, 20

W/b-ratios marked with red have been calculated assuming an efficiency factor of 1.0 and 0.3 for silica fume and fly ash, respectively

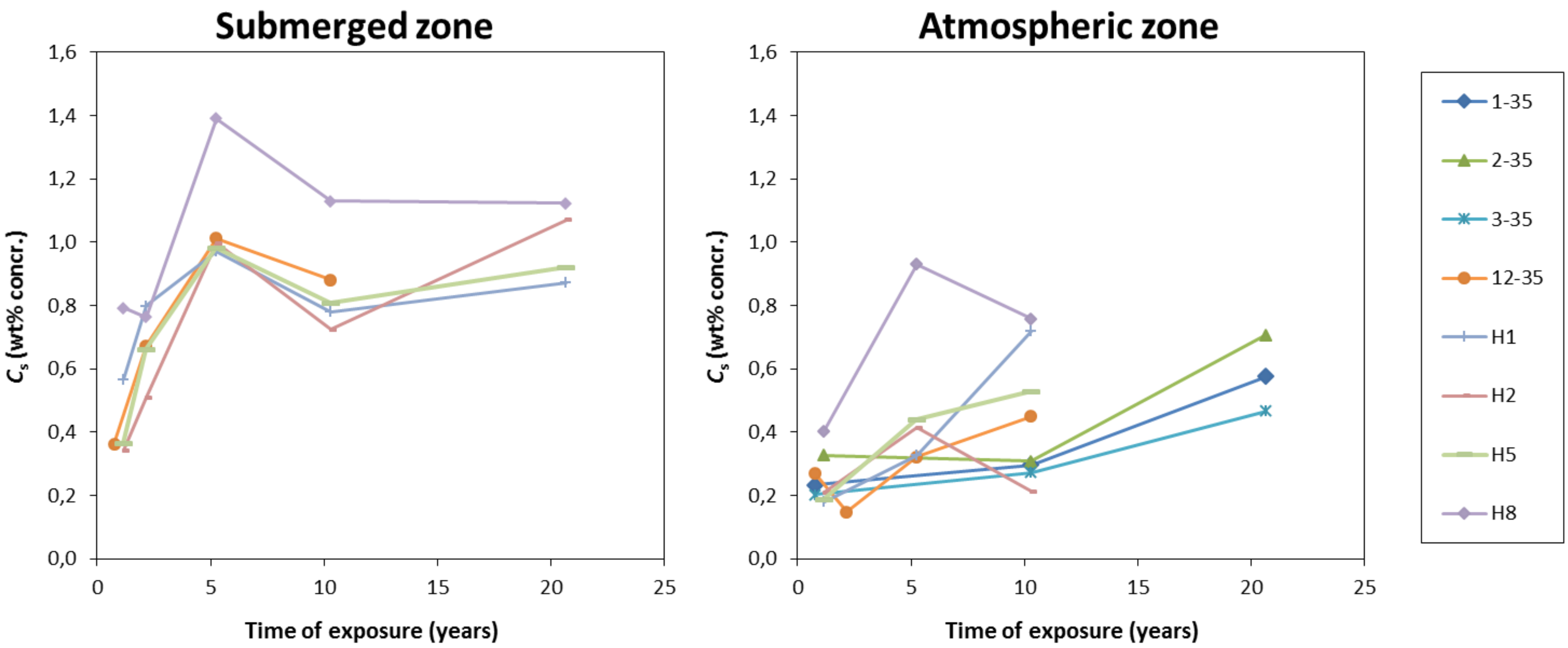
Results from Träslövsläge – diffusion coefficients

Apparent diffusion coefficients versus exposure time



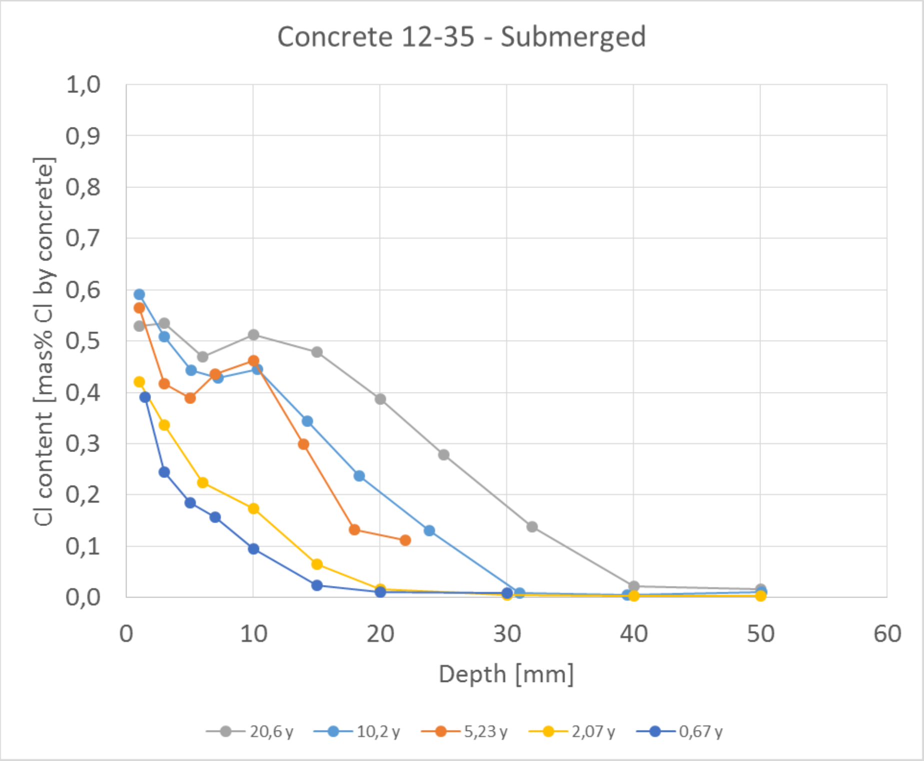
Results from Träslövsläge – Surface concentrations

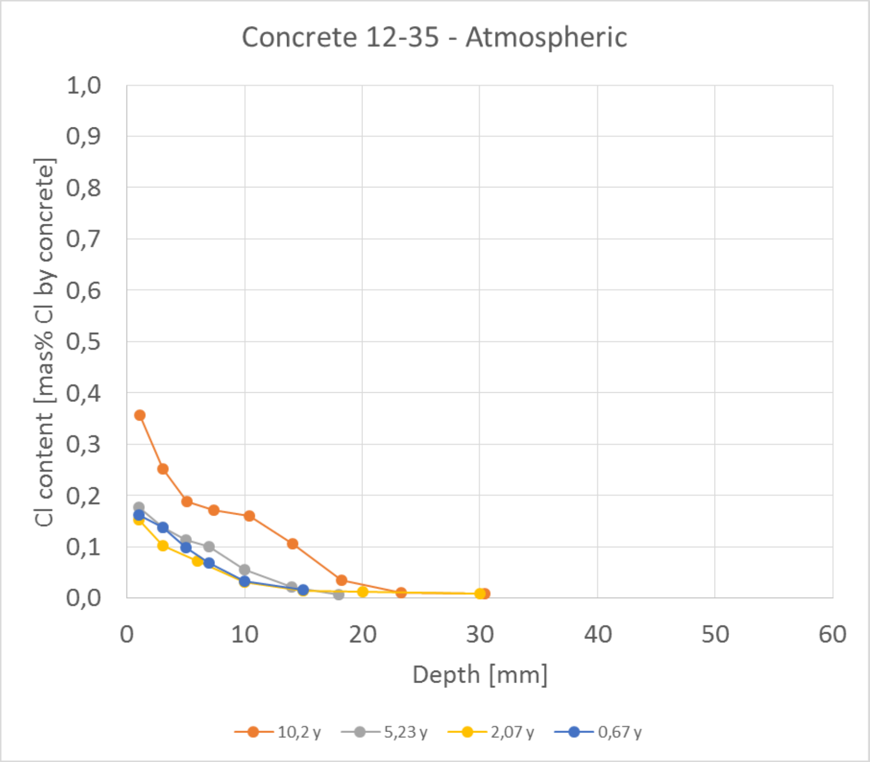
Calculated surface concentrations versus exposure time



Results from Träslövsläge – some chloride profiles

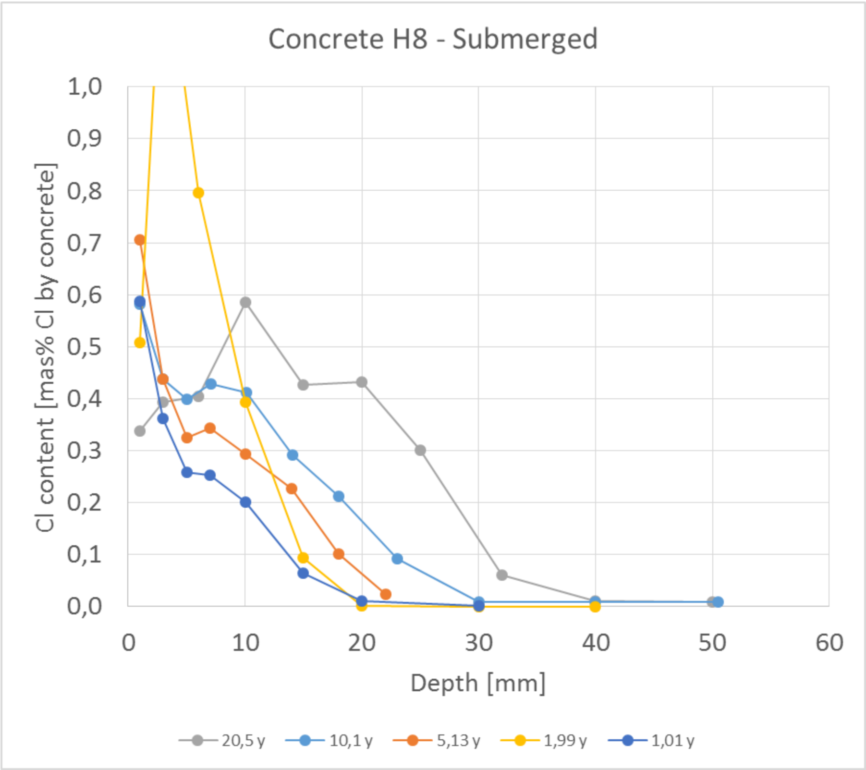
Concrete 12-35 (85% SRPC + 10% FA + 5% SF, w/b = 0.30)

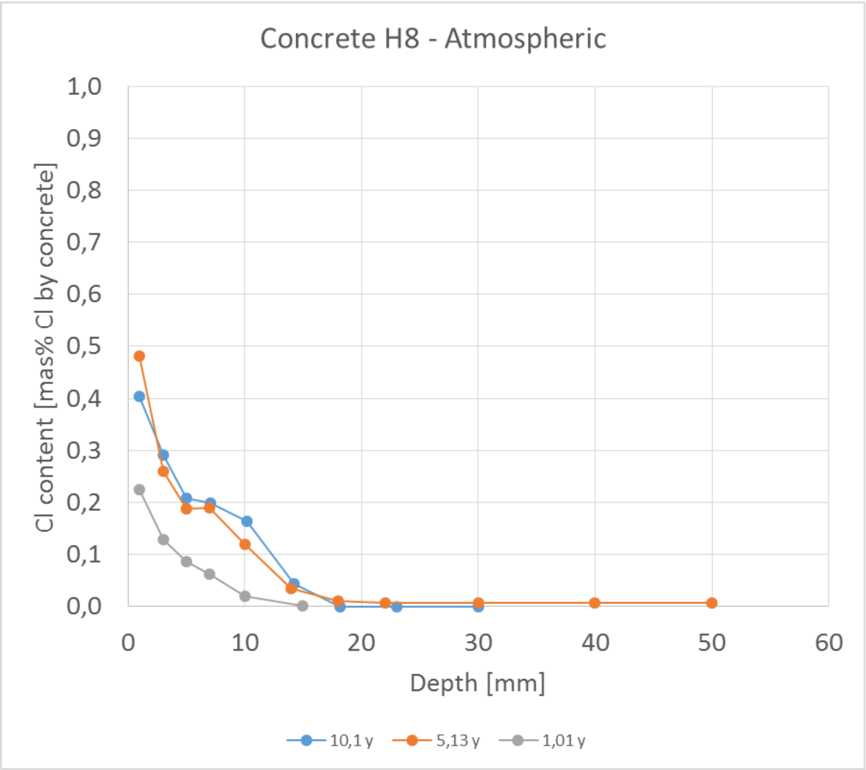




Results from Träslövsläge – some chloride profiles

Concrete H8 (80% SRPC + 20% FA, w/b = 0.35)





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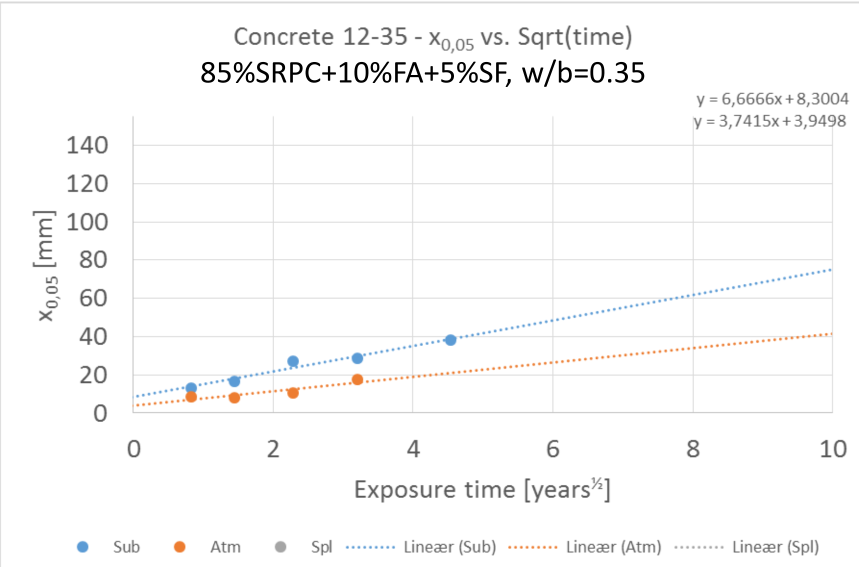
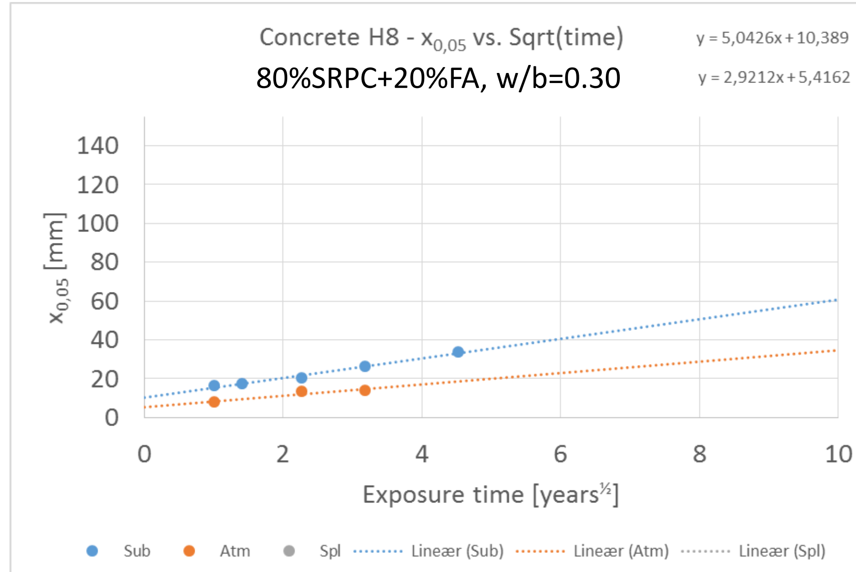
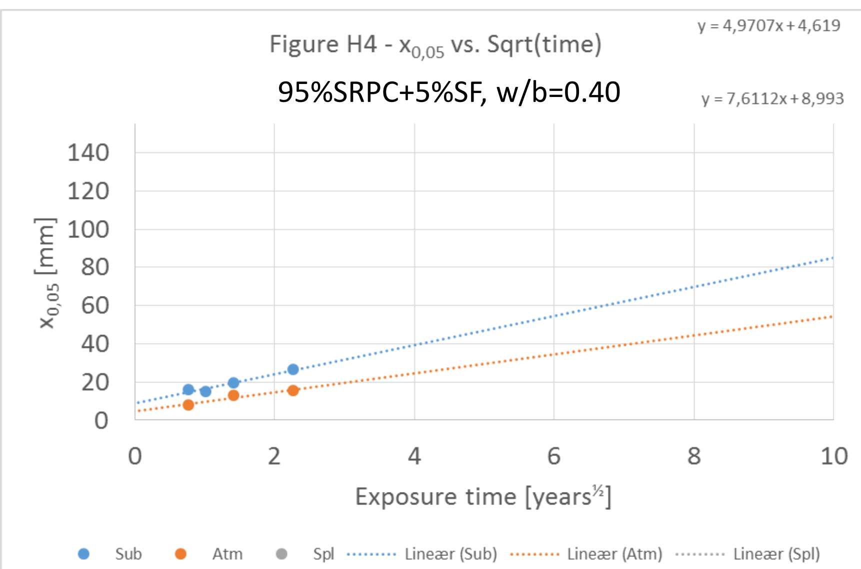
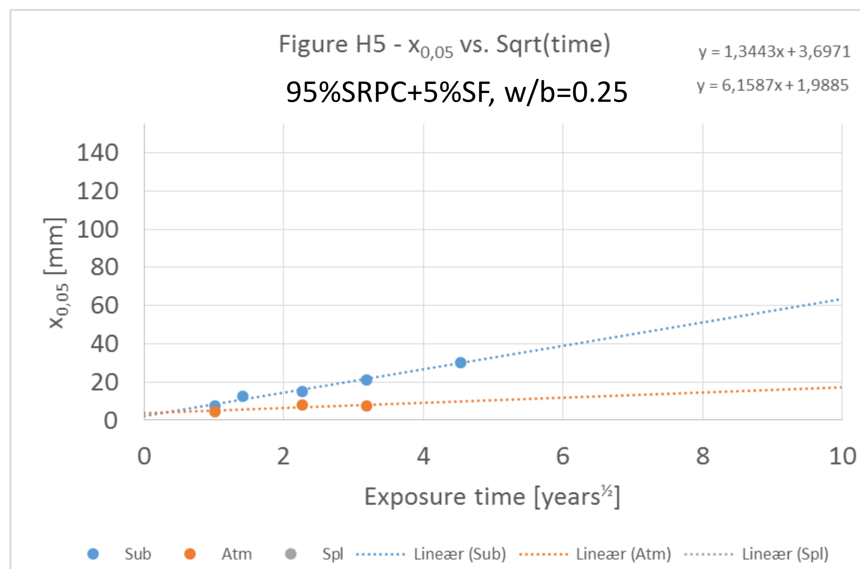
Results from Träslövsläge – penetration depths

Penetration depth of 0.05% Cl versus square root of exposure time









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Comparison of bridge data to results from Träslövsläge

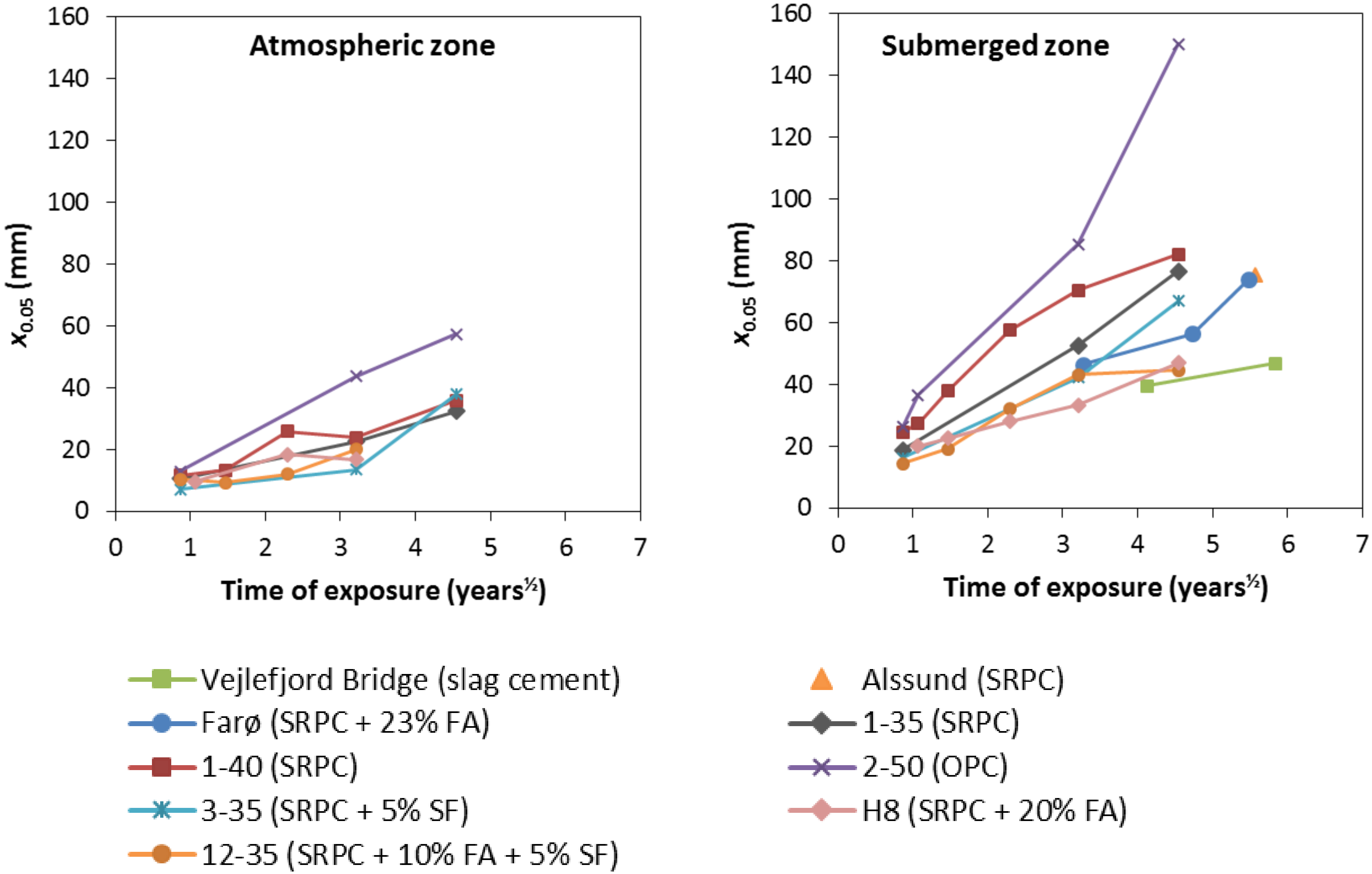
Binder types and sampling ages

ID	w/b ratio	Binder type	Binder (kg/m³)	Sampling age (years)
Vejle Fjord bridge	*0.45*	*100% CEM III/B*	*400 kg CE*	*17, 34*
Träslövsläge 2-50	0.50	100% OPC	390 kg CE	0.75, 1, 10, 20
Alssund bridge Träslövsläge 1-40 Träslövsläge 1-35	*0.39* 0.40 0.35	*100% SRPC* 100% SRPC 100% SRPC	*380 kg CE* 420 kg CE 450 kg CE	*31* 0.75, 1, 2, 5, 10, 20 0.75, 10, 20
Faroe bridges Träslövsläge H8	*0.42* 0.35	*77% SRPC + 23% FA* 80% SRPC + 20% FA	*330 kg CE + 100 kg FA* 493 kg CE + 123 kg FA	*11, 22, 30* 1, 2, 5, 10, 20
Träslövsläge 3-35	0.35	95% SRPC + 5% SF	428kg CE + 22kg SF	0.75, 10, 20
Träslövsläge 12-35	0.30	85% SRPC + 10% FA + 5% SF	383 kg CE + 45 kg FA + 22 kg SF	0.75, 2, 5, 10, 20

W/b-ratios marked with red have been calculated assuming an efficiency factor of 1.0 and 0.3 for silica fume and fly ash, respectively

Results from Träslövsläge – penetration depths

Penetration depth of 0.05% Cl versus square root of exposure time



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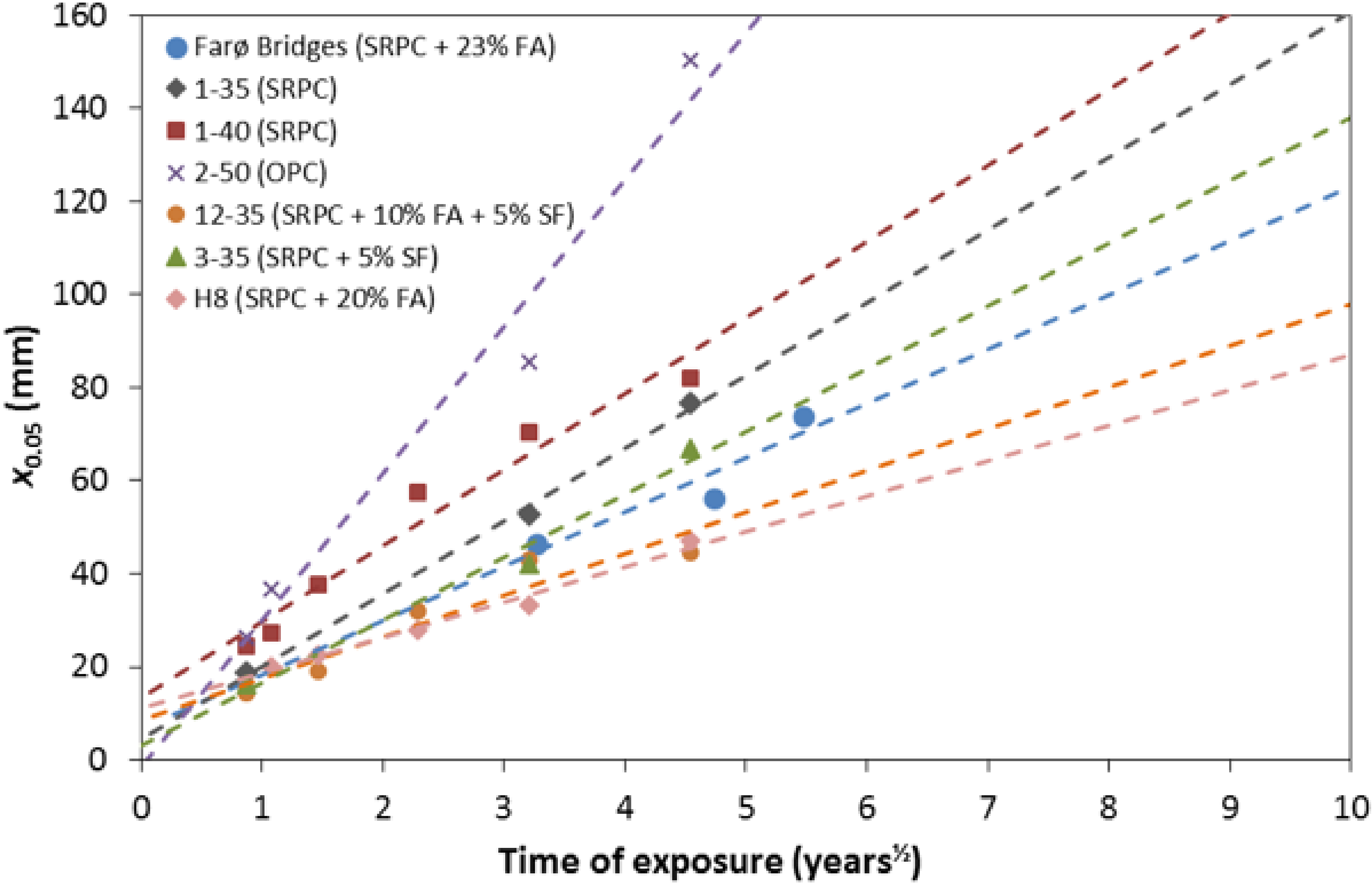
Modified penetration model – submerged zone

Linear regression analysis by $x_{C_r} = a_{C_r} \cdot \sqrt{t} + b_{C_r}$ (C_r = 0.05)



Modified penetration model

"Physical" explanation of the parameters a_{C_r} and b_{C_r}

The suggested model : $x_{C_r} = a_{C_r} \cdot \sqrt{t} + b_{C_r}$

a_{C_r} : Penetration rate of reference concentration (C_r) when a constant ingress situation is achieved

$$a_{C_r} = K_{C_r} = 2\sqrt{D_a} \cdot erf^{-1}\left(\frac{C_s - C_r}{C_s - C_i}\right) \quad \text{when} \quad b_{C_r} = 0$$

b_{C_r} : Sum of additional ingress resulting from e.g. early fast chloride penetration due to inital capillary suction and increased permeability at young age

Modified penetration model

The parameters a_{C_r} and b_{C_r} in the suggested model (below) is calculated by linear regression analysis on data for penetration depths of a reference concentration (C_r) versus square root of time.

The suggested model : $x_{C_r} = a_{C_r} \cdot \sqrt{t} + b_{C_r}$

Rearranging for t gives: $t = \left(\frac{x_{Cr} - b_{C_r}}{a_{C_r}}\right)^2$

This equation can be used to calculate the time for a reference concentration C_r to reach the depth x_{Cr}.

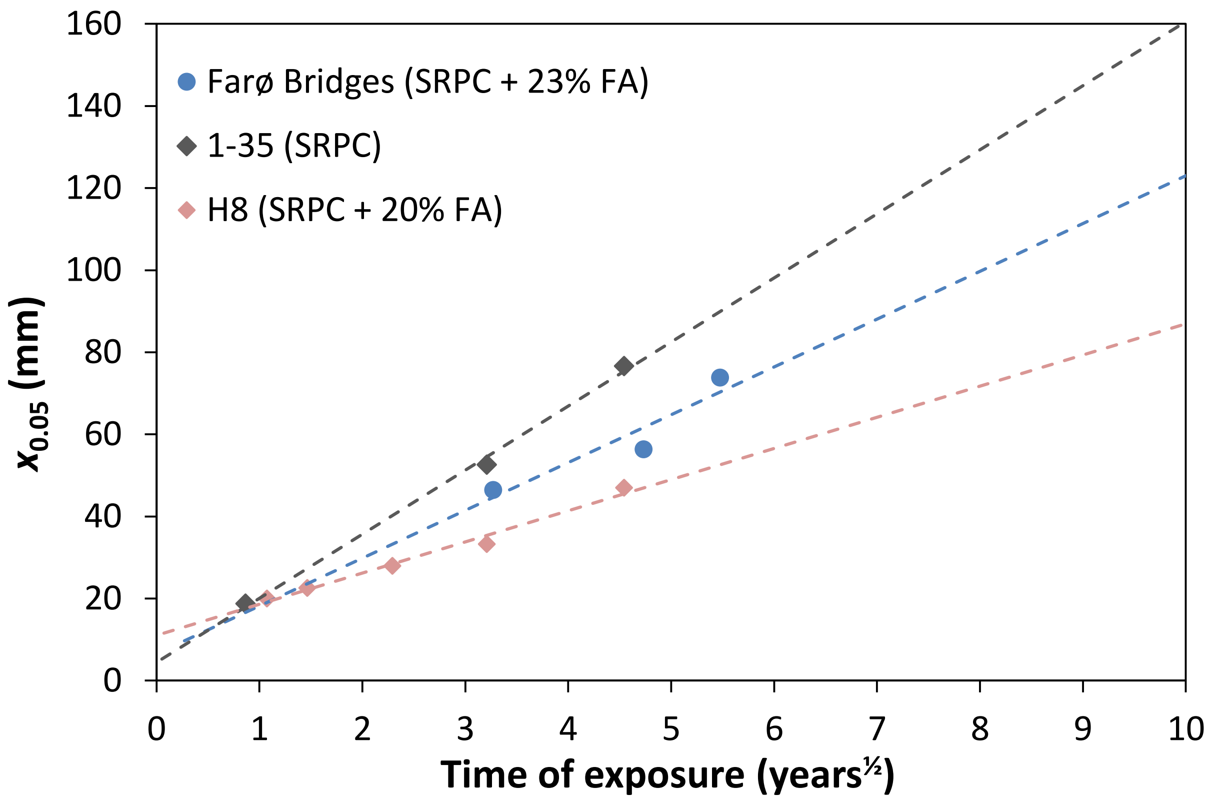
Subsequently, the service life (defined as time-to-corrosion-initiation) can be estimated by equating the value of x_{Cr} with the thickness of the concrete cover, and by setting the reference concentration C_r equal to the chloride threshold value for reinforcement corrosion initiation in the given concrete structure.

Modified penetration model – regression results

Penetration parameters $a_{0.05}$ and $b_{0.05}$ for submerged concrete

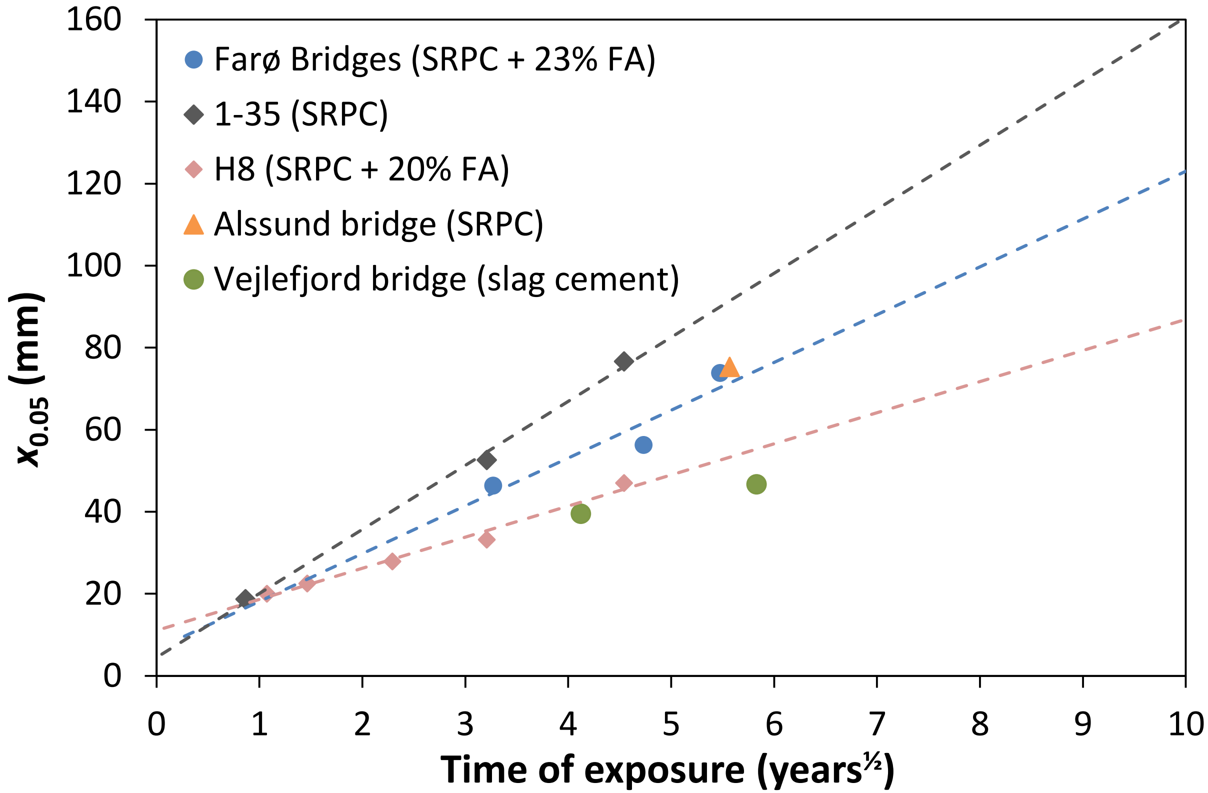
Bridge/ concrete ID	Binder type	w/b ratio	$a_{0.05}$ [mm/year$^{0.5}$]	$b_{0.05}$ [mm]
Träslövsläge 2-50	100% OPC	0.50	32	-2
Träslövsläge 1-40	100% SRPC	0.40	16	13
Träslövsläge 1-35	100% SRPC	0.35	16	4
Faroe bridges	77% SRPC + 23% FA	0.35	12	7
Träslövsläge H8	80% SRPC + 20% FA	0.30	8	11
Träslövsläge 3-35	95% SRPC + 5% SF	0.35	13	3
Träslövsläge 12-35	85% SRPC + 10% FA + 5% SF	0.30	9	8

Estimated penetration depth – Faroe Bridges



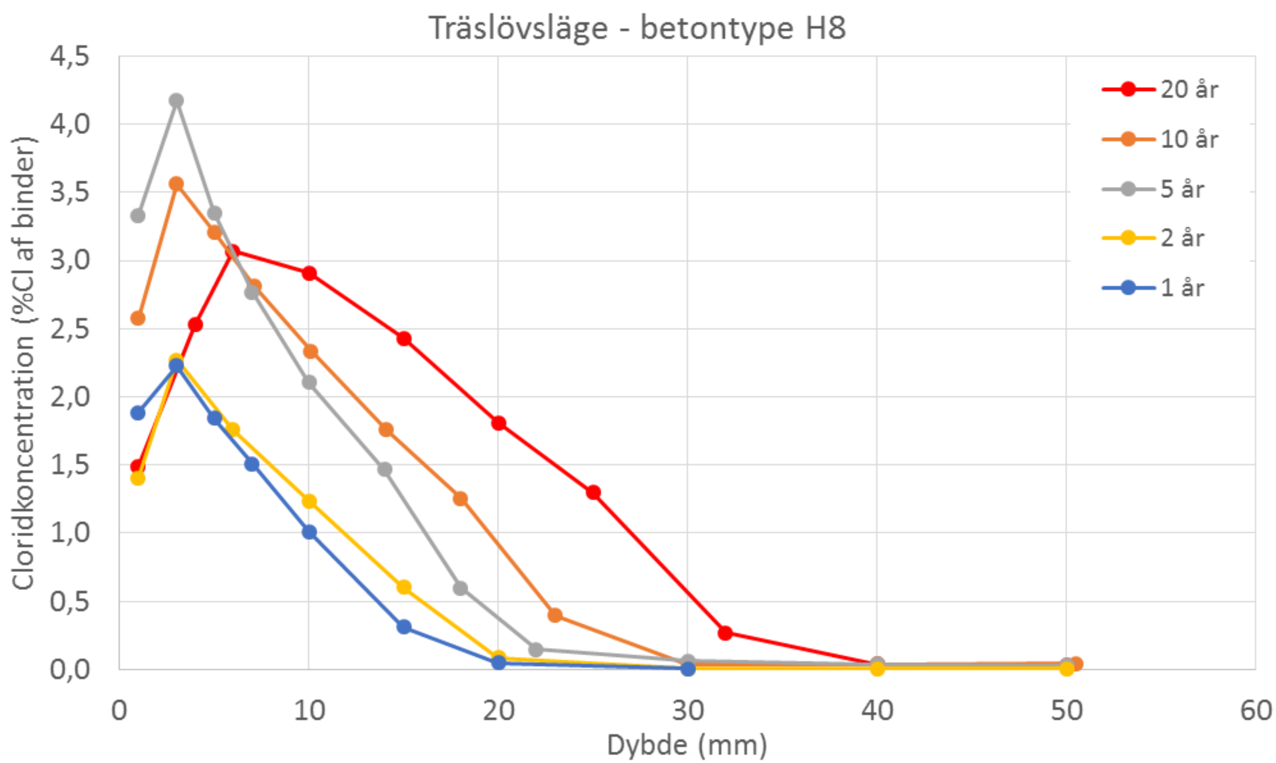
Bridge/ concrete ID	Binder type	w/b ratio	$a_{0.05}$ [mm/year$^{0.5}$]	$b_{0.05}$ [mm]	$x_{0.05}$ (100 yr) [mm]
Träslövsläge 1-35	100% SRPC	0.35	16	4	164
Faroe bridges	77% SRPC + 23% FA	0.42	12	7	127
Träslövsläge H8	80% SRPC + 20% FA	0.30	8	11	91

Estimated penetration depth – other bridges



Bridge/ concrete ID	Binder type	w/b ratio	$a_{0.05}$ [mm/year$^{0.5}$]	$b_{0.05}$ [mm]	$x_{0.05}$ (100 yr) [mm]
Alssund bridge	100% SRPC	0.40	≈12	≈7	≈127
Faroe bridges	77% SRPC + 23% FA	0.42	12	7	127
Vejlefjord bridge	100% slag cement	0.45	≈6	≈11	≈71

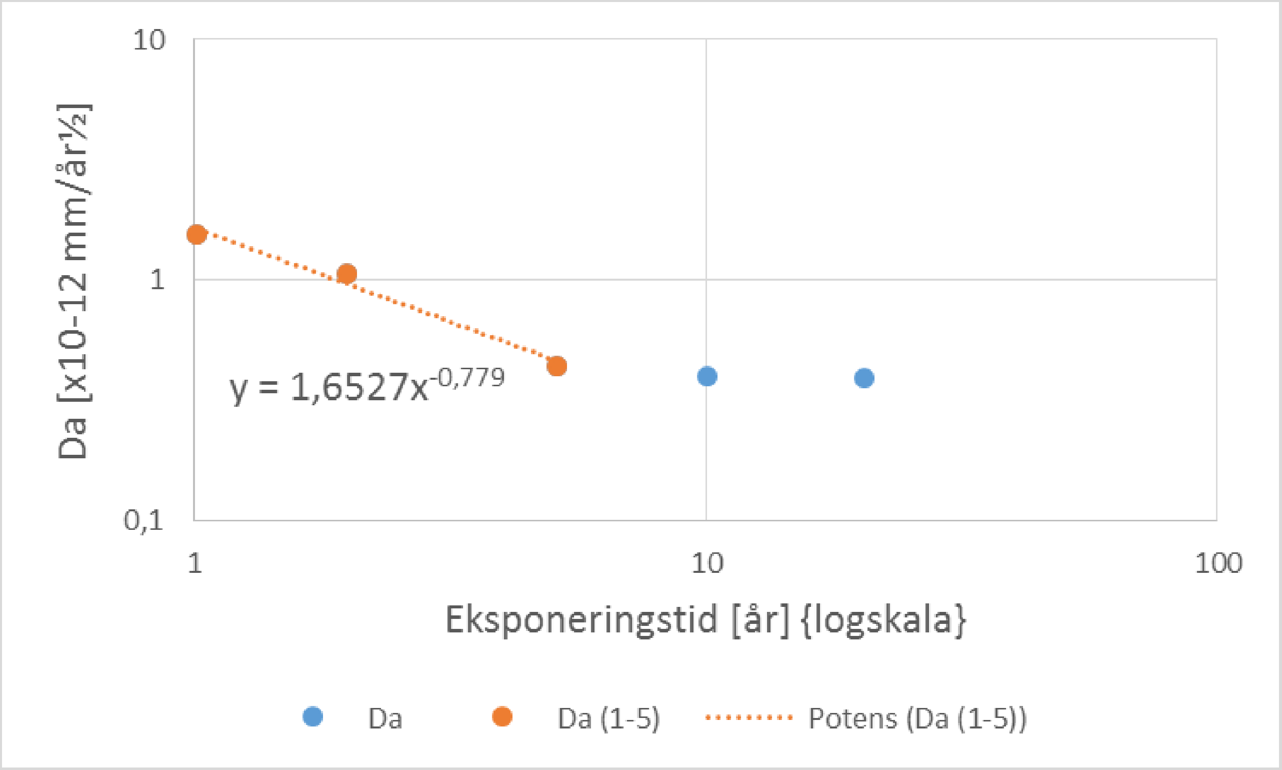
CASE: ”age factor” model vs. new model – Concrete H8



Eksponeringstid [døgn]	D_a [$*10^{-12}$ m^2/s]	C_s [vgt% af binder]	C_i [vgt% af binder]	$K_{0.4}$ [mm/year^{½}]	$x_{0.4}$ [mm]
370	1,540	2,992	0,010	14,9	13,7
728	1,070	2,902	0,010	12,3	16,0
1874	0,443	5,101	0,010	9,3	18,9
3682	0,399	4,285	0,010	8,4	22,4
7476	0,394	4,268	0,010	8,3	30,4

CASE: ”age factor” model vs. ny model – Concrete H8

Kalibrering af ”Age factor” model:

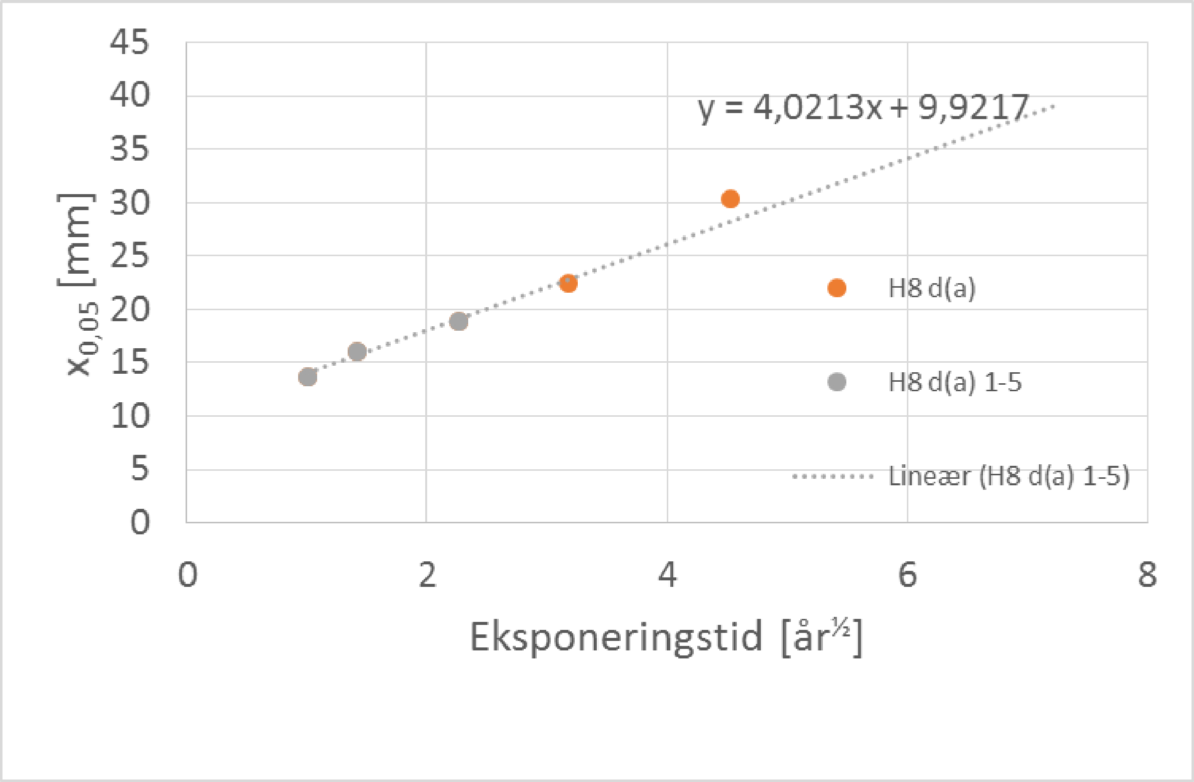


”Age factor” beregnes af data fra de første 5 eksponeringsår, Alfa = 0,779
Overfladekoncentration (konstant) efter 5 års eksponering anvendes, C_s = 5,100
Initiel chloridkoncentration, C_i = 0,010

Til beregning af $D_a(t)$ benyttes: $$D_a(t) = D_{aex}\left(\frac{t_{ex}}{t}\right)^{\alpha}$$

CASE: ”age factor” model vs. ny model – Concrete H8

Kalibrering af Ny model:



Modelparametre beregnes af data fra de første 5 eksponeringsår (3 terminer), $a_{0,4}$ = 4,0 mm/år½ og $b_{0,4}$ = 9,9 mm

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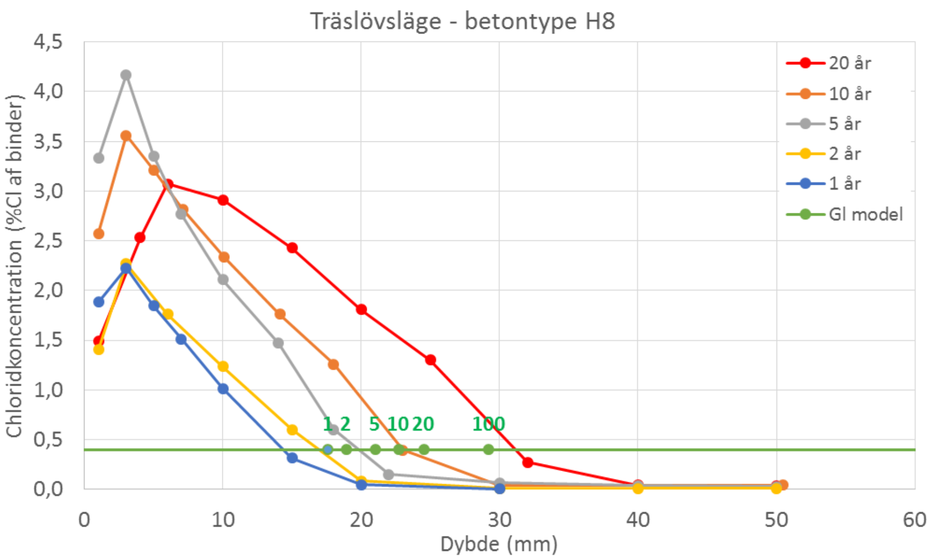
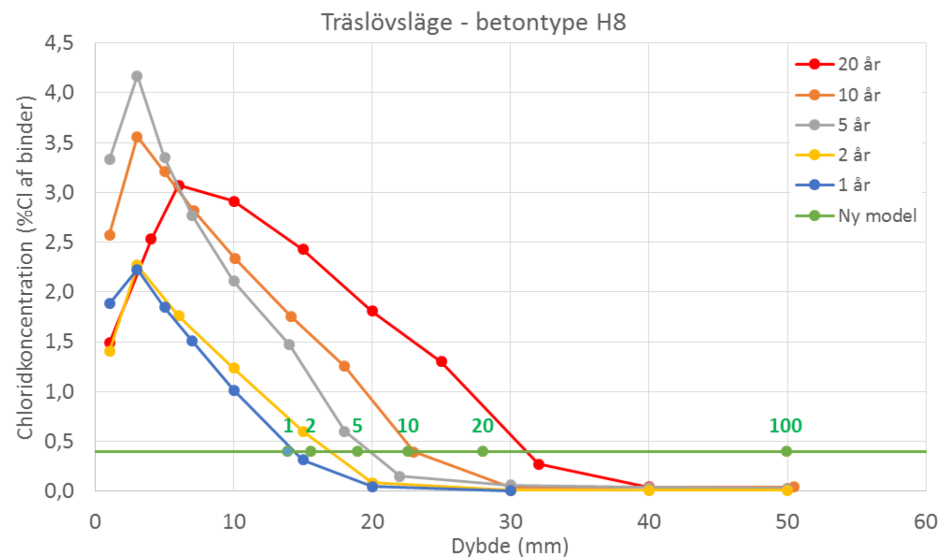
CASE: ”age factor” model vs. ny model – Concrete H8

”Age factor” model:



”Ny” model:



Eksponeringstid	1 år	2 år	5 år	10 år	20 år	100 år
Träslövsläge H8	14 mm	16 mm	19 mm	22 mm	30 mm	-
Ny model	14 mm	16 mm	19 mm	23 mm	28 mm	50 mm
Gl. model	18 mm	19 mm	21 mm	23 mm	25 mm	29 mm

Beregnede indtrængningsdybder ($x_{0,4}$) af 0,4vgt% Cl af binder

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Conclusions

- The highest resistance to chloride ingress is observed for the bridge constructed with a concrete based on slag cement.
- The apparent chloride diffusion coefficients are observed to be more or less independent of time for chloride exposure times beyond ten years.
- The chloride ingress into marine exposed submerged- and atmospheric concrete structures may be modelled by a simple linear relationship between the penetration depth and the square root of the exposure time.
- Estimation of service life based on the above mentioned relationship require data from the actual exposure situation regarding both the chloride penetration rate and the chloride threshold value. Therefore, more high quality data is needed to verify the suggested model, and also to quantify the parameters in the model for different concretes and exposures.
- The use of field exposure sites like Träslövsläge and Rødbyhavn is highly recommended as they produce valuable high quality data for future service life estimations.