Recurrent studies of chloride ingress in uncracked marine concrete at various exposure times and - elevations

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1998

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ISRN LUTVDG/TVBM--98/3080--SE(1-19)
ISSN 0348-7911 TVBM

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PREFACE

This report is a compilation of the total chloride profiles measured in selected concrete mixes with w/c ratio 0.25 – 0.50, field exposed at the Träslövsläge Marine Field Station in a harbor at the Swedish west coast. Total chloride profiles have been measured in the selected concrete mixes exposed at 3 different exposure levels, the submerged zone, the splash zone, and the atmospheric zone, at 3 or 4 different exposure times within 0.5 to 5.3 years of exposure. The raw data is available in *Raw data on total chloride penetration profiles*, Lund Institute of Technology, Division of Building Materials, Report TVBM 7126, 1998.

The development of the field station and the concrete specimens exposed was lead by the author. The concrete specimens were manufactured by the author and Gert-Olof Johansson at the Swedish National Testing and Research Institute (SP). The operation of the field station was carried out by SP. The procedure for sampling concrete dust for the analysis of total chloride profiles was developed by Jens Frederiksen and Henrik Sørensen at AEC Consulting Engineers, Denmark. Most of the analysis work has been carried out by Tang Luping and Alf Andersen at Chalmers University of Technology, Division of Building Materials, following a procedure for analysis of total chloride content by weight of binder in concrete as developed by Tang Luping. The same procedure was used for all analysis work covered by this report. Parts of the analysis work were carried out at AEC Consulting Engineers, the Swedish Cement and Concrete Research Institute, Division of Building Materials at Lund Institute of Technology, and the Swedish National Testing and Research Institute. The analysis work has been planned and coordinated by the author.

Separate reports on the moisture state and moisture transport coefficients in concrete field exposed at the Träslövsläge field station are available through L-O Nilsson at Chalmers University of Technology, Division of Building Materials. The results were summarized and evaluated against the total chloride penetration profiles, by L-O Nilsson in *Durability of Concrete in Saline Environment* (Ed. Sandberg), Cementa AB and Aalborg Portland, 1996, pp. 23-47, available at Cementa AB, Danderyd.

This report also includes the following work by the author:

1) Evaluation of the apparent surface chloride concentration and the corresponding effective chloride diffusivity, both parameters calculated by fitting the measured total chloride profiles to a solution to Fick´s second law of diffusion assuming constant diffusivity and linear chloride binding. In addition an evaluation of the measured maximum total chloride concentration in each total chloride profile was carried out.

2) Predictions of the effective chloride diffusivity, the apparent surface chloride concentration and the maximum total chloride concentration have been carried out with the aid of logarithmic and power trend lines fitted by regression analysis to the calculated and measured data. The predictions were used to calculate the time to initiation of active reinforcement corrosion in concrete mixes with w/c $\leq$ 0.40.

Lund in April, 1998.

Paul Sandberg

UNIVERSITY OF LUND
LUND INSTITUTE OF TECHNOLOGY
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Report TVBM-3080
Lund, 1998

Recurrent studies of chloride ingress in uncracked marine concrete at various exposure times and - elevations

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Abstract
Uncracked reinforced concrete slabs have been field exposed at the Träslövsläge marine field station at the Swedish west coast since April 1992 as a part of a national Swedish project, "Durability of Marine Concrete Structures". The concrete slabs were mounted on a floating pontoon and exposed partly submerged. The chloride ingress was analysed at various exposure times at 3 elevations representing a submerged-, a splash- and an atmospheric exposure zone. This report is a compilation of the total chloride profiles and calculated chloride transport rates in 13 concrete mixes exposed for 1, 2 and 5 years. The concrete mixes varied in w/c ratio, type of cement and amount and type of pozzolan used in the binder.

The data is unique as it represents recurrently measured chloride penetration profiles in field exposed concrete at various exposure ages. Therefore the data provides a foundation for the prediction of chloride ingress in marine concrete structures.

The results after 5 years of exposure confirmed the expected relationship between water to binder ratio and chloride ingress. The use of 5-10% silica fume in the binder had a very positive effect on reducing the chloride ingress, but little or no benefit at all was found for concrete with fly ash in the binder as compared to the use of 5% silica fume. The chloride penetration rate as expressed by a calculated effective chloride diffusivity has a tendency to decrease over time. High performance concrete with w/c ≤ 0.4 and a minimum of 5 % silica fume added to the concrete as a well dispersed slurry exhibited a effective chloride diffusivity in the range of 1 E-13 to 5 E-13 m^2/s after 5 years exposure in the splash zone.

Calculations of the required cover for 100 years initiation time for active reinforcement corrosion were carried out, using different approaches to the prediction of the average effective chloride diffusivity and the surface chloride concentration. As expected the results vary extensively with the approach used, but nevertheless the results indicated that the required cover can be reduced by 50 % if concrete with w/c 0.30 and 5-10 % silica fume is used as compared to a pozzolan free concrete with w/c 0.40.

1. INTRODUCTION

Chloride induced reinforcement corrosion is one of the most common durability problem associated with modern good quality reinforced concrete structures exposed to a marine environment or to de-icing salts. The time to corrosion initiation depends on i) how fast chloride ions penetrate the concrete cover to reach the reinforcement, and ii) the critical chloride concentration needed for depassivation of the steel reinforcement. This report is a compilation of total chloride profiles and calculated chloride transport rates in marine concrete exposed for ½ to 5 years.

2. CHLORIDE TRANSPORT INTO CONCRETE

Traditionally, chloride penetration into concrete has been modelled by the use of Fick's second law of diffusion, assuming constant diffusivity and linear chloride binding /1/. On the other hand recent field studies of concrete structures have indicated that the traditional use of Fick's second law of diffusion was not applicable for long term chloride transport into concrete /2-6/. When fitting a solution to Fick's second law of diffusion to measured total chloride profiles from field exposed concrete, the calculated "effective chloride diffusivity" was found to vary with the exposure time and -conditions.

Table 1. Details of cementing materials used

Material		**Sulfate resisting Portland cement (SRPC)**	**Ordinary Portland cement (OPC)**	**Silica fume (SF)**	**Fly ash (FA)**
Fineness - % passing	45 µm	85.9	97.4	100	73
	20 µm	51.3	64.0		
	10 µm	33.1	41.7		
	5 µm	19.5	26.0		
	1 µm	3.8	5.4		
Specific surface m^2/kg	Blaine	300	360		227
	BET			23 000	625
Compressive Strength of standard 40 mm mortar cubes, MPa	1 day	10.1	18.9		
	7 days	35.6	45.2		
	28 days	56.2	55.2		
Chemical analysis %	CaO	63.8	62.5	0.4	1.87
	SiO_2	22.8	19.6	94.2*	57.0
	Al_2O_3	3.5	4.17	0.62	29.1
	Fe_2O_3	4.7	2.17	0.95	6.56
	MgO	0.80	3.45	0.65	0.79
	SO_3	1.9	3.29	0.33	0.21
	K_2O	0.55	1.29	0.5	1.76
	Na_2O	0.06	0.26	0.2	0.28
	Loss of ignition	0.55	2.65	1.8	1.9
Bouge potential compounds -%	C_3S	51.5	61.4		
	C_2S	25.5	9.9		
	C_3A	1.3	7.6		
	C_4AF	14.3	6.6		

*amorphous silica content

Nevertheless solutions to Fick's second law of diffusion are still widely used as a tool to evaluate and predict chloride transport rate in concrete /5,6/. The "effective chloride diffusivity" calculated from total chloride profiles in concrete represents an indication of the average chloride transport rate in the concrete at the exposure time and –condition considered.

3. EXPERIMENTAL

3.1 Concrete mixes and types of binder

Cementing materials was used according to Table 1. Natural glacial Granite aggregates were used both in the finer (0-8 mm) and the coarser (8-16 mm) aggregate fractions according to Table 2. A Melamine type (Formaldehyde and melamine sulfonate condensate) of superplastiziser was used in concrete with w/c ratio < 0.50 in order to reach a slump value in the range of 10-18 cm 5 minutes after mixing. A vinsol resin type of air entrainer was used in concrete with an air content of 3-6 % according to Table 2. 13 different concrete qualities including 7 different binder compositions were tested, with w/c ratios between 0.25 to 0.5.

Table 2. Details of concrete mixes

Mix No.	ID	w/c ratio *	OPC kg/m³	SRPC kg/m³	Silica fume ** kg/m³	Fly ash kg/m³	Aggr. 0-8 mm kg/m³	Aggr. 8-16 mm kg/m³	fc 28d *** MPa	Air cont. vol %
1	OPC 0.40	0.40	420	-	-	-	871	804	54	5
2	SRPC 0.50	0.50	-	370	-	-	876	808	41	6
3	SRPC 0.40	0.40	-	420	-	-	873	806	58	6
4	SRPC 0.30	0.30	-	492	-	-	791	892	96	4
5	SRPC 5%SF 0.50	0.50	-	351	19 dry	-	840	840	45	6
6	SRPC 5%SF 0.40	0.40	-	399	21 dry	-	835	835	61	6
7	SRPC 5%SF 0.40	0.40	-	399	21 slu	-	840	840	62	6
8	SRPC 5%SF 0.30	0.30	-	475	25 slu	-	836	942	112	1
9	SRPC 5%SF 0.25	0.25	-	525	26 slu	-	806	946	125	1
10	SRPC 10%SF 0.30	0.30	-	450	50 slu	-	820	963	117	1
11	SRPC 5%SF 10%FA 0.35	0.35	-	382	23 slu	45	781	917	84	6
12	SRPC 5%SF 17%FA 0.40	0.40	-	345	21 slu	75	770	905	69	6
13	SRPC 20%FA 0.30	0.30	-	493	-	123	680	865	98	3

*w/c ratio defined as w/(C+SF+0.3FA). w = water, C = cement (SRPC = sulfate resisting portland cement, OPC = ordinary portland cement), SF = silica fume, FA = fly ash.
** Silica fume added "dry" = compacted, or "slu" = as a 50 % slurry. Figure denotes amount of solid.
*** fc 28d = 28 d compressive cube strength (MPa).

3.2 Concrete Mixing Procedure

The following procedure was adopted for mixing of fresh concrete in a 250 liters mixer:

	mixing time, minutes
1. Aggregates, cement, fly ash (if any), dry silica fume (if any)	1
2. Water, 50% of superplasticizer, silica fume slurry (if any), air entrainment (if any)	2
3. Remaining 50% of superplasticizer	1.5

3.3 Field Exposure of reinforced concrete slabs at the Träslövsläge Marine Field Station

Reinforced concrete slabs, height 100 cm, width 70 cm, thickness 10-20 cm, were cast according to Table 2 and moist cured for 10 days prior to marine exposure in 1992. The slabs were mounted on a floating pontoon in the harbor of the village Träslövsläge on the Swedish west coast. The use of a floating pontoon allowed the bottom half of each slab to be continuously submerged in sea water according to Figure 1.The floating field station was protected from waves inside the harbor behind a breakwater, thereby minimizing wave action on the upper part of each slab to a minimum. Consequently the exposure condition at the upper part of each slab was defined as "atmospheric zone" with mainly wind borne salt while the middle part at the water line of each slab was defined as "splash zone", see Figure 1.

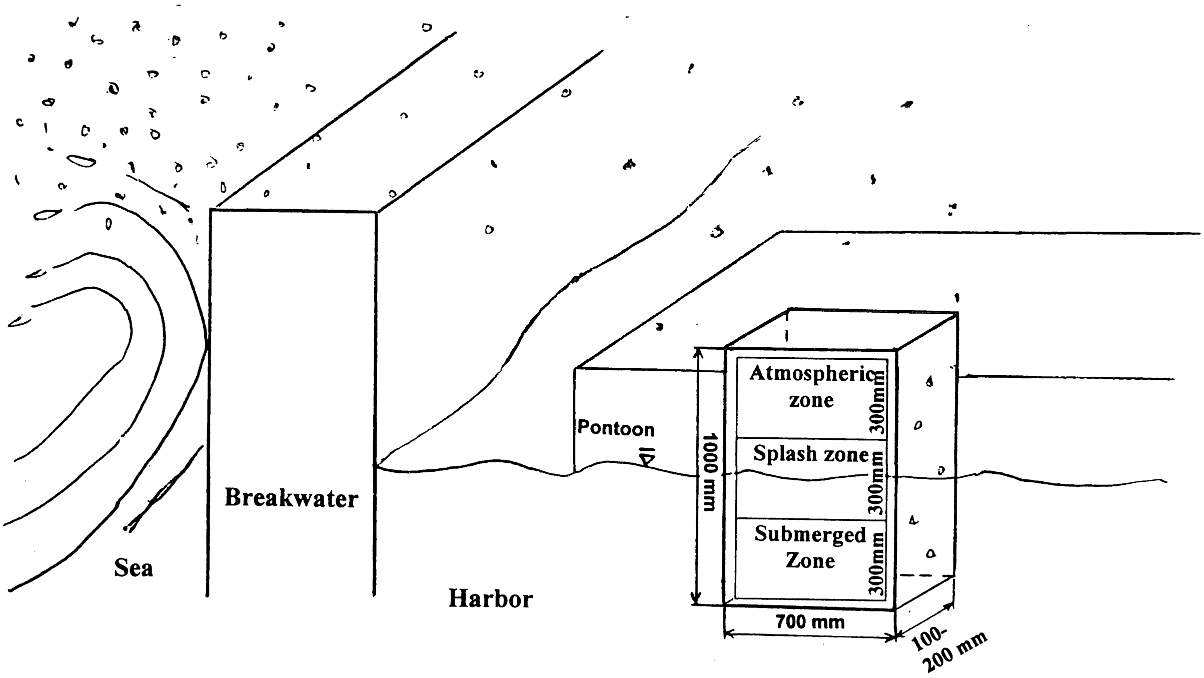


Figure 1. Exposure conditions at the Träslövsläge Field Station.

3.4 Analysis of chloride- and binder profiles

Total chloride profiles were analysed after 7 or 12 months, 2 years, and after 5 years exposure. Ø 100 mm cylinders were drilled from the concrete slabs at > 50 mm distance from the edges. The concrete cylinders were immediately sealed in airtight bags and brought to the laboratory for immediate processing and analysis:

The concrete cover was abraded from the exposed surface and inwards in steps of 1 mm using a diamond tool according to the Nordic standard NT Build 443 /7/. The pulverised samples were analysed for total chloride content according to AASHTO T 260-A, by potentiometric titration using a chloride ion selective electrode and a silver nitrate solution of 0.01 N.

After chloride titration, 5 ml of 1:2 diluted triethanolamine was added to the sample solution and the pH value was adjusted to pH > 12 using sodium hydroxide. The calcium content was determined by potentiometric titration using a calcium ion selective electrode and a 0.1 N EDTA solution /8/. Since the aggregate contained no acid soluble calcium, the binder content in each 1 mm fraction of concrete was calculated from the measured calcium content in each fraction. The result was presented as total chloride by weight of binder for each 1 mm fraction.

The total chloride profiles were analysed as described by Chalmers and Lund Institute of Technology, Sweden, AEC, Denmark, the Swedish Cement and Concrete Research Institute and the Swedish National Testing and Research Institute.

3.5 Evaluation of chloride profiles

Acid soluble chloride profiles, expressed as % Cl by weight of binder, were evaluated by fitting the measured chloride data to a theoretical profile calculated from a solution to Fick´s second law of diffusion /9/, as shown in Figure 2. The fitting procedure was started at the maximum chloride concentration which was sometimes several datapoints below the concrete surface. The theoretical total chloride profile was defined by the chloride transport coefficient, "effective chloride diffusivity", and the calculated or apparent surface chloride concentration, "Cs, calc.".

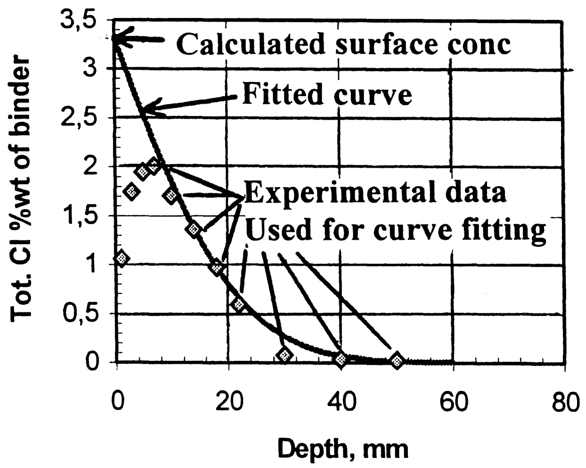


Figure 2. Curve fitting procedure for estimation of the "effective chloride diffusivity".

4. RESULTS

4.1 Presentation of results

The chloride profiles expressed as total Cl by weight of binder as a function of the distance from the exposed concrete surface were measured after 3 or 4 different exposure times and presented as shown in

Figure 3. Each total chloride profile was labeled according to the ID label in Table 2, with the addition of the exposure condition, "atm" (atmosphere) "spl" (splash zone) or "subm" (submerged), as indicated in Figure 1, and the exposure time. A graph of the corresponding calculated chloride transport coefficient, Deff,Cl (xE-12m^2/s), and the calculated apparent surface chloride concentration, Cs, calc. (Cl %binder) was included as shown in Figure 3.

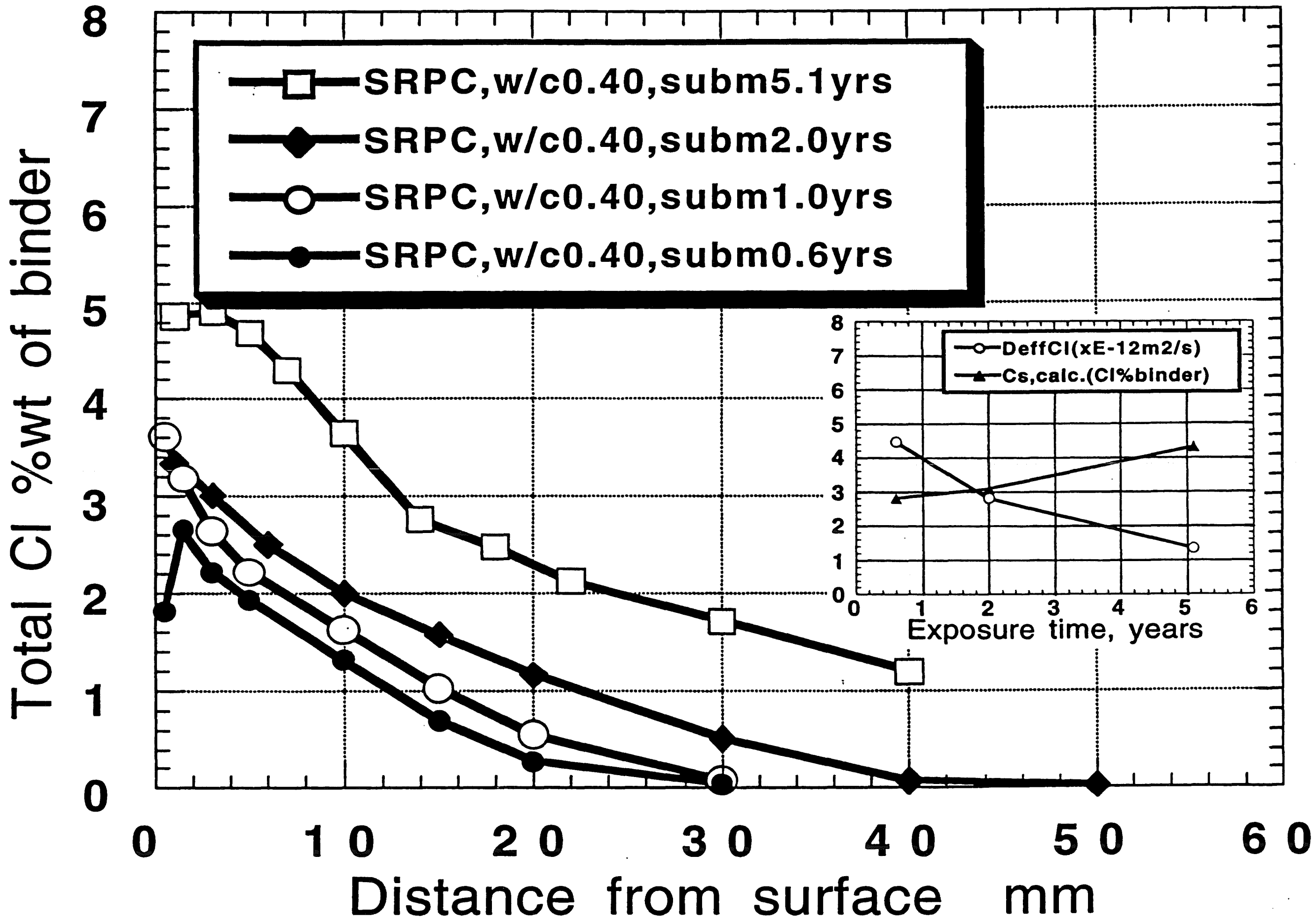


Figure 3. Presentation of total chloride profiles and corresponding calculated chloride transport coefficient and apparent surface chloride concentration.

4.2 Compilation of results

The total chloride profiles and the curve fitting parameters for all concrete mixes and exposure elevations are shown in Appendix A, as shown for plain OPC concrete, w/c 0.40, and plain SRPC concrete, w/c 0.50, in Figure 4. Two concrete mixes are shown in the following order on each page in Appendix A:

Top figure – Atmospheric exposure, top of concrete slab.
Middle figure – Splash zone exposure, middle of slab at the water level.
Bottom figure – Submerged exposure, bottom of concrete slab, continuously submerged.

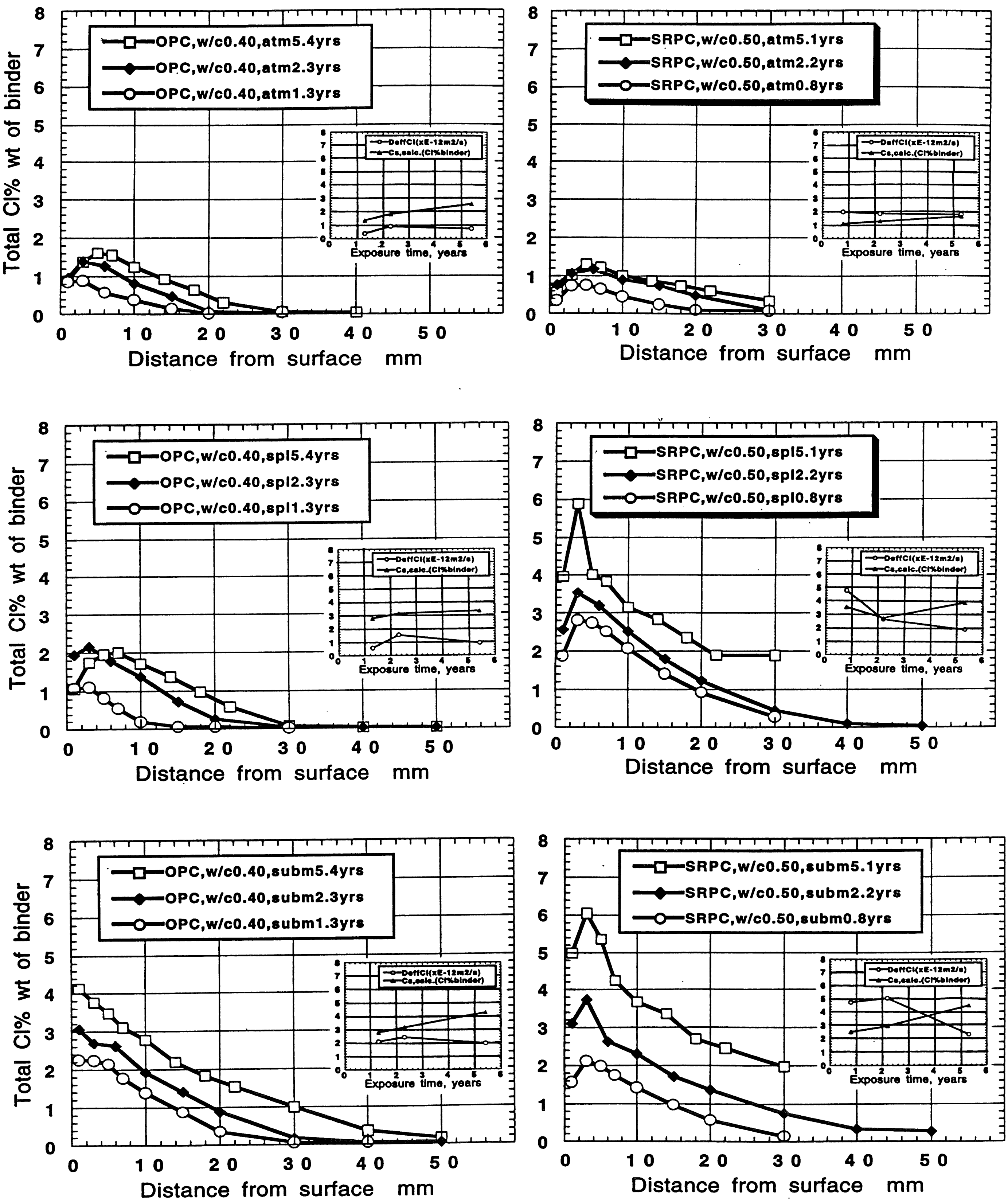


Figure 4. Total chloride penetration profiles in plain OPC concrete, w/c 0.40, and in plain SRPC concrete w/c 0.50, exposed in a marine environment.

The calculated effective chloride diffusivity, DeCl (xE-12m^2/s), and the calculated apparent surface chloride concentration, Cscalc. (Cl % by weight of binder), from fitting total chloride profiles to a solution to Fick´s second law of diffusion, assuming constant diffusivity and linear chloride binding, are presented for submerged concrete in Table 3 and for concrete exposed in the splash zone in Table 4.

Table 3. Curve fitting results at various exposure times for concrete exposed submerged

Concrete exposed in the submerged zone			**DeCl** xE-12m^2/s and **Cscalc.** Cl % by weight of binder							
Mix	**Exposure time**		**0.6-0.8 years**		**1.0-1.3 years**		**2.0-2.3 years**		**5.1-5.4 years**	
No.	**ID**	**w/c**	**DeCl**	Cscalc	**DeCl**	Cscalc	**DeCl**	Cscalc	**DeCl**	Cscalc
1	OPC 0.40	0.40	-	-	**2.1**	2.7	**2.4**	3.2	**1.9**	4.2
2	SRPC 0.50	0.50	**4.7**	2.5	-	-	**5.1**	2.9	**2.3**	4.5
3	SRPC 0.40	0.40	**4.5**	2.8	**3.6**	3.1	**2.8**	3.1	**1.4**	4.4
4	SRPC 0.30	0.30	-	-	**1.8**	2.7	**2.4**	2.6	**1.5**	3.8
5	SRPC 5%SFdry 0.50	0.50	**4.8**	2.4	-	-	**2.6**	3.9	**1.2**	4.2
6	SRPC 5%SFdry 0.40	0.40	**3.4**	3.2	-	-	**1.4**	3.4	**1.3**	4.9
7	SRPC 5%SF 0.40	0.40	**2.0**	3.5	-	-	**0.8**	4.3	**0.8**	4.9
8	SRPC 5%SF 0.30	0.30	-	-	**0.9**	2.7	**0.7**	3.9	**0.5**	4.7
9	SRPC 5%SF 0.25	0.25	-	-	**0.4**	1.6	**0.5**	2.9	**0.2**	4.4
10	SRPC 10%SF 0.30	0.30	-	-	**0.6**	1.6	**0.5**	2.5	**0.2**	4.9
11	SRPC 5%SF 10%FA 0.35	0.35	**1.0**	1.3	-	-	**0.9**	3.5	**0.8**	5.2
12	SRPC 5%SF 17%FA 0.40	0.40	**1.6**	2.3	-	-	**0.8**	3.4	**0.8**	7.4
13	SRPC 20%FA 0.30	0.30	-	-	**1.4**	2.8	**1.1**	2.9	**0.5**	5.3

Table 4. Curve fitting results at various exposure times for concrete exposed in the splash zone

Concrete exposed in the splash zone			**DeCl** xE-12m^2/s and **Cscalc.** Cl % by weight of binder							
Mix	**Exposure time**		**0.6-0.8 years**		**1.0-1.3 years**		**2.0-2.3 years**		**5.1-5.4 years**	
No.	**ID**	**w/c**	**DeCl**	Cscalc	**DeCl**	Cscalc	**DeCl**	Cscalc	**DeCl**	Cscalc
1	OPC 0.40	0.40	-	-	**0.6**	2.7	**1.6**	3.1	**0.9**	3.3
2	SRPC 0.50	0.50	**4.8**	3.5	-	-	**2.6**	2.7	**1.9**	3.8
3	SRPC 0.40	0.40	**2.3**	1.3	-	-	**2.6**	3.1	**1.4**	1.9
4	SRPC 0.30	0.30	-	-	**0.5**	1.3	**1.4**	2.5	**1.2**	3.8
5	SRPC 5%SFdry 0.50	0.50	**2.0**	1.4	-	-	**2.3**	3.3	**1.5**	5.7
6	SRPC 5%SFdry 0.40	0.40	**1.4**	1.5	-	-	**0.7**	2.9	**0.4**	2.4
7	SRPC 5%SF 0.40	0.40	**1.2**	1.9	-	-	**0.8**	2.0	**0.5**	2.6
8	SRPC 5%SF 0.30	0.30	-	-	**0.4**	1.6	**0.2**	1.6	**0.2**	1.3
9	SRPC 5%SF 0.25	0.25	-	-	**0.3**	1.3	**0.2**	2.0	**0.2**	4.8
10	SRPC 10%SF 0.30	0.30	-	-	**0.4**	1.2	**0.4**	3.3	**0.2**	2.8
11	SRPC 5%SF 10%FA 0.35	0.35	**0.9**	1.0	-	-	**0.8**	3.2	**0.3**	1.6
12	SRPC 5%SF 17%FA 0.40	0.40	**0.5**	1.4	-	-	**0.4**	2.5	**0.3**	2.9
13	SRPC 20%FA 0.30	0.30	-	-	**0.7**	2.5	**0.5**	2.3	**0.4**	3.1

5. SIMPLE PREDICTIONS OF CHLORIDE INGRESS

5.1 General

Simple predictions of the total chloride profiles were undertaken in 3 different ways for all total chloride profiles measured in the splash- and in the submerged zone according to the following assumptions:

A) 100 years exposure time, the effective chloride diffusivity and the calculated apparent surface concentration remained constant from 5 years of exposure and onwards.

B) 100 years exposure time, the effective chloride diffusivity was reduced to 50% of its value after 5 years of exposure. This value was chosen from extrapolations of the calculated effective chloride diffusivity as presented in Figure 5 and 6. The extrapolated general trend lines in Figure 5 and 6 indicated a reduction of the effective chloride diffusivity in the range of 50-75 % from 5 to 100 years of exposure. A 50 % reduction of the effective chloride diffusivity was considered as conservative. The calculated apparent surface concentration was fixed as 10 % Cl by weight of binder, as extrapolated from the data in Figure 6 and 7 using the general trend lines indicated. This value was also the highest chloride concentration measured in concrete in Japan after 96 years marine field exposure /10/.

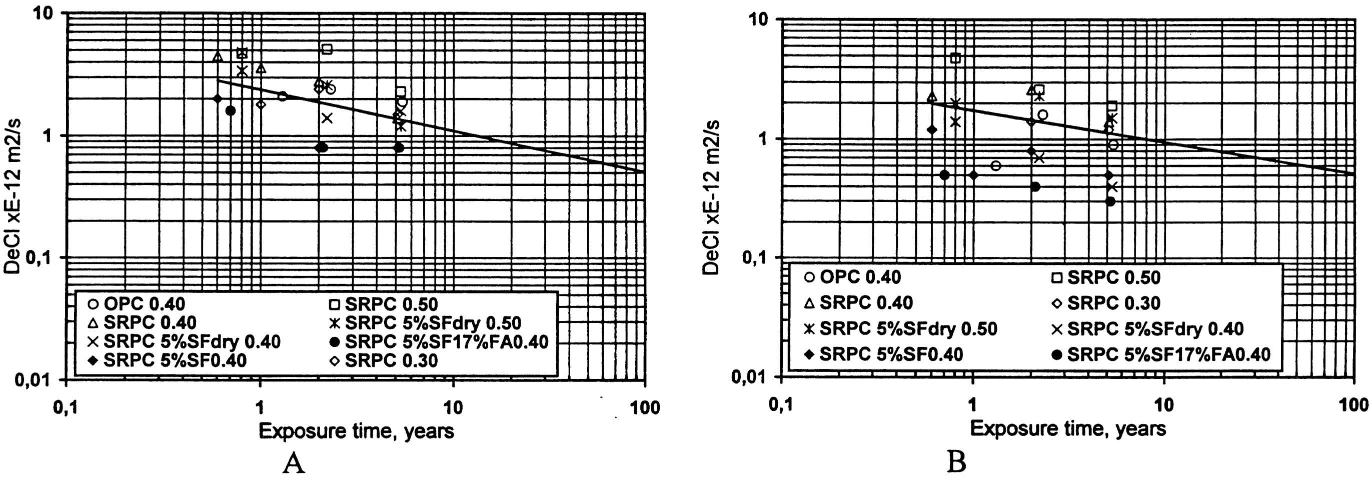


Figure 5. Calculated effective chloride diffusivity for concrete mixes with w/c ≥ 0.40 and for plain SRPC concrete with w/c 0.30, exposed submerged (A) and in the splash zone (B). Solid power trend lines extrapolated by regression analysis.

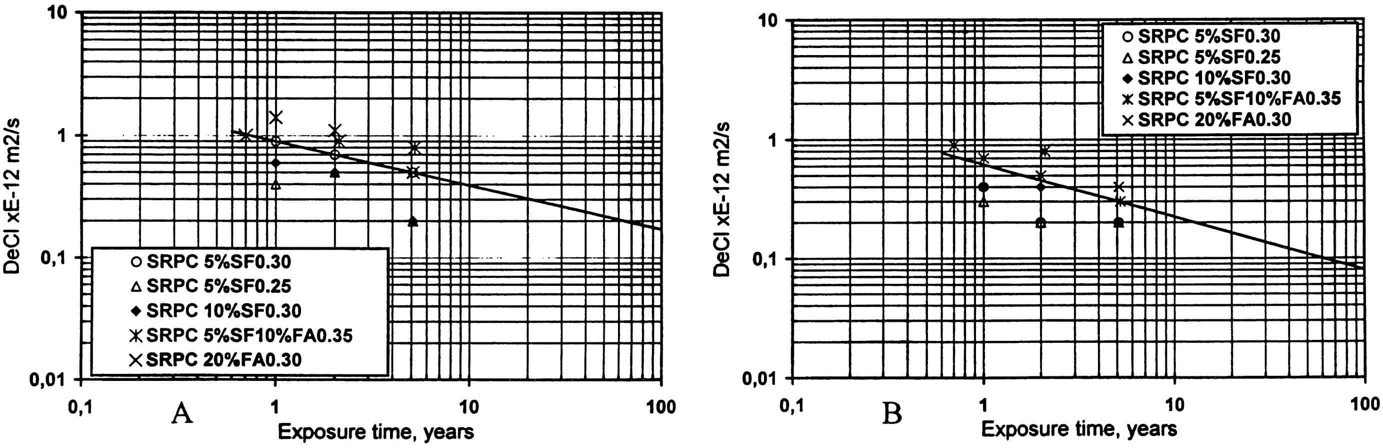
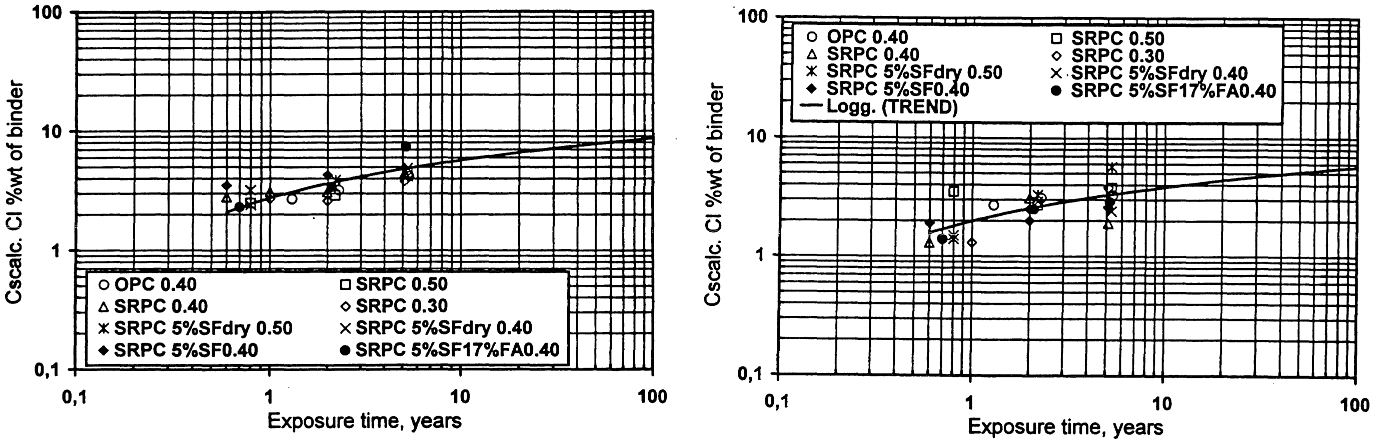
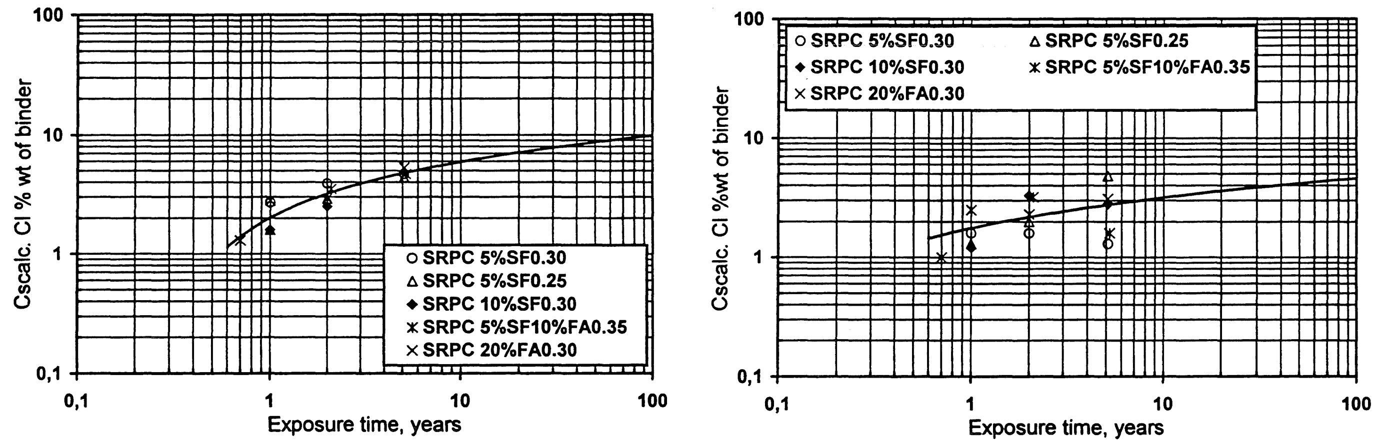


Figure 6. Calculated effective chloride diffusivity for concrete mixes with pozzolan in the binder and w/c ≤0.35, exposed submerged (A) and in the splash zone (B). Solid power trend lines extrapolated by regression analysis.



A B

Figure 7. Calculated apparent surface chloride concentration for concrete mixes with w/c ≥ 0.40 and for plain SRPC concrete with w/c 0.30, exposed submerged (A) and in the splash zone (B). Solid logarithmic trend lines extrapolated by regression analysis.



A B

Figure 8. Calculated apparent surface chloride concentration for concrete mixes with pozzolan in the binder and w/c ≤0.35, exposed submerged (A) and in the splash zone (B). Solid logarithmic trend lines extrapolated by regression analysis.

C) The concrete cover was divided into a "convection zone" and a "diffusion zone" as shown in Figure 9 /11/. The "convection zone" is strongly affected by leaching of hydroxide ions, penetration of carbonate and sulfate ions, and also wetting and drying, if the concrete is exposed above water. The "diffusion zone has a relatively constant moisture state and the chloride diffusion is mainly affected by the moisture state and the counter-diffusion of hydroxide ions. The border between the "convection zone" and the "diffusion zone" was defined as the depth of the maximum measured total chloride concentration. The depth of the maximum chloride concentration was assumed to be constant in the predictions for the sake of simplicity. The simulation was carried out in the "diffusion zone" only, thus with the calculated apparent surface concentration equal to the maximum total chloride concentration, labeled Cmax, and located at the depth of Cmax after 5 years of exposure. The values on the effective chloride diffusivity and the maximum chloride concentration (Cmax) was extrapolated from the corresponding data in Figures 5-6 and 10-11 respectively, using the slope of the general trend lines for the extrapolation of individual data series.

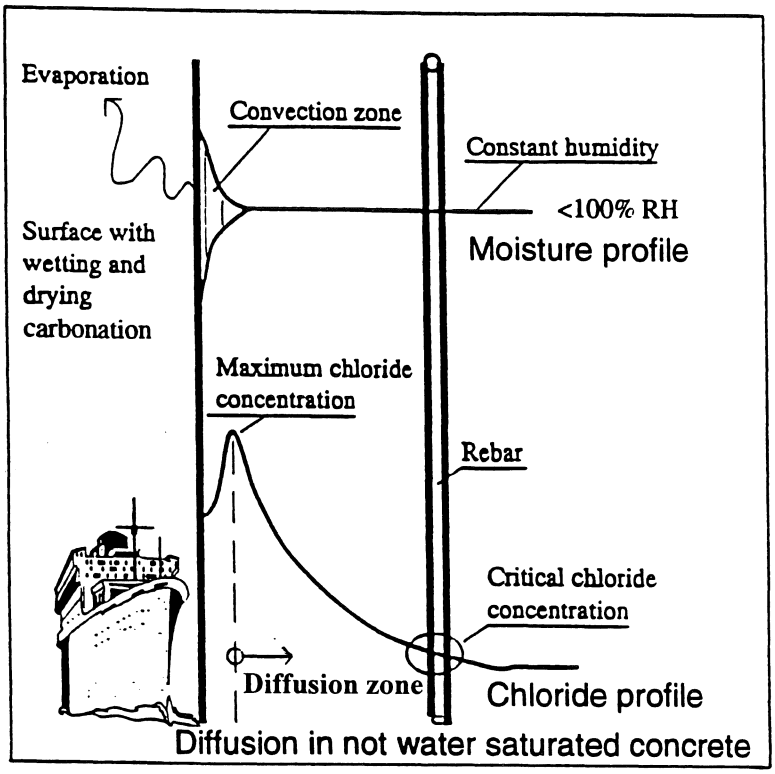
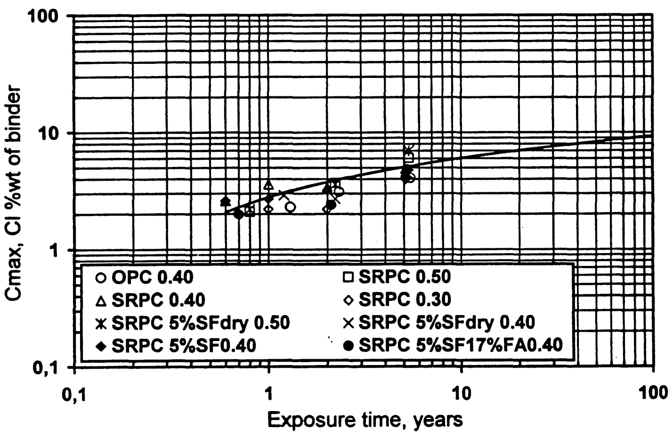
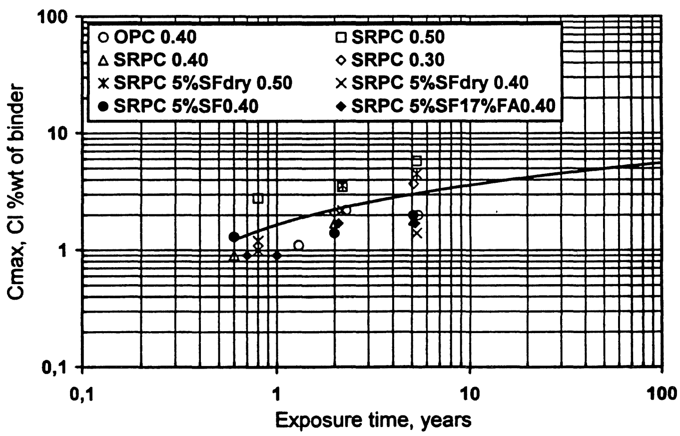


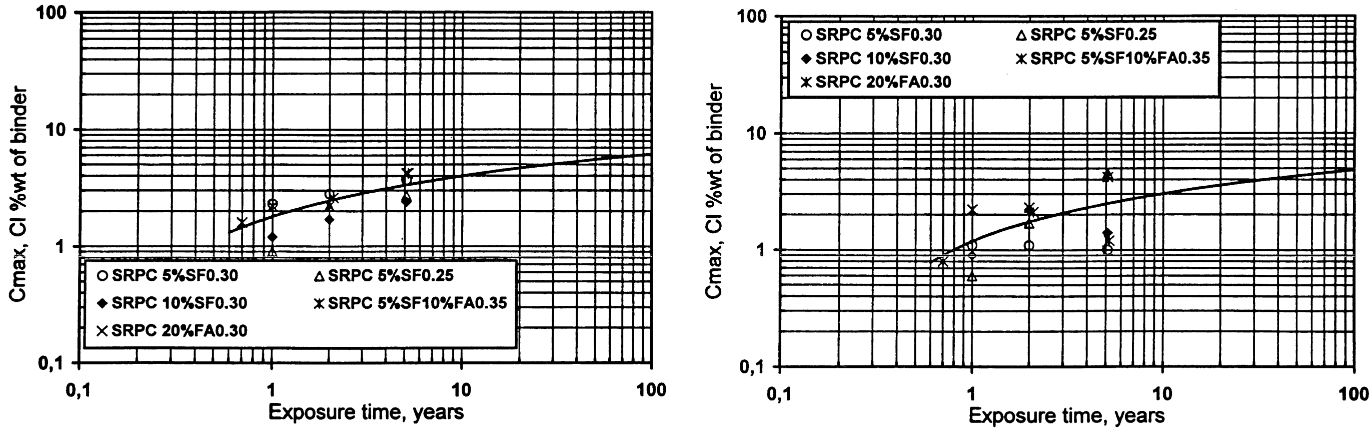
Figure 9. Illustration of the proposed "convection zone" and the "diffusion zone" in concrete exposed above the water line.





A B

Figure 10. Maximum total chloride concentrations for concrete mixes with w/c ≥ 0.40 and. for plain SRPC concrete with w/c 0.30, exposed submerged (A) and in the splash zone (B). Solid logarithmic trend lines extrapolated by regression analysis.



A B

Figure 11. Maximum total chloride concentrations for concrete mixes with pozzolan in the binder and w/c ≤0.35, exposed submerged (A) and in the splash zone (B). Solid logarithmic trend lines extrapolated by regression analysis.

The results from the prediction of the total chloride profile after 100 years of exposure time are presented in Appendix B as shown for plain OPC concrete, w/c 0.40, in Figure 12. The results in Appendix B are presented with 1 concrete mix on each page in the following order:

Mix No.	**Label**	**w/c ratio**	**Cement**	**Pozzolan**	**Remarks**
1	2-40	0.40	OPC	none	
2	1-50	0.50	SRPC	none	
3	Ö	0.40	SRPC	none	
4	H3	0.30	SRPC	none	
5	3-50	0.50	SRPC	5 % SF	SF dry compacted
6	3-40	0.40	SRPC	5 % SF	SF dry compacted
7	H4	0.40	SRPC	5 % SF	"Öresund bridge concrete"
8	H1	0.30	SRPC	5 % SF	
9	H5	0.25	SRPC	5 % SF	
10	H2	0.30	SRPC	10 % SF	
11	12-35	0.35	SRPC	5 % SF, 10 % FA	"Store Baelt bridge concrete"
12	10-40	0.40	SRPC	5 % SF, 17 % FA	"Store Baelt bridge concrete"
13	H8	0.30	SRPC	20 % FA	

Exposure levels and simulations:

Top left figure – Simulation A, splash zone exposure, middle of slab at the water level.
Top right figure – Simulation A, submerged exposure, bottom of concrete slab.

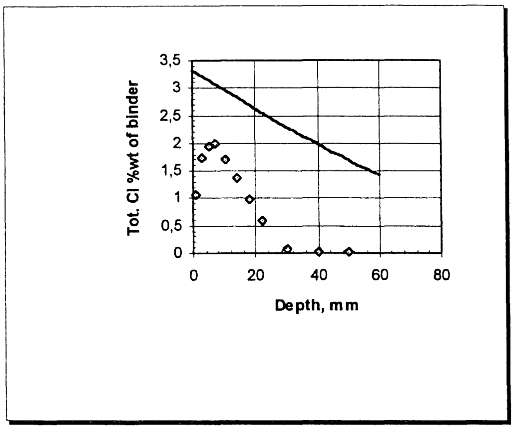
Middle left figure – Simulation B, splash zone exposure, middle of slab at the water level.
Middle right figure – Simulation B, submerged exposure, bottom of concrete slab.

Bottom left figure – Simulation C, splash zone exposure, middle of slab at the water level.
Bottom right figure – Simulation C, submerged exposure, bottom of concrete slab.

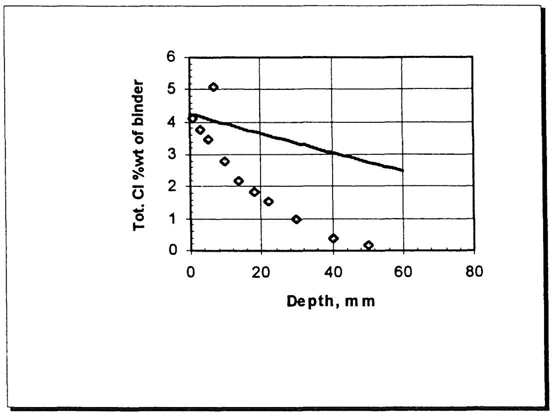
Squares - Datapoints after 5 years exposure.
Solid line - Predicted total chloride profile after 100 years of exposure.

Splash zone **Submerged zone**

A

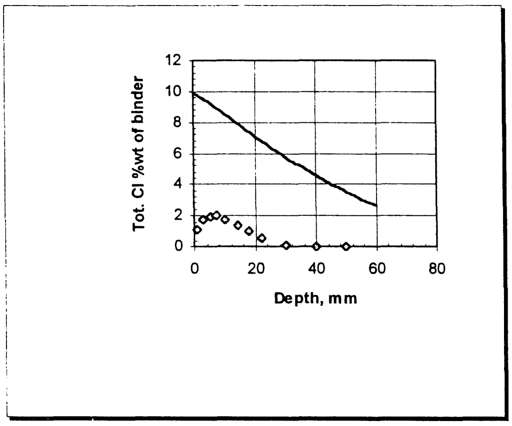


2-40 splash 100 yrs no change DCl or Cs

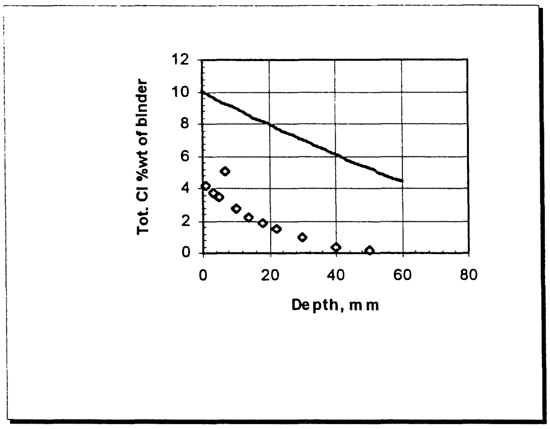


2-40 sub 100 yrs no change DCl or Cs

B

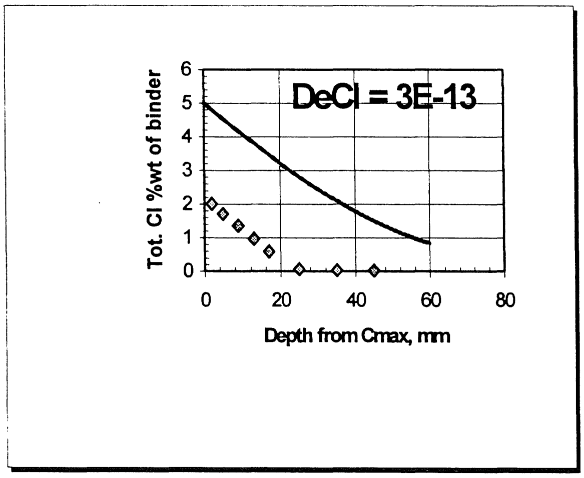


2-40 splash 100 yrs DCl 50 % reduction, Cs = 10 %

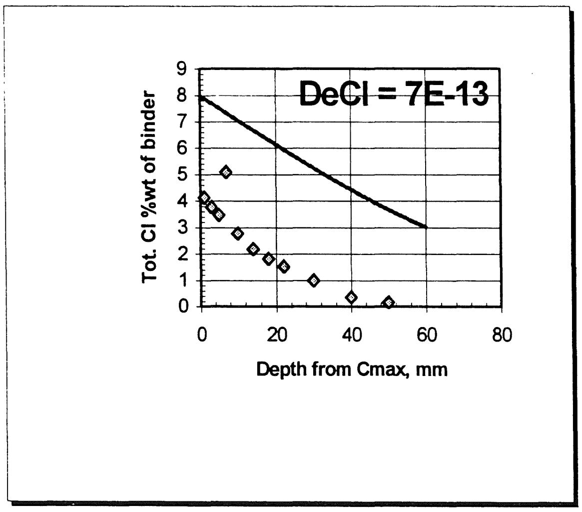


2-40 sub 100 yrs DCl 50 % reduction, Cs = 10 %

C



2-40 splash 100 yrs diffusion zone, extrapolation of trend



2-40 sub 100 yrs diffusion zone, extrapolation of trend

100 years prediction 2-40 OPC w/c 0.40

Figure 12. Prediction of total chloride profiles after 100 years of marine exposure of a plain OPC concrete, w/c 0.40.

6. DISCUSSION

6.1 General

Most of the discussion relates to the chloride penetration in concrete exposed in the submerged- and the splash zone. The splash zone is the most critical zone in practice, but the exposure condition is more well defined in the submerged zone. The chloride penetration rate may be higher in submerged concrete, but the chloride threshold is also higher and it is relatively easy to prevent corrosion by the use of inexpensive protection systems /6/.

Small differences in the sampling height from the water level may have large impact on the salt- and moisture load, and thus on the chloride penetration profile in the splash zone. In addition, concrete itself is an inhomogeneous material with local variations in the porosity and therefore local variations in the chloride diffusivity. As a consequence the spread in measured total chloride profiles may be relatively high, and it should be higher in the splash zone compared to the submerged zone as the exposure conditions vary less in the submerged zone.

An indication on the spread which can be expected in the submerged- and in the splash zone was given in Figure 13, which shows less chloride penetration in the splash zone for a concrete with w/c 0.40 than with w/c 0.30. One should therefore be careful no to use individual profiles for service life prediction, but rather extract information from trends observed from several profiles.

6.2 The effect of w/c ratio

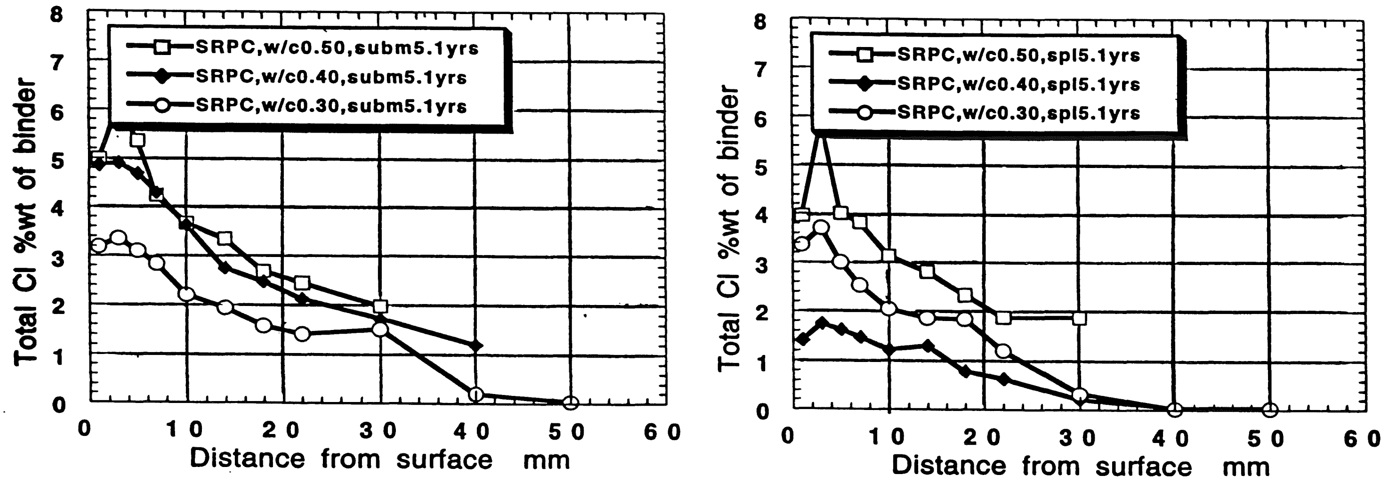


Figure 13. Total chloride profiles in SRPC concrete exposed submerged and in the splash zone for 5 years.

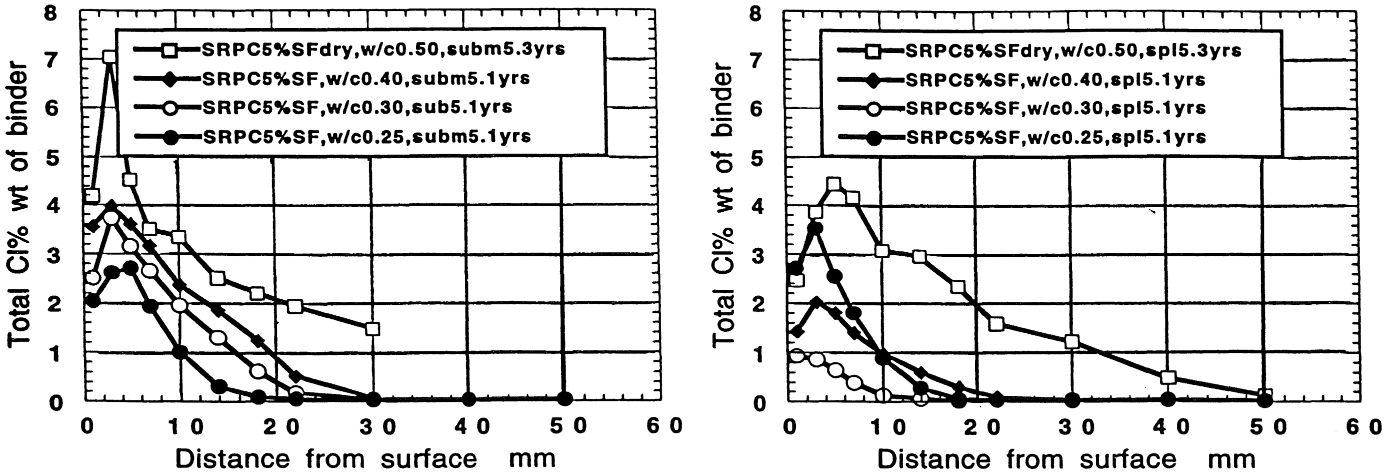


Figure 14. Total chloride profiles in SRPC concrete with 5 % silica fume in the binder fraction, exposed submerged and in the splash zone for 5 years.

The effect of w/c ratio on the chloride penetration profiles in concrete exposed submerged and in the splash zone for 5 years was shown for plain SRPC concrete in Figure 13 and for SRPC concrete with 5 % silica fume in the binder in Figure 14. As expected, the effect of w/c ratio is significant on chloride penetration in concrete.

6.3 The effect of pozzolan in the binder

The effect silica fume and/or fly ash in the binder on the chloride penetration profiles in concrete exposed submerged and in the splash zone for 5 years was shown for w/c 0.40 in Figure 15 and for w/c 0.30 in Figure 16. The relative efficiency of silica fume seems far higher than that of fly ash.

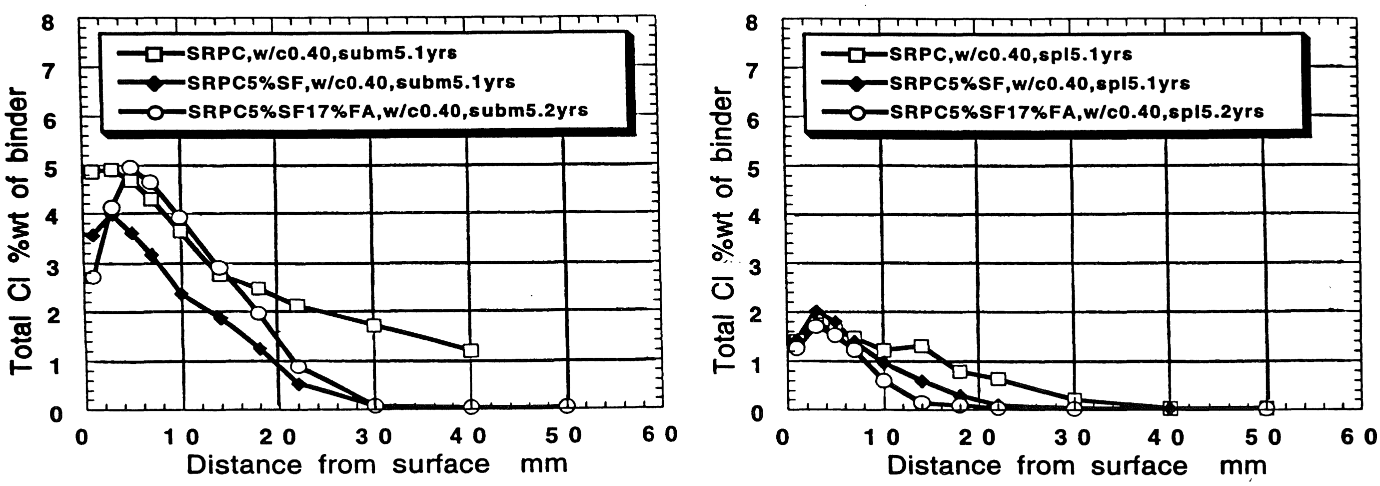


Figure 15. Total chloride profiles in plain concrete and in concrete with silica fume and/or fly ash in the binder fraction, w/c ratio 0.40, exposed submerged and in the splash zone for 5 years.

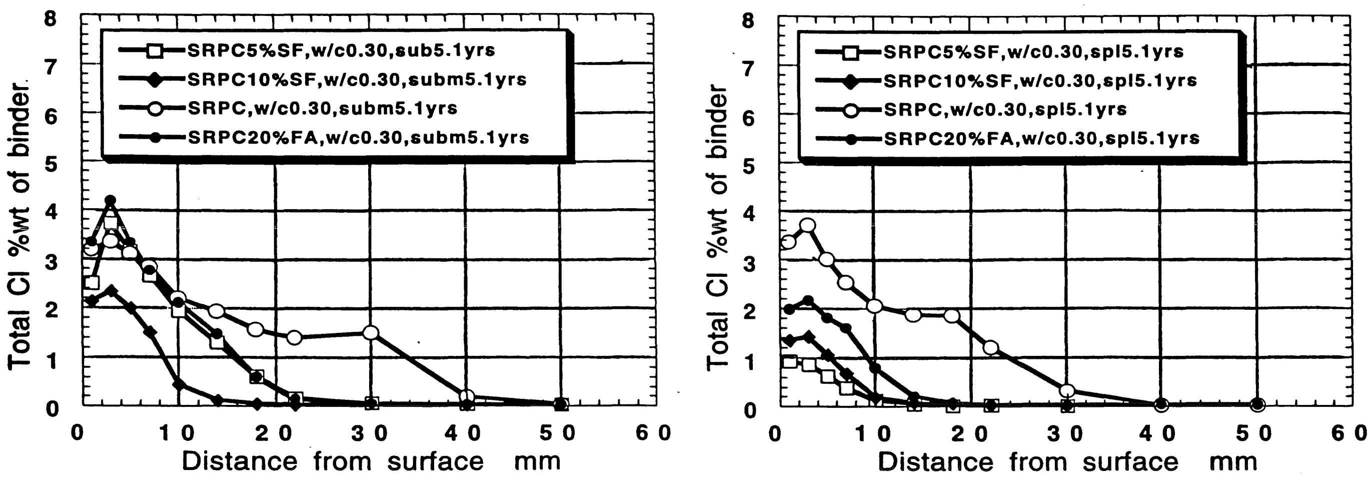


Figure 16. Total chloride profiles in plain concrete and in concrete with silica fume and/or fly ash in the binder fraction, w/c ratio 0.30, exposed submerged and in the splash zone for 5 years.

6.4 The effect of the type of silica fume in the binder

The effect the type of silica fume in the binder on the chloride penetration profiles in concrete exposed submerged and in the splash zone for 5 years was shown for w/c 0.40 in Figure 17. The relative efficiency of silica fume when added as a 50 % slurry seems higher than when the same amount of solid silica fume is added as a compacted powder.

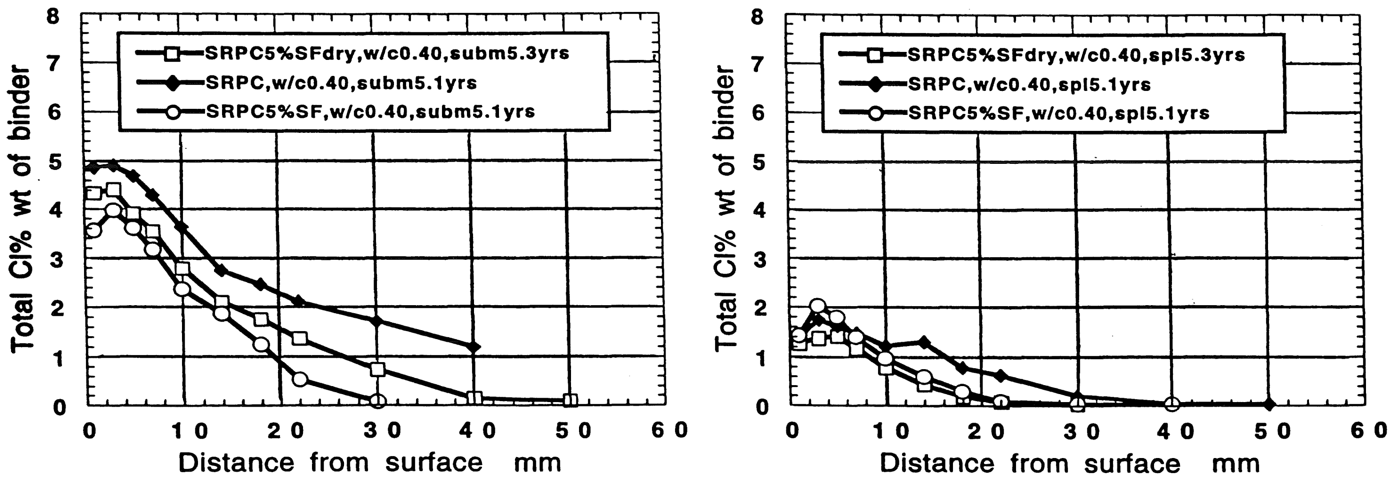


Figure 17. Total chloride profiles in plain concrete and in concrete with silica fume added as a 50 % slurry or as a compacted powder, w/c ratio 0.40, exposed submerged and in the splash zone for 5 years.

6.5 The combined effect of w/c ratio and of pozzolan in the binder

The combined effect of w/c ratio and of silica fume in the binder on the calculated effective chloride diffusivity was shown in Figure 18, for concrete exposed in the splash zone and for concrete tested in a standard laboratory immersion test according to NT Build 443 /6,7/. The results in Figure 18 indicate that for a w/c ratio of 0.40, which is the maximum w/c ratio recommended for marine concrete in several codes of practice, the effective chloride diffusivity can be reduced by a factor of 3-5 by using 5 % silica fume in the form of a well dispersed slurry in the binder fraction of the concrete. If on the other hand the w/c ratio is reduced from 0.40 to 0.30 besides the introduction of 5 % silica fume in the binder, it seems that the effective chloride diffusivity can be reduced by a factor of 8-10.

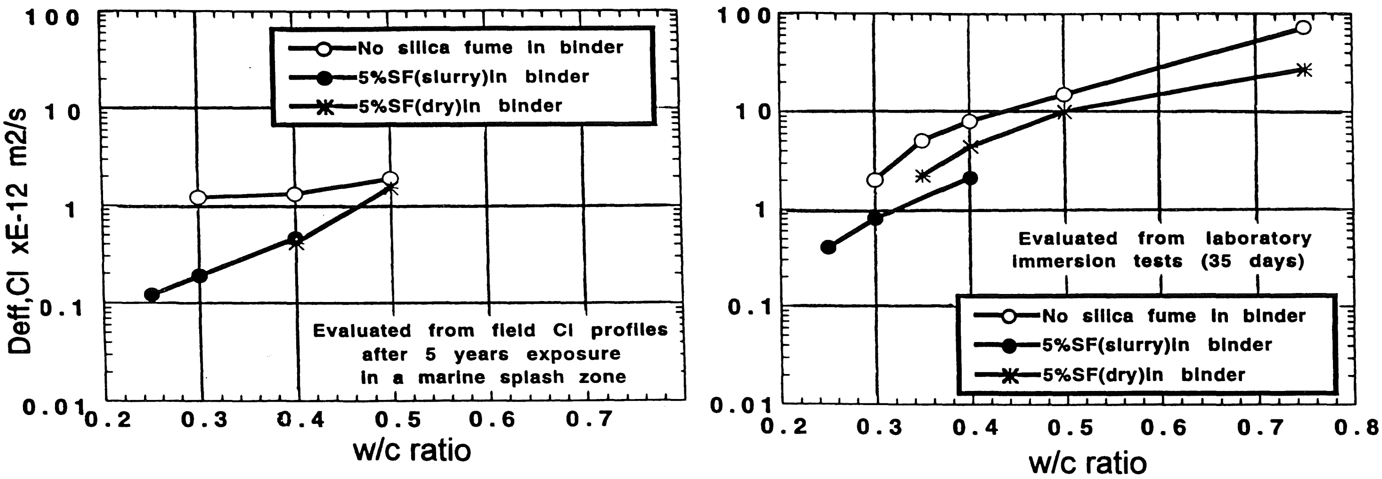


Figure 18. Calculated effective chloride diffusivity in plain concrete and in concrete with silica fume and/or fly ash in the binder fraction, exposed in the splash zone for 5 years and exposed in a standard laboratory immersion test in 16 % NaCl.

6.6 Prediction of required concrete cover

A simple service life prediction with respect to the required cover for a 100 years initiation time for reinforcement corrosion in the splash zone can be undertaken by the use of the simulations presented in Appendix B and chloride threshold levels measured on field exposed concrete slabs as presented in /12/.

The results are shown in Table 5, considering concrete with w/c ratio ≤ 0.40 and corresponding chloride thresholds from /12/ also shown in Table 5. The required cover thickness was calculated using these thresholds and the results from the simulations in Appendix B carried out as described in Chapter 5:

A) Simulation of the total chloride profile after 100 years of exposure, with no changes in the effective chloride diffusivity and in the apparent surface chloride concentration.

B) Simulation of the total chloride profile after 100 years of exposure, with a 50 % reduction of the effective chloride diffusivity measured after 5 years and a fixed apparent surface chloride concentration of 10 %.

C) Simulation of the total chloride profile after 100 years of exposure, with the concrete cover divided into a "convection zone" and a "diffusion zone". The simulation was carried out in the "diffusion zone" only, with the calculated apparent surface concentration equal to the maximum total chloride concentration, labeled Cmax, and located at the depth of Cmax after 5 years of exposure. The values on the effective chloride diffusivity and the maximum chloride concentration (Cmax) was extrapolated from the data in Figures 5-6 and 10-11 respectively, using the slope of the general trend lines for the extrapolation of individual data series.

Table 5. Concrete mixes, threshold levels and calculated required cover thickness in the splash zone

Mix No.	ID	w/c ratio	OPC or SRPC kg/m³	Silica fume kg/m³	Fly ash kg/m³	Chloride threshold %Cl of binder	Required cover mm Procedure A/B/C	Required cover mm Mean value of A, B & C
1	OPC 0.40	0.40	420	-	-	1.4	70/76/53	66
3	SRPC 0.40	0.40	420	-	-	1.2	43/88/74	68
4	SRPC 0.30	0.30	492	-	-	1.5	76/76/70	74
6	SRPC 5%SF 0.40	0.40	399	21 dry	-	1.1	38/60/41	46
7	SRPC 5%SF 0.40	0.40	399	21 slu	-	1.1	45/62/49	52
8	SRPC 5%SF 0.30	0.30	475	25 slu	-	>1.2	*/38/25	32
9	SRPC 5%SF 0.25	0.25	525	26 slu	-	>1.2	41/38/28	36
10	SRPC 10%SF 0.30	0.30	450	50 slu	-	>1.0	28/32/28	29
11	SRPC 5%SF 10%FA 0.35	0.35	382	23 slu	45	1.1	18/48/27	31
12	SRPC 5%SF 17%FA 0.40	0.40	345	21 slu	75	1.1	34/42/40	39
13	SRPC 20%FA 0.30	0.30	493	-	123	>1.0	43/50/50	48

* Active corrosion cannot be induced according to Simulation A.

As seen in table 5, for most concrete mixes the calculated required cover vary considerably depending on the simulation procedure chosen. In order to compare the results for the different mixes, a mean value of procedures A, B and C was calculated.

The calculations of the required cover thickness indicate that the use of 5% silica fume and a reduction of the w/c ratio from 0.40 to 0.30 would reduce the required cover with approximately 50 % as compared to a typical Swedish pozzolan free bridge concrete of w/c 0.40. It is however important to point out that other durability issues such as the durability to freezing and thawing may completely alter the overall judgement of the most durable concrete mix. Generally speaking, the addition of pozzolans, especially so for fly ash and ground granulated blast furnace slag, to the concrete binder has a strong negative effect on the durability to freezing and thawing /13/. Considering the durability to both reinforcement corrosion and freezing and thawing, the optimum binder is probably a mix with SRPC and 5% silica fume, as this relatively small amount of pozzolan has a strong positive effect on the resistance to chloride penetration, but only a small negative effect on the chloride threshold and on the resistance to freezing and thawing /14/.

Potentially it would be of great interest to consider high performance concrete with 5-10 % silica fume in the binder and a maximum w/b ratio of 0.30. As indicated in table 3 the required cover would be relatively thin. Furthermore, research on the durability of high performance concrete with respect to freezing and thawing indicates that concrete with such low w/c ratios are potentially very durable to freezing and thawing as a consequence of self desiccation /13/. Another strong benefit from using high performance concrete with silica fume is the very high resistivity of such concrete, which may depress active corrosion rates to insignificant levels /15/.

7. REFERENCES

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APPENDIX A

Appendix A

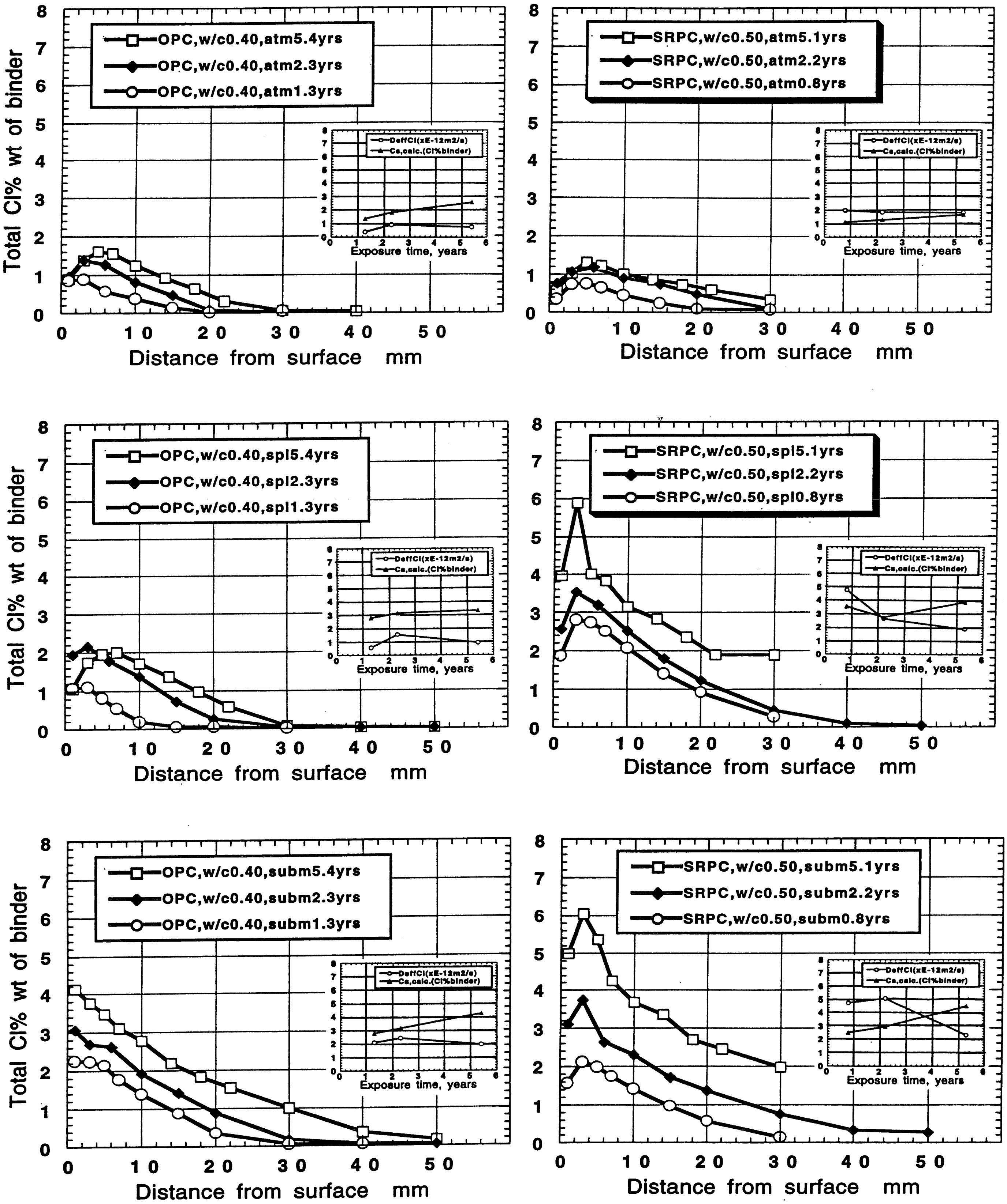
The total chloride profiles and the curve fitting parameters for all concrete mixes are shown in the following order:

Mix No.	Label	w/c ratio	Cement	Pozzolan	Remarks
1	2-40	0.40	OPC	none	
2	1-50	0.50	SRPC	none	
3	Ö	0.40	SRPC	none	
4	H3	0.30	SRPC	none	
5	3-50	0.50	SRPC	5 % SF	SF dry compacted
6	3-40	0.40	SRPC	5 % SF	SF dry compacted
7	H4	0.40	SRPC	5 % SF	"Öresund bridge concrete"
8	H1	0.30	SRPC	5 % SF	
9	H5	0.25	SRPC	5 % SF	
10	H2	0.30	SRPC	10 % SF	
11	12-35	0.35	SRPC	5 % SF, 10 % FA	"Store Baelt bridge concrete"
12	10-40	0.40	SRPC	5 % SF, 17 % FA	"Store Baelt bridge concrete"
13	H8	0.30	SRPC	20 % FA	

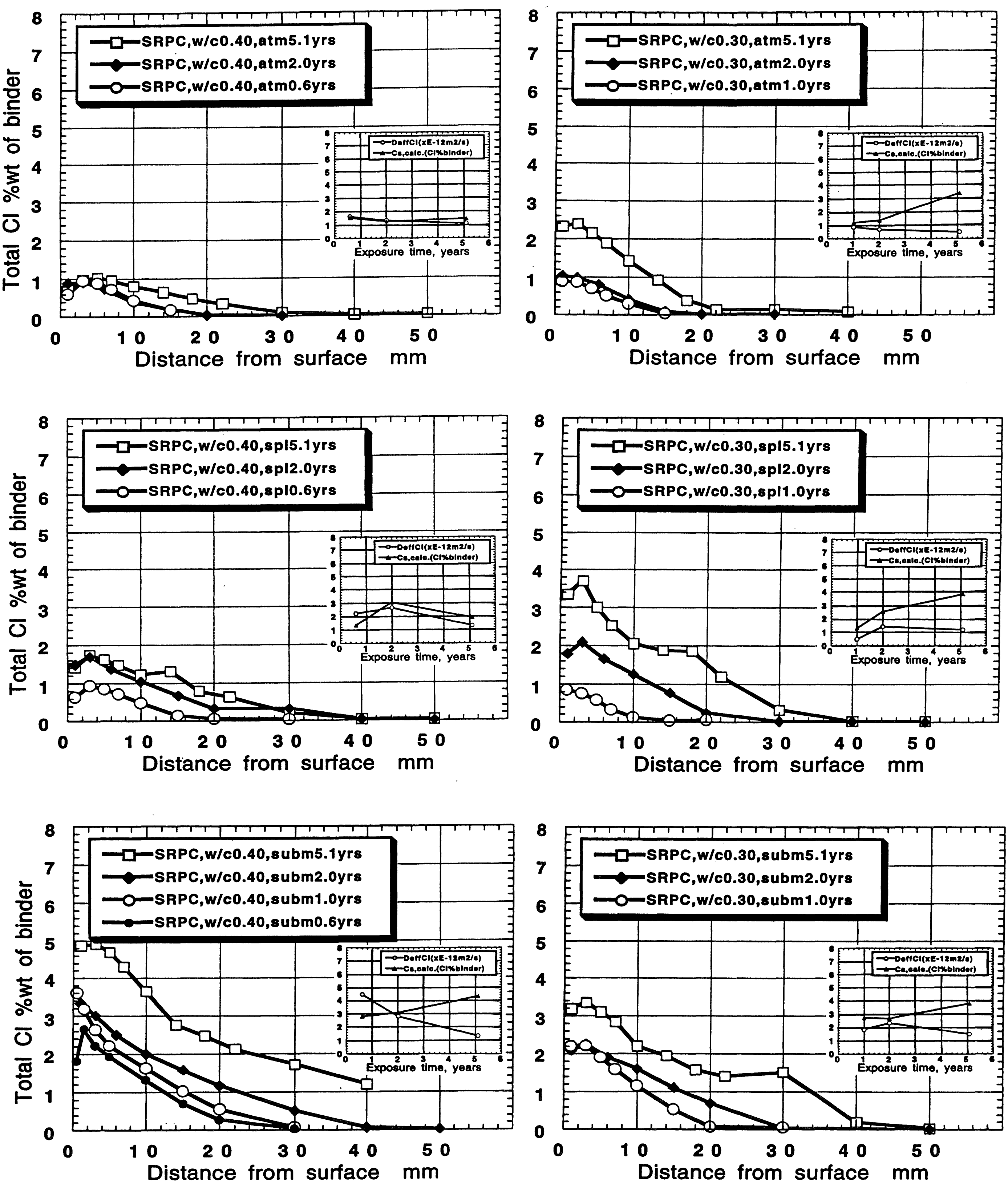
Two concrete mixes are shown on each page.

Exposure levels:

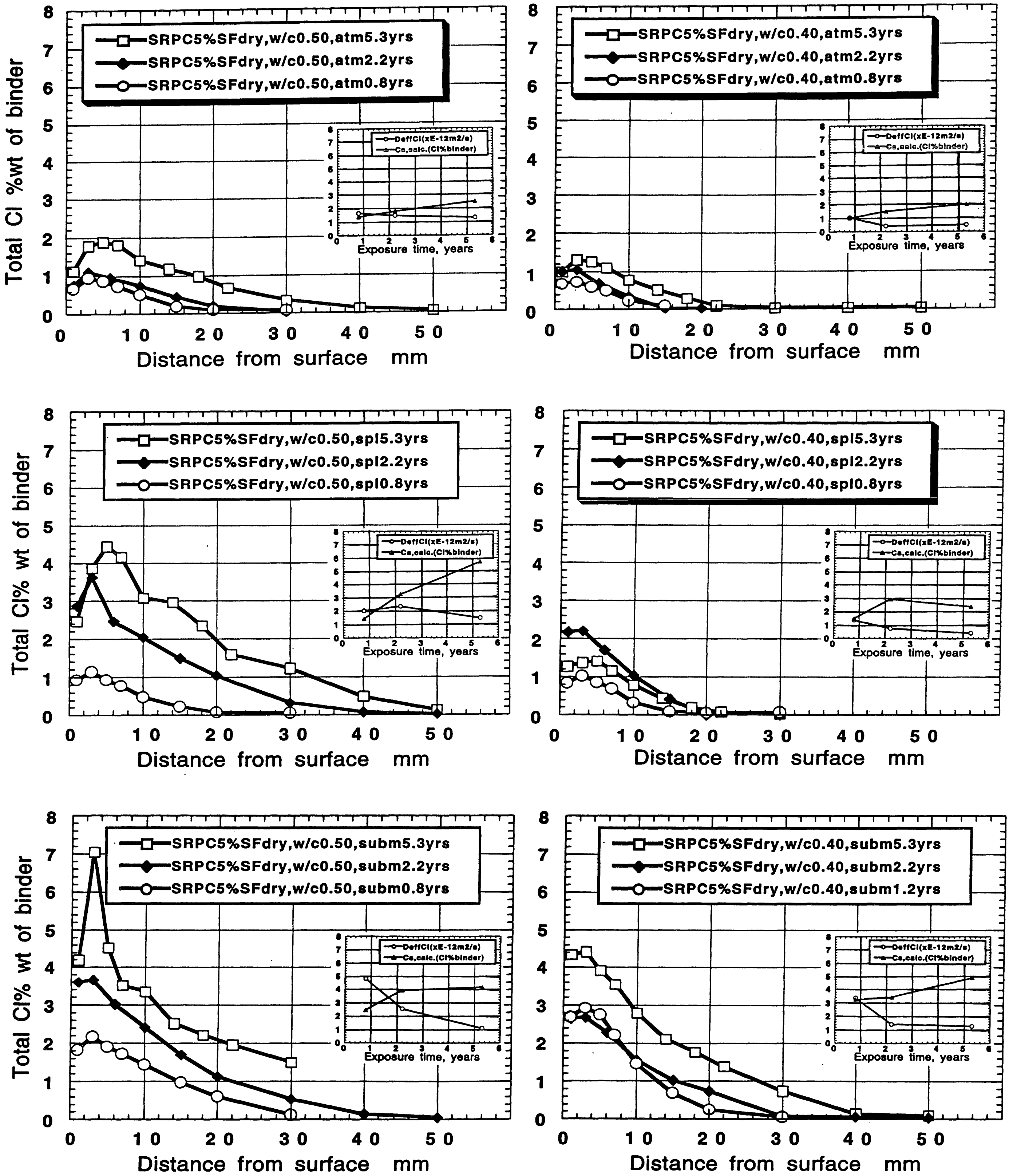
Top figure – Atmospheric exposure, top of concrete slab.
Middle figure – Splash zone exposure, middle of slab at the water level.
Bottom figure – Submerged exposure, bottom of concrete slab, continuously submerged.



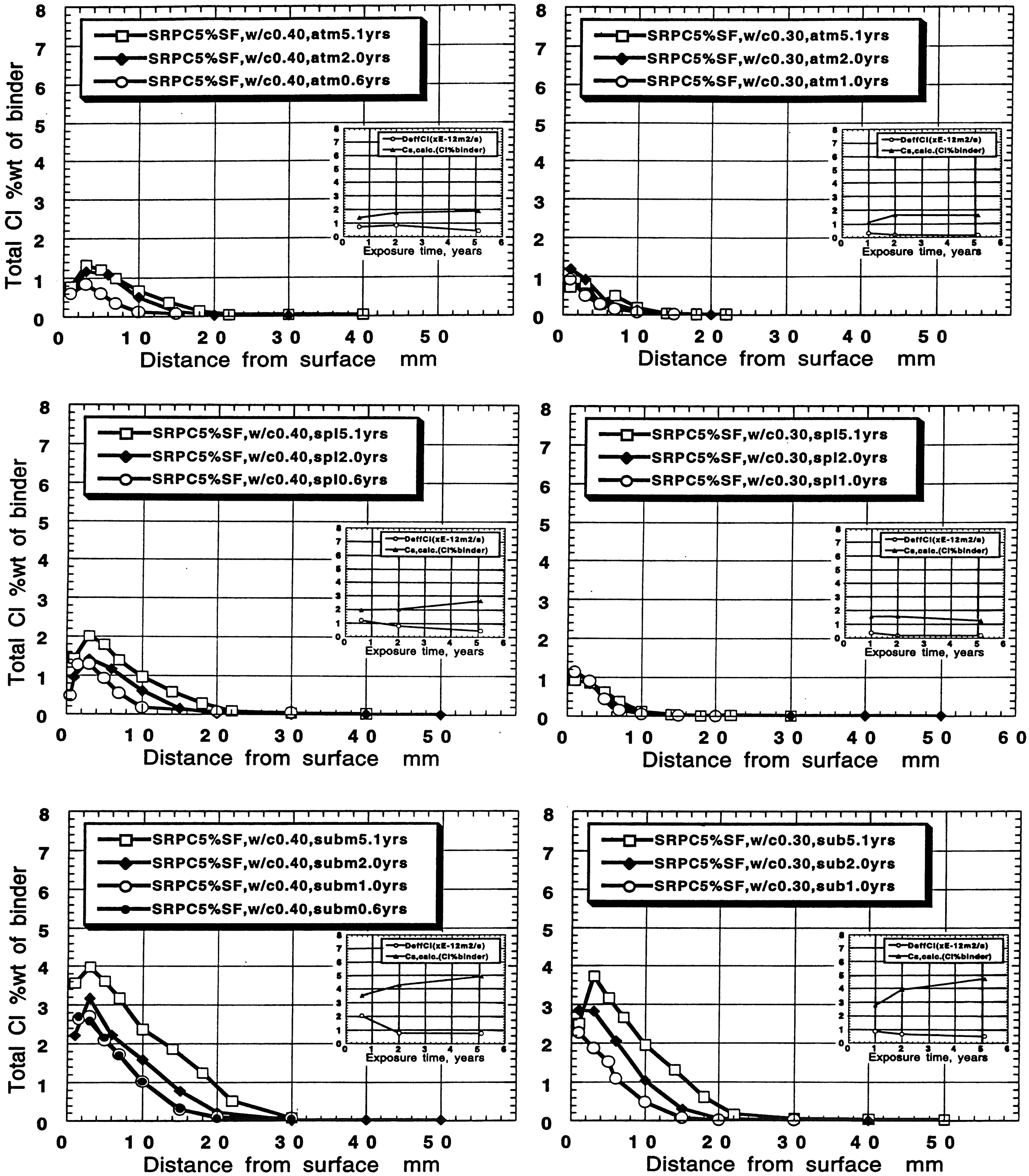
Appendix A. Total chloride penetration profiles in concrete exposed in a marine environment.



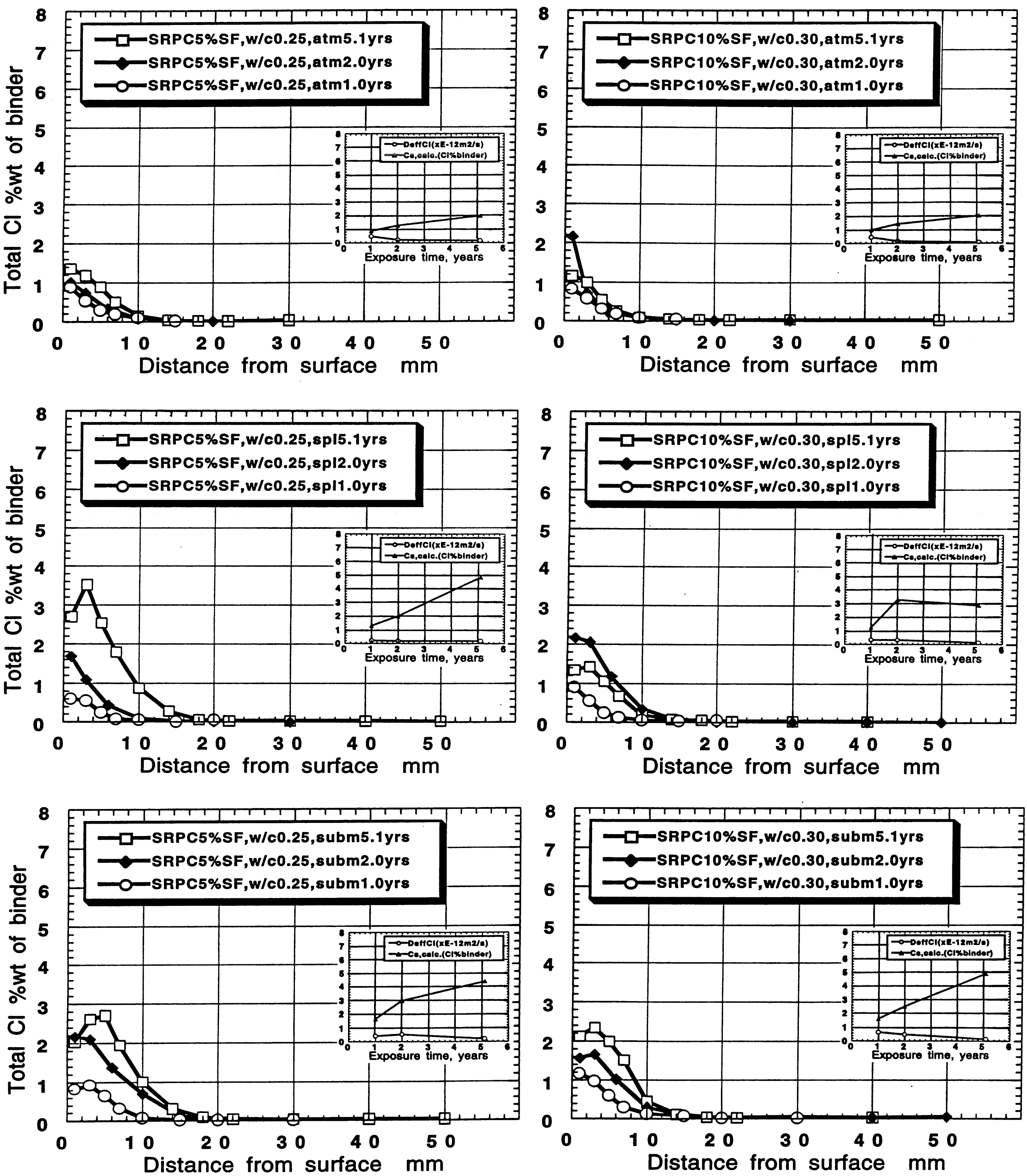
Appendix A. Total chloride penetration profiles in concrete exposed in a marine environment.



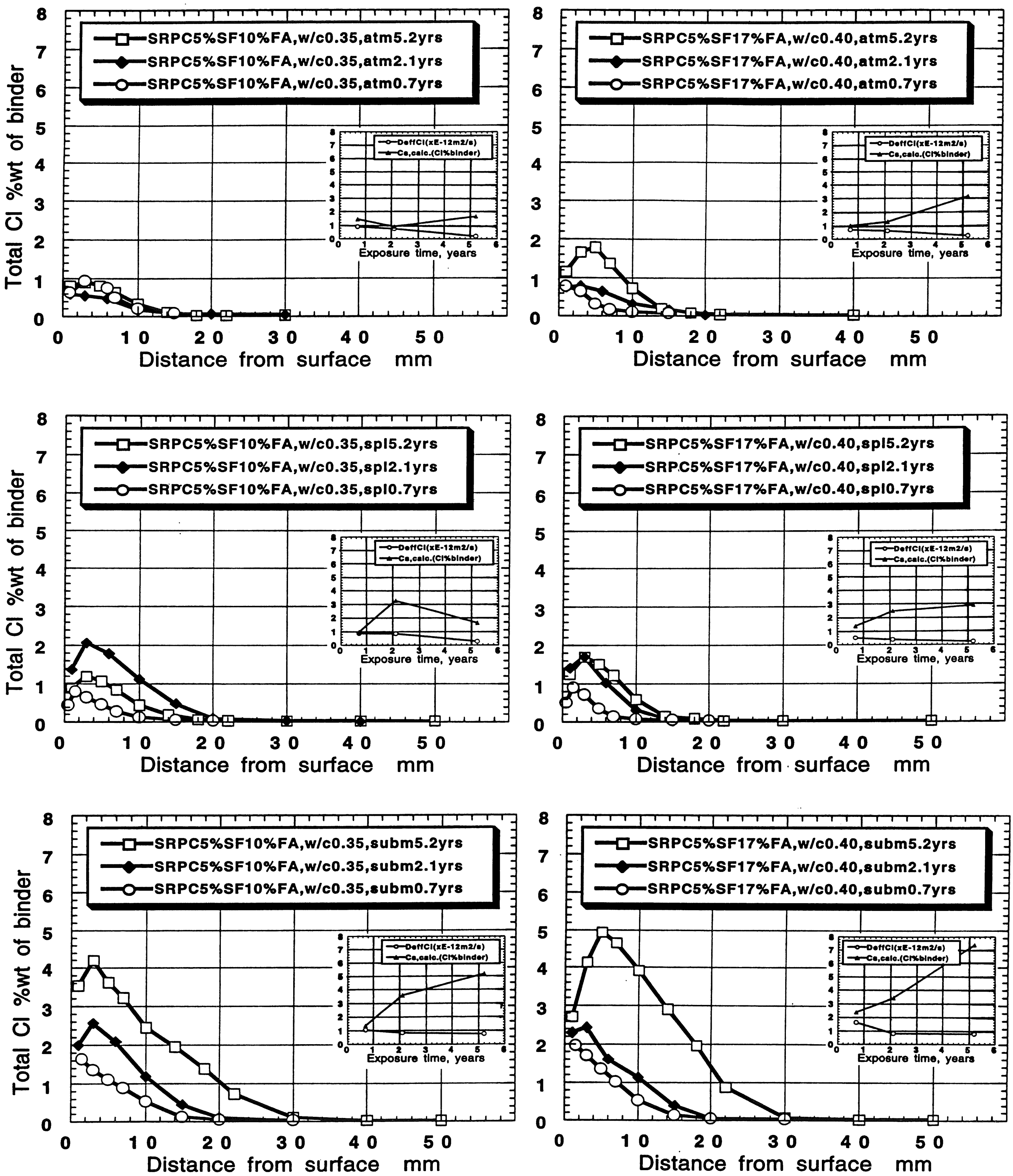
Appendix A. Total chloride penetration profiles in concrete exposed in a marine environment.



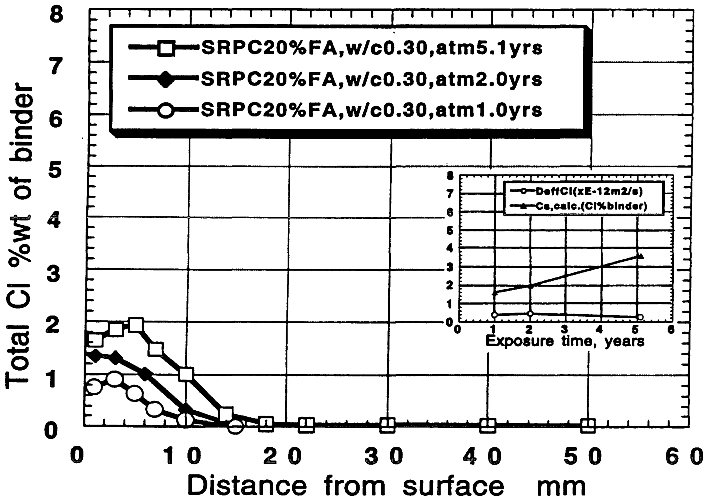
Appendix A. Total chloride penetration profiles in concrete exposed in a marine environment.

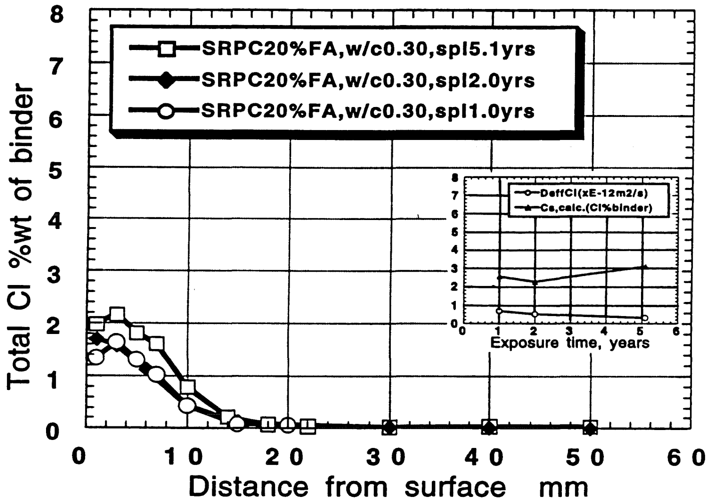


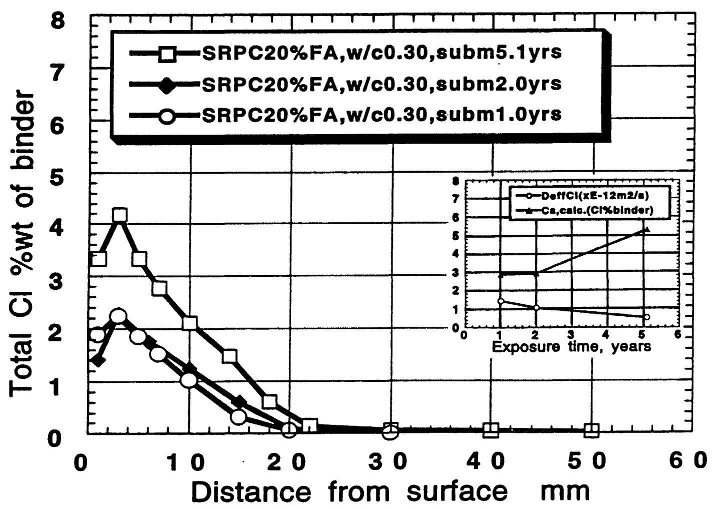
Appendix A. Total chloride penetration profiles in concrete exposed in a marine environment.



Appendix A. Total chloride penetration profiles in concrete exposed in a marine environment.







Appendix A. Total chloride penetration profiles in concrete exposed in a marine environment.

APPENDIX B

Appendix B

The results from the prediction of the total chloride profile after 100 years of exposure time are presented with 1 concrete mix on each page in the following order:

Mix No.	Label	w/c ratio	Cement	Pozzolan	Remarks
1	2-40	0.40	OPC	none	
2	1-50	0.50	SRPC	none	
3	Ö	0.40	SRPC	none	
4	H3	0.30	SRPC	none	
5	3-50	0.50	SRPC	5 % SF	SF dry compacted
6	3-40	0.40	SRPC	5 % SF	SF dry compacted
7	H4	0.40	SRPC	5 % SF	"Öresund bridge concrete"
8	H1	0.30	SRPC	5 % SF	
9	H5	0.25	SRPC	5 % SF	
10	H2	0.30	SRPC	10 % SF	
11	12-35	0.35	SRPC	5 % SF, 10 % FA	"Store Baelt bridge concrete"
12	10-40	0.40	SRPC	5 % SF, 17 % FA	"Store Baelt bridge concrete"
13	H8	0.30	SRPC	20 % FA	

Exposure levels and simulations:

Top left figure – Simulation A, splash zone exposure, middle of slab at the water level.
Top right figure – Simulation A, submerged exposure, bottom of concrete slab.

Middle left figure – Simulation B, splash zone exposure, middle of slab at the water level.
Middle right figure – Simulation B, submerged exposure, bottom of concrete slab.

Bottom left figure – Simulation C, splash zone exposure, middle of slab at the water level.
Bottom right figure – Simulation C, submerged exposure, bottom of concrete slab.

Squares - Datapoints after 5 years exposure.
Solid line - Predicted total chloride profile after 100 years of exposure.

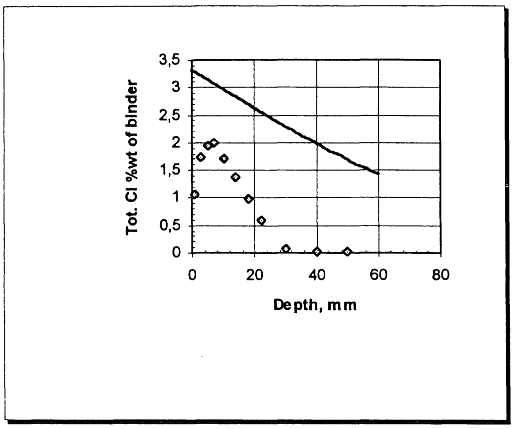
A) Simulation of the total chloride profile after 100 years of exposure, with no changes in the effective chloride diffusivity and in the apparent surface chloride concentration.

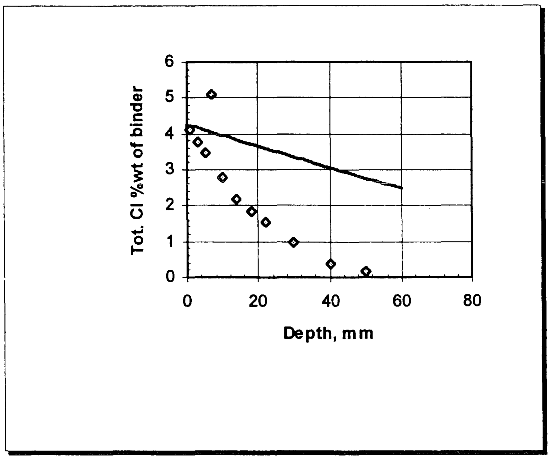
B) Simulation of the total chloride profile after 100 years of exposure, with a 50 % reduction of the effective chloride diffusivity measured after 5 years and a fixed apparent surface chloride concentration of 10 %.

C) Simulation of the total chloride profile after 100 years of exposure, with the concrete cover divided into a "convection zone" and a "diffusion zone". The simulation was carried out in the "diffusion zone" only, with the calculated apparent surface concentration equal to the maximum total chloride concentration, labeled Cmax, and located at the depth of Cmax after 5 years of exposure. The values on the effective chloride diffusivity and the maximum chloride concentration (Cmax) was extrapolated from the data in Figures 5-6 and 10-11 respectively, using the slope of the general trend lines for the extrapolation of individual data series.

Splash zone **Submerged zone**

A

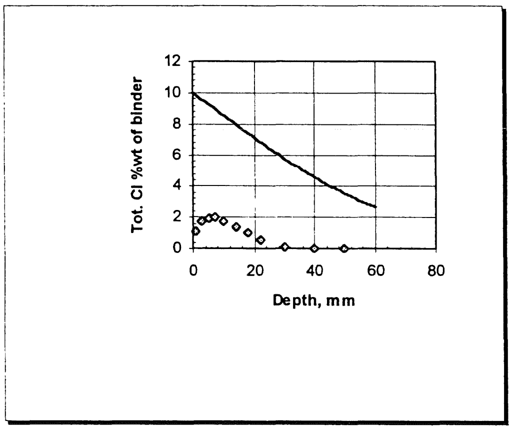


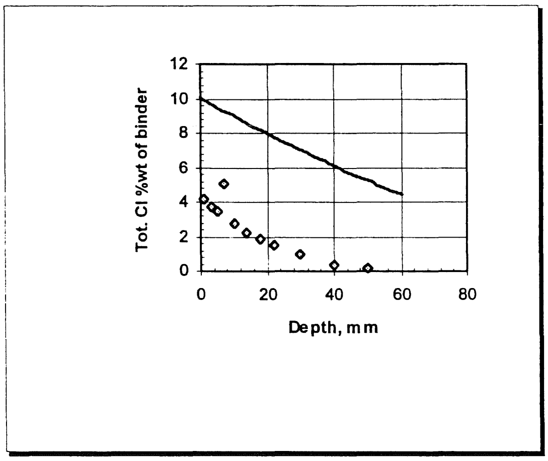


2-40 splash 100 yrs no change DCl or Cs

2-40 sub 100 yrs no change DCl or Cs

B

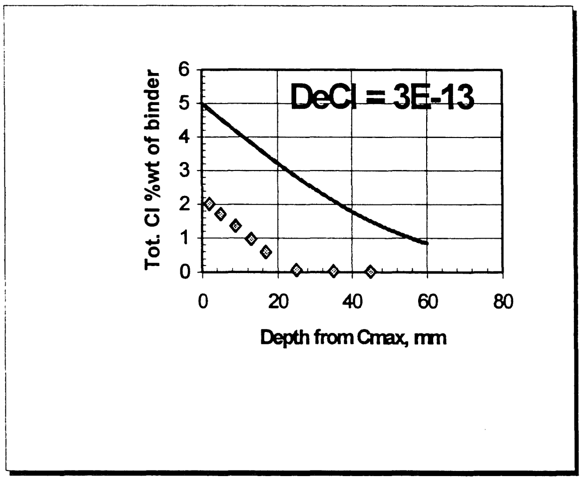


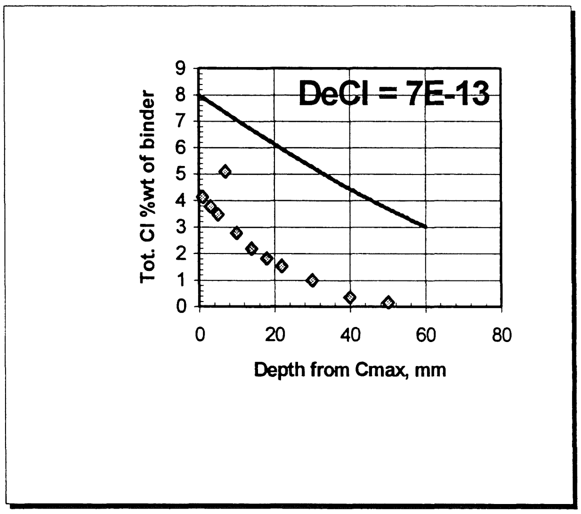


2-40 splash 100 yrs DCl 50 % reduction, Cs = 10 %

2-40 sub 100 yrs DCl 50 % reduction, Cs = 10 %

C





2-40 splash 100 yrs diffusion zone, extrapolation of trend

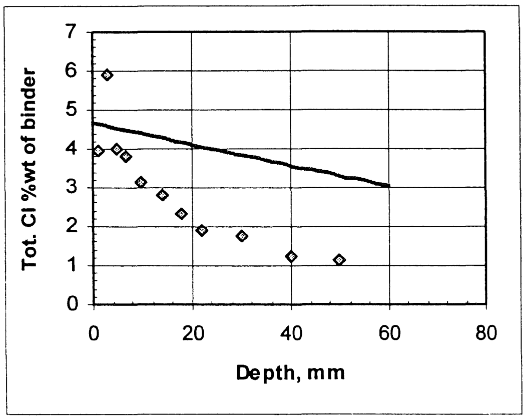
2-40 sub 100 yrs diffusion zone, extrapolation of trend

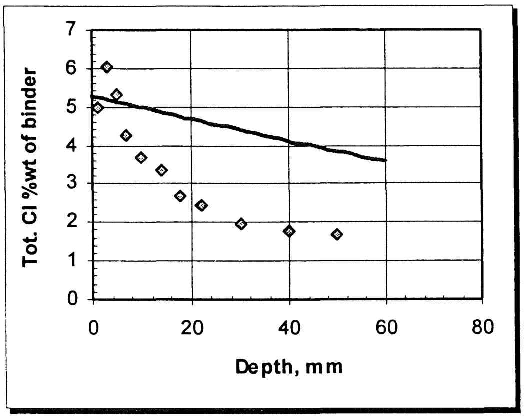
100 years prediction 2-40 OPC w/c 0.40

Appendix B. Prediction of total chloride profiles after 100 years of marine exposure.

Splash zone / Submerged zone

A

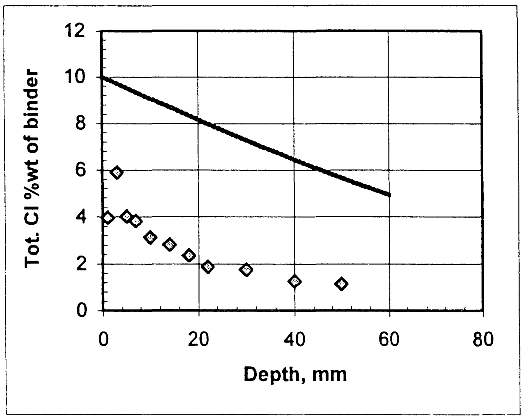


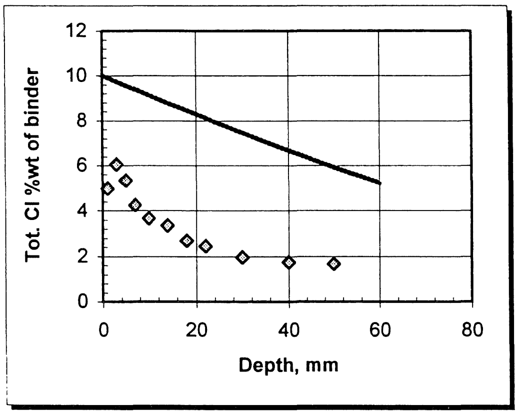


1-50 splash 100 yrs no change DCl or Cs

1-50 sub 100 yrs no change DCl or Cs

B

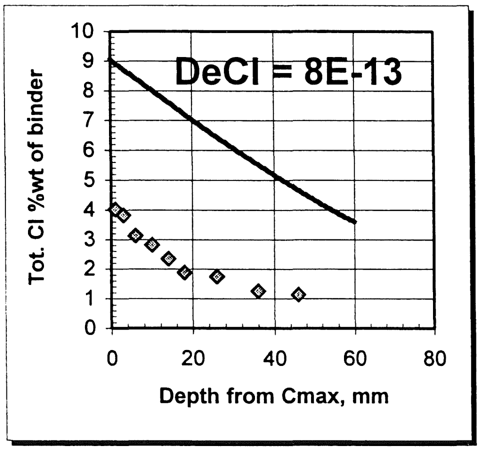


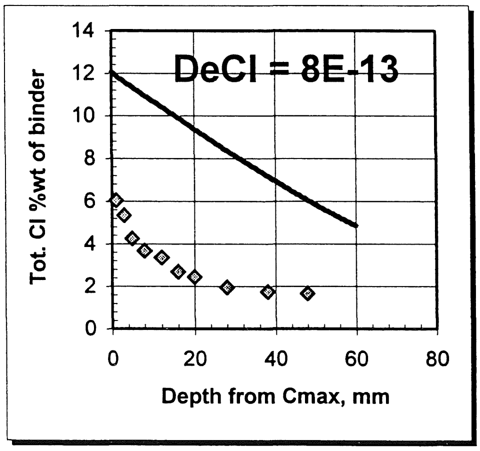


1-50 splash 100 yrs DCl 50 % reduction, Cs = 10 %

1-50 sub 100 yrs DCl 50 % reduction, Cs = 10 %

C





1-50 splash 100 yrs diffusion zone, extrapolation of trend

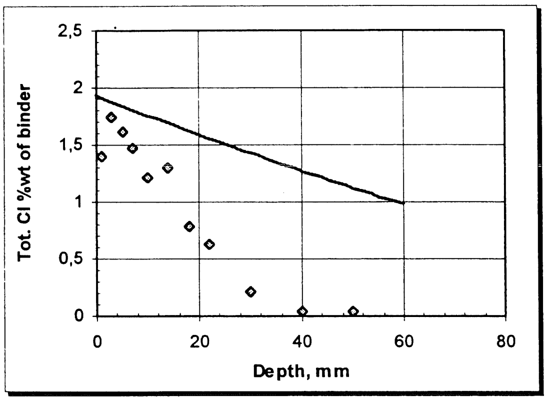
1-50 sub 100 yrs diffusion zone, extrapolation of trend

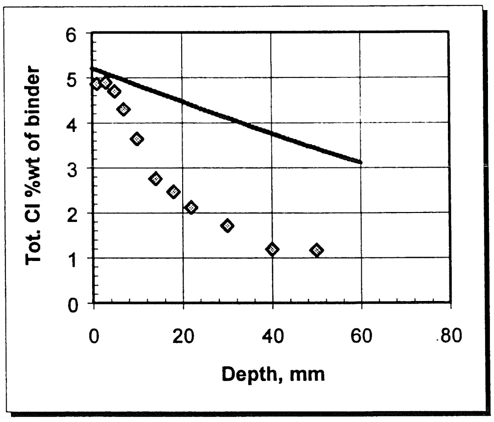
100 years prediction 1-50 SRPC w/c 0.50

Appendix B. Prediction of total chloride profiles after 100 years of marine exposure.

Splash zone | **Submerged zone**

A

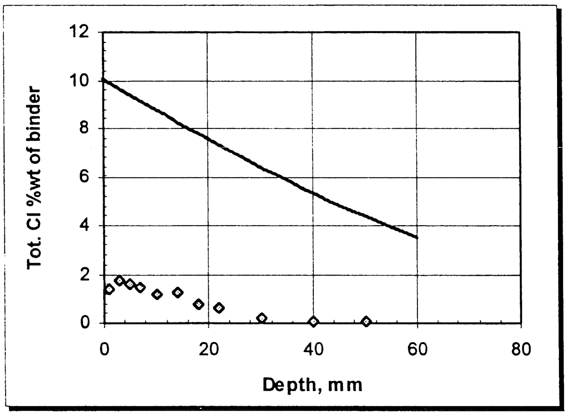


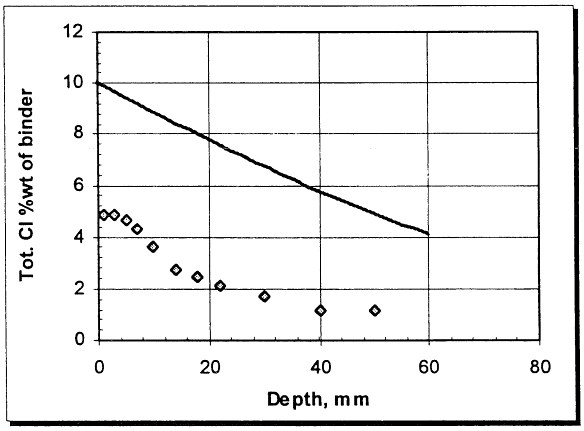


Ösplash 100 yrs no change DCl or Cs

Ösub 100 yrs no change DCl or Cs

B

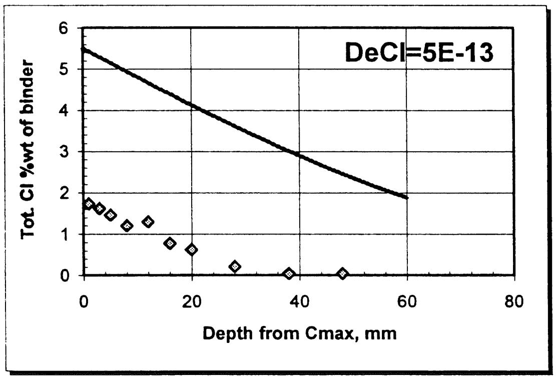


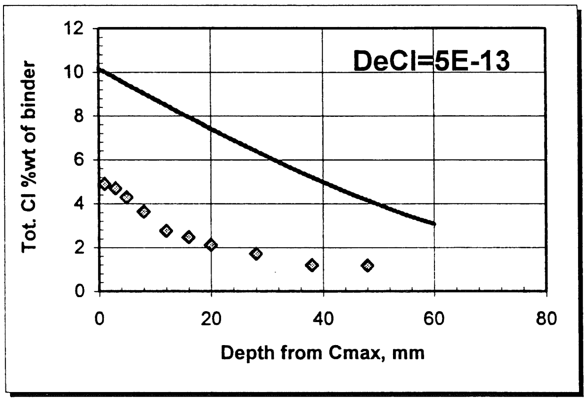


Ösplash 100 yrs DCl 50 % reduction, Cs = 10 %

Ösub 100 yrs DCl 50 % reduction, Cs = 10 %

C





Ösplash 100 yrs diffusion zone, extrapolation of trend

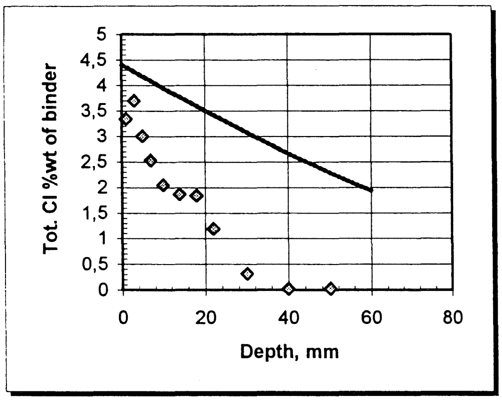
Ösub 100 yrs diffusion zone, extrapolation of trend

100 years prediction Ö SRPC w/c 0.40

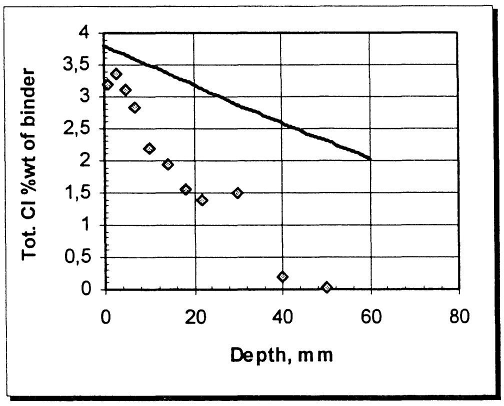
Appendix B. Prediction of total chloride profiles after 100 years of marine exposure.

Splash zone / Submerged zone

A

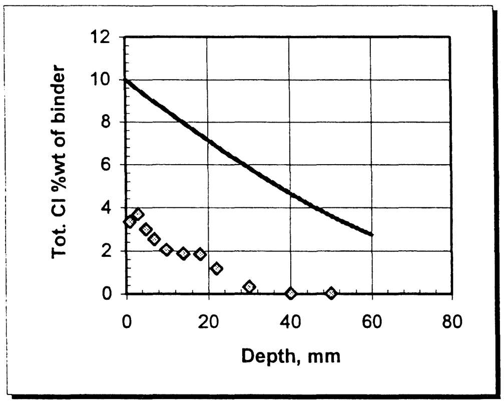


H3 splash 100 yrs no change DCl or Cs

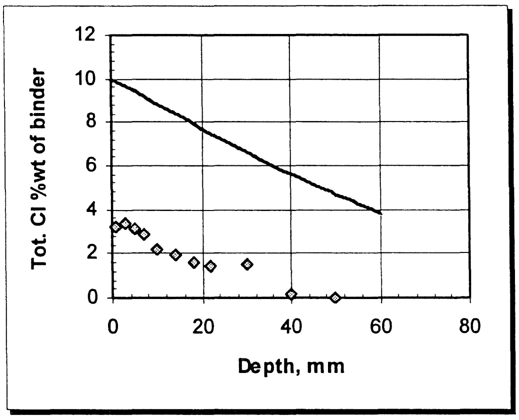


H3 sub 100 yrs no change DCl or Cs

B

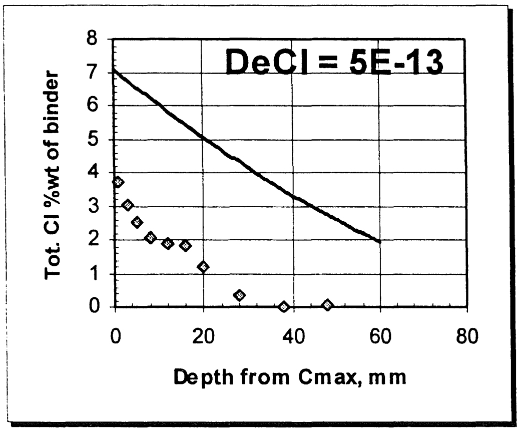


H3 splash 100 yrs DCl 50 % reduction, Cs = 10 %

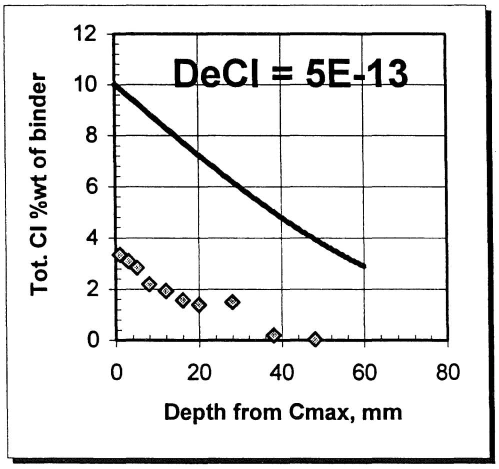


H3 sub 100 yrs DCl 50 % reduction, Cs = 10 %

C



H3 splash 100 yrs diffusion zone, extrapolation of trend



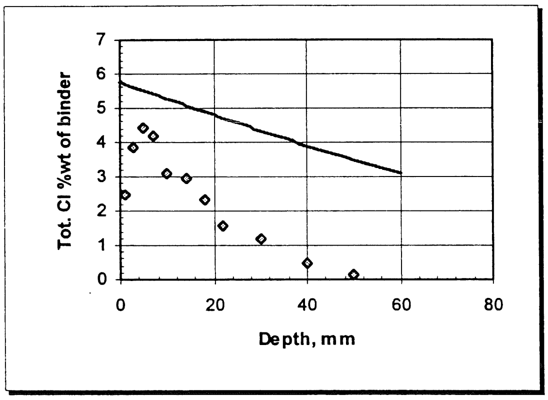
H3 sub 100 yrs diffusion zone, extrapolation of trend

100 years prediction H3 SRPC w/c 0.30

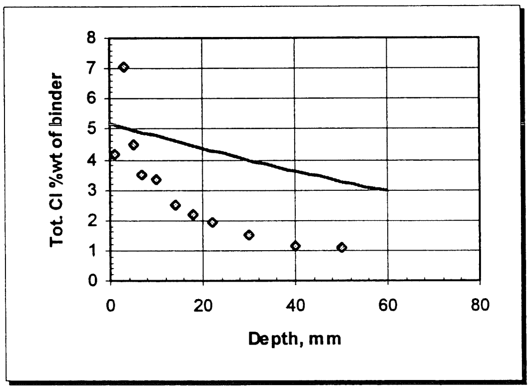
Appendix B. Prediction of total chloride profiles after 100 years of marine exposure.

Splash zone | **Submerged zone**

A

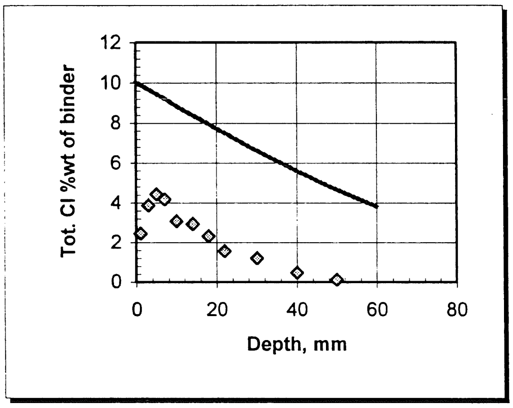


3-50 splash 100 yrs no change DCl or Cs

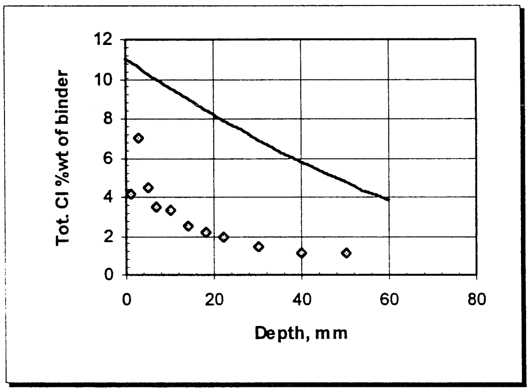


3-50 sub 100 yrs no change DCl or Cs

B

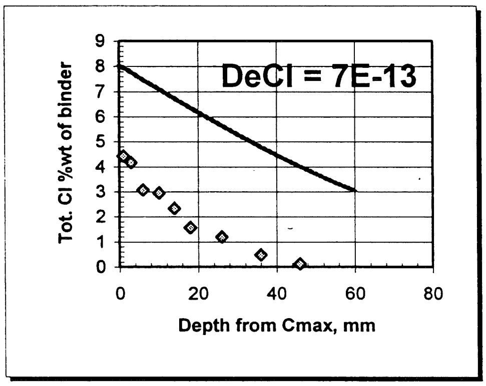


3-50 splash 100 yrs DCl 50 % reduction, Cs = 10 %

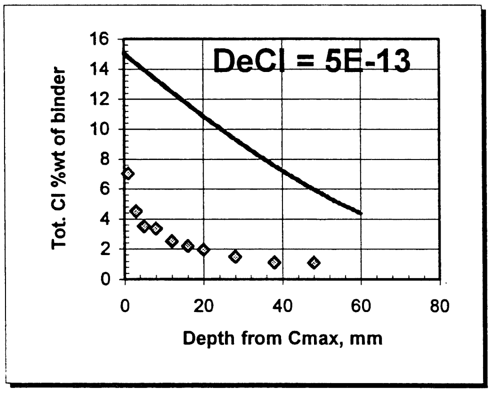


3-50 sub 100 yrs DCl 50 % reduction, Cs = 10 %

C



3-50 splash 100 yrs diffusion zone, extrapolation of trend



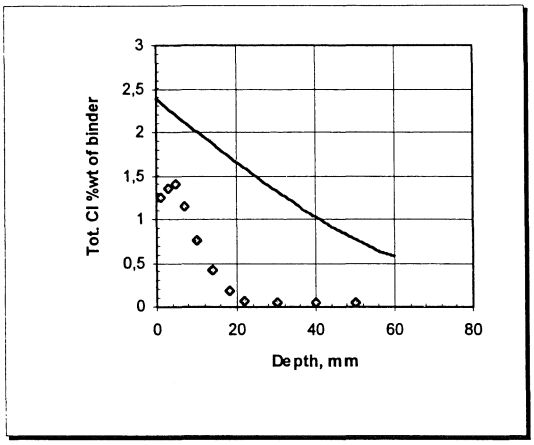
3-50 sub 100 yrs diffusion zone, extrapolation of trend

100 years prediction 3-50 SRPC 5% SF w/c 0.50

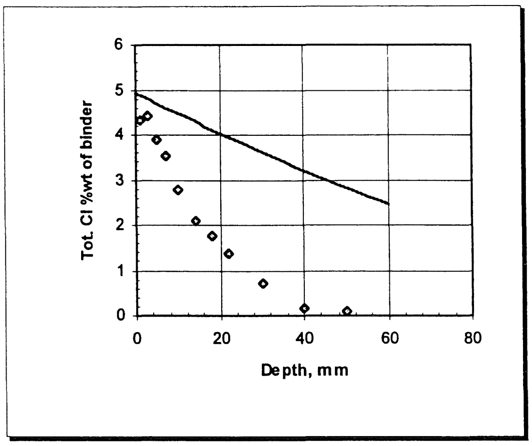
Appendix B. Prediction of total chloride profiles after 100 years of marine exposure.

Splash zone | Submerged zone

A

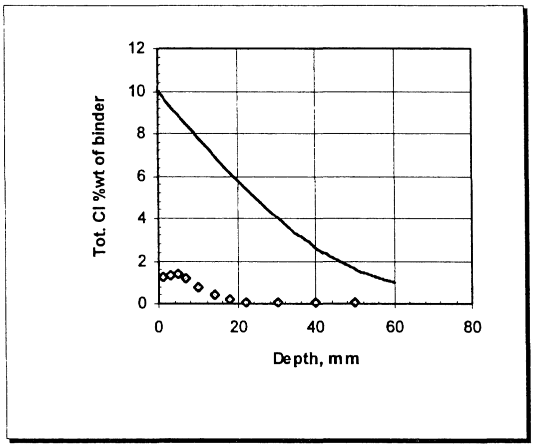


3-40 splash 100 yrs no change DCl or Cs

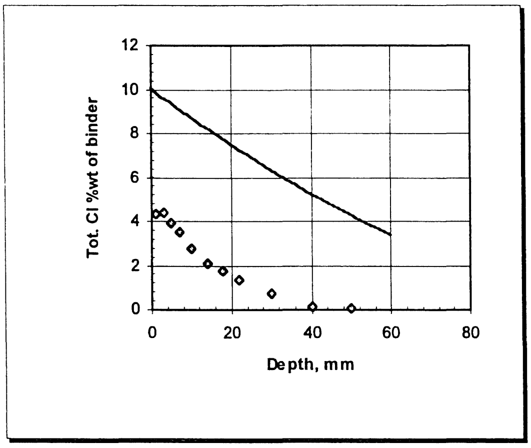


3-40 sub 100 yrs no change DCl or Cs

B

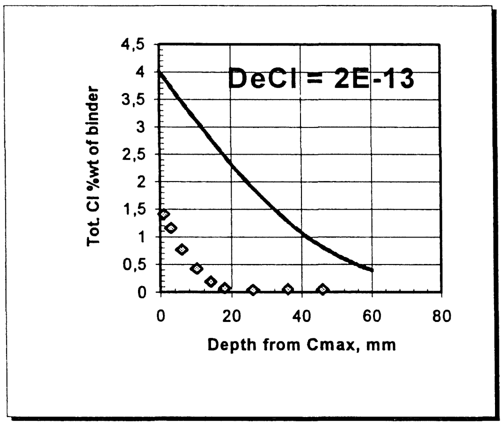


3-40 splash 100 yrs DCl 50 % reduction, Cs = 10 %

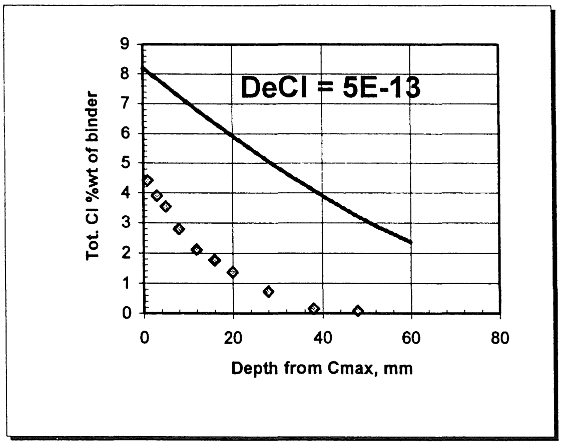


3-40 sub 100 yrs DCl 50 % reduction, Cs = 10 %

C



3-40 splash 100 yrs diffusion zone, extrapolation of trend



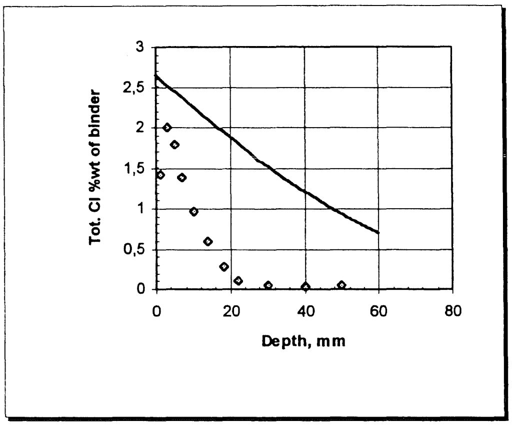
3-40 sub 100 yrs diffusion zone, extrapolation of trend

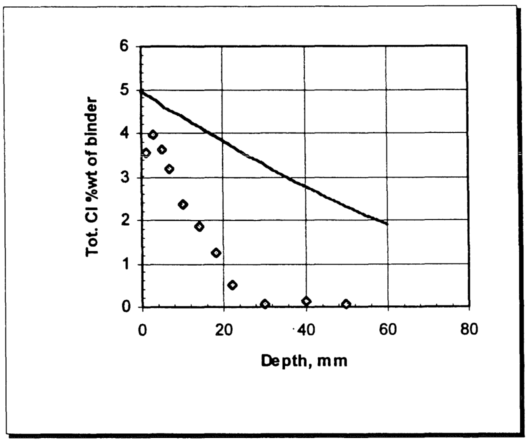
100 years prediction 3-40 SRPC 5% SF w/c 0.40

Appendix B. Prediction of total chloride profiles after 100 years of marine exposure.

	Splash zone	Submerged zone

A

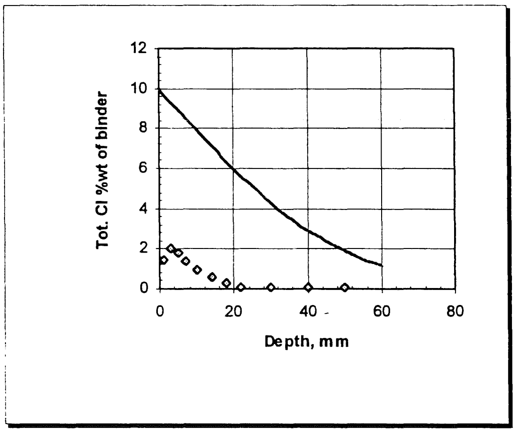


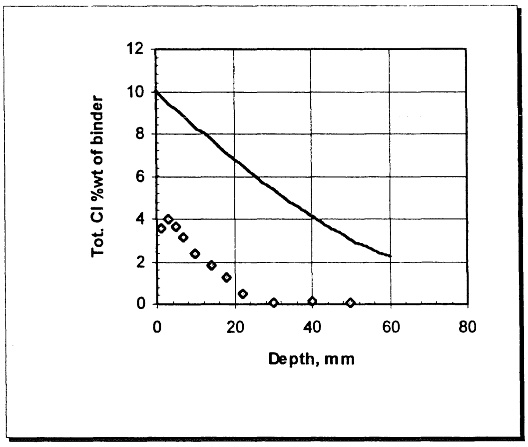


H4 splash 100 yrs no change DCl or Cs

H4 sub 100 yrs no change DCl or Cs

B

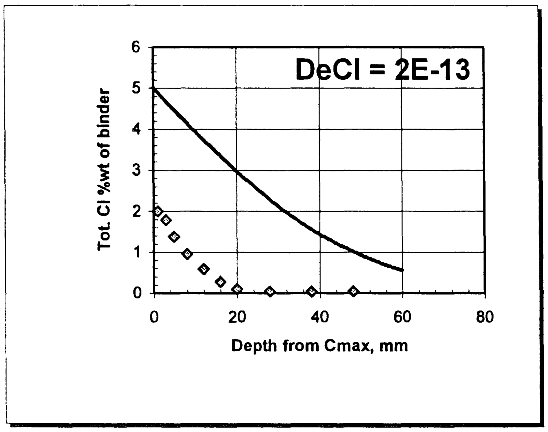


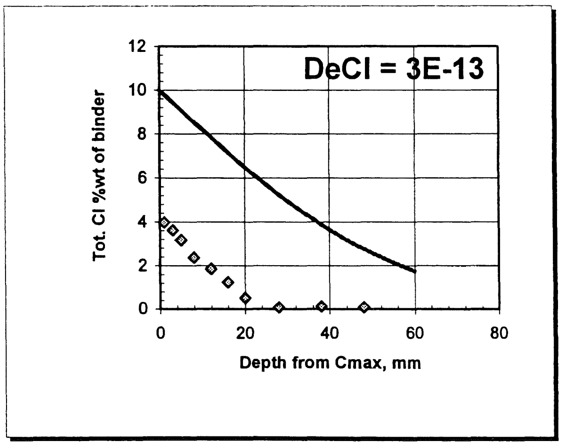


H4 splash 100 yrs DCl 50 % reduction, Cs = 10 %

H4 sub 100 yrs DCl 50 % reduction, Cs = 10 %

C





H4 splash 100 yrs diffusion zone, extrapolation of trend

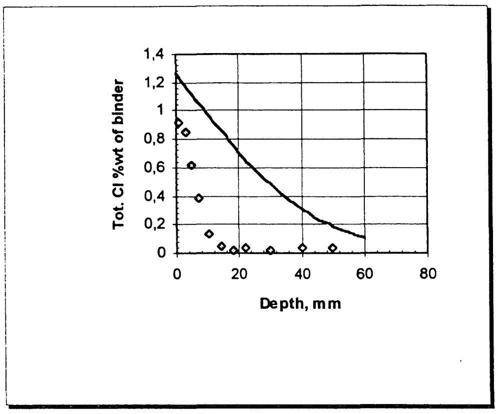
H4 sub 100 yrs diffusion zone, extrapolation of trend

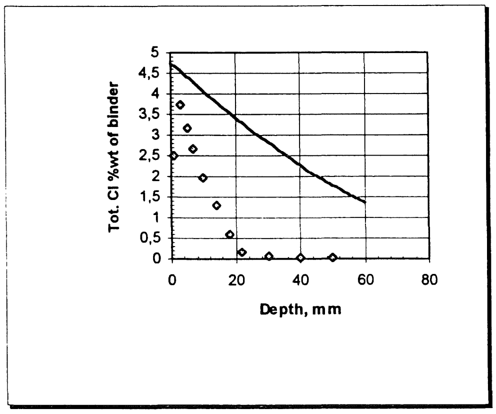
100 years prediction H4 SRPC 5% SF w/c 0.40

Appendix B. Prediction of total chloride profiles after 100 years of marine exposure.

Splash zone   Submerged zone

A

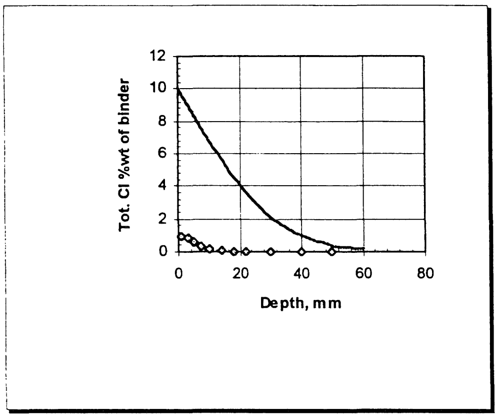


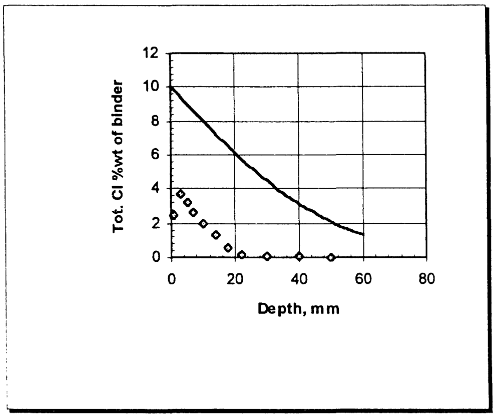


H1 splash 100 yrs no change DCl or Cs

H1 sub 100 yrs no change DCl or Cs

B

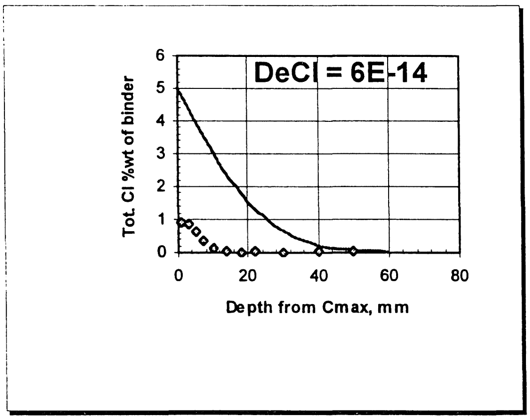


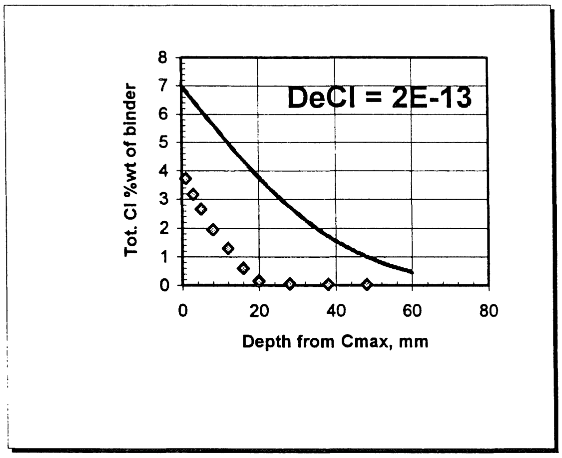


H1 splash 100 yrs DCl 50 % reduction, Cs = 10 %

H1 sub 100 yrs DCl 50 % reduction, Cs = 10 %

C



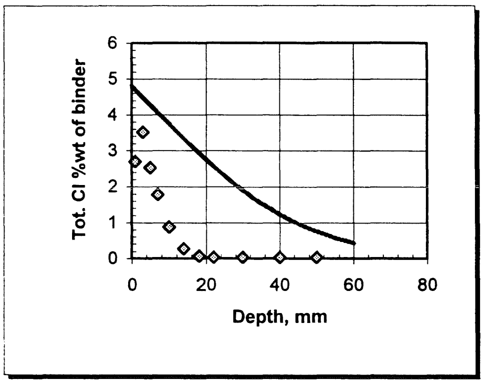
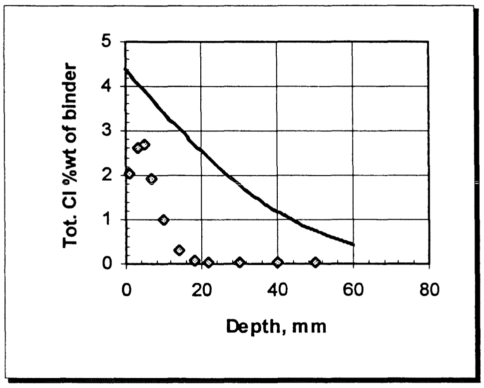
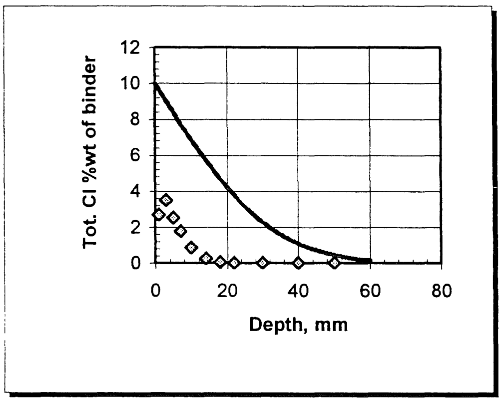
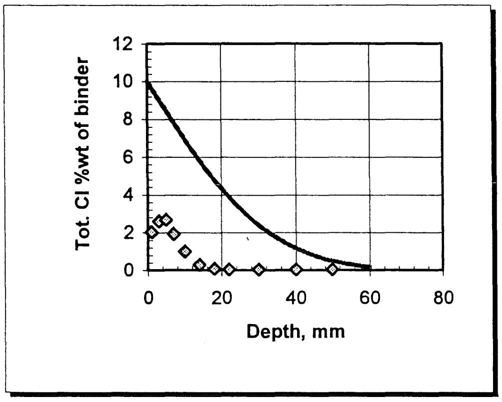
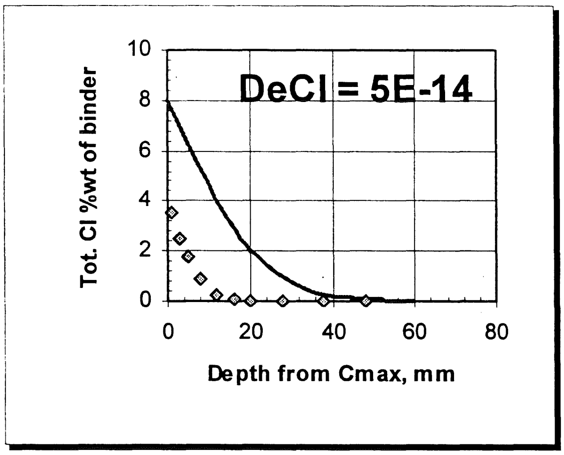
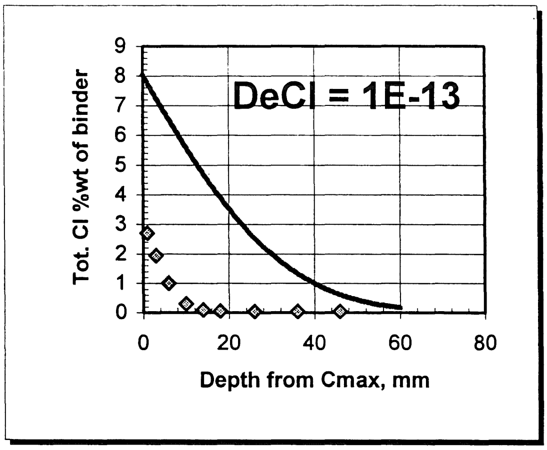


H1 splash 100 yrs diffusion zone, extrapolation of trend

H1 sub 100 yrs diffusion zone, extrapolation of trend

100 years prediction   H1   SRPC 5% SF w/c 0.30

Appendix B. Prediction of total chloride profiles after 100 years of marine exposure.

	Splash zone	Submerged zone
A		
	H5 splash 100 yrs no change DCl or Cs	H5 sub 100 yrs no change DCl or Cs
B		
	H5 splash 100 yrs DCl 50 % reduction, Cs = 10 %	H5 sub 100 yrs DCl 50 % reduction, Cs = 10 %
C		
	H5 splash 100 yrs diffusion zone, extrapolation of trend	H5 sub 100 yrs diffusion zone, extrapolation of trend

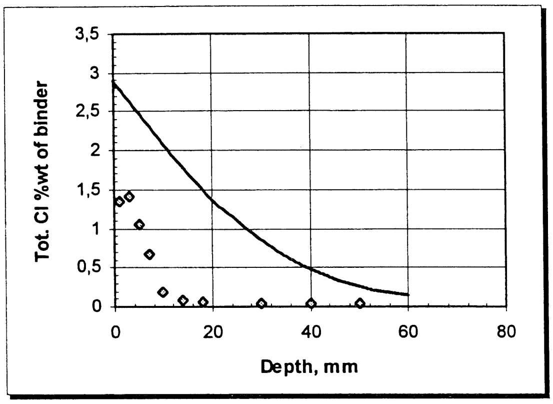
100 years prediction H5 SRPC 5% SF w/c 0.25

Appendix B. Prediction of total chloride profiles after 100 years of marine exposure.

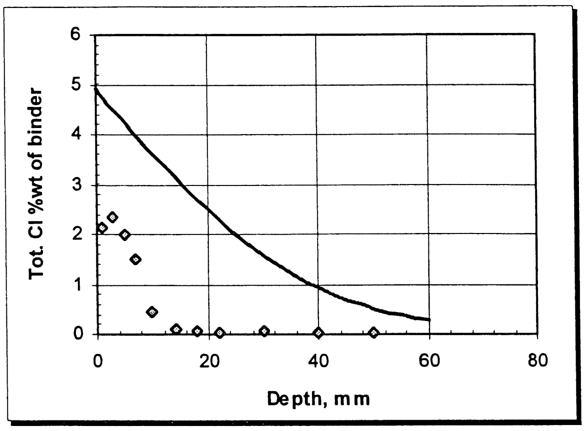
Splash zone

Submerged zone

A

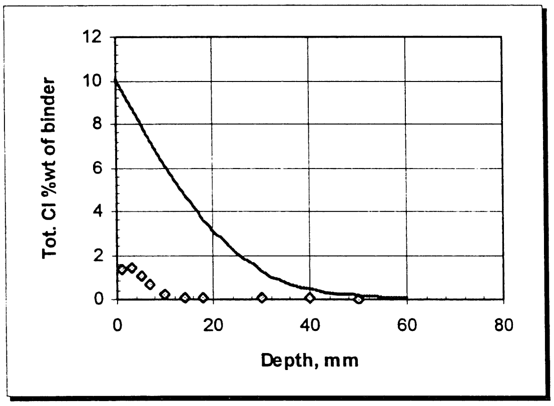


H2 splash 100 yrs no change DCl or Cs

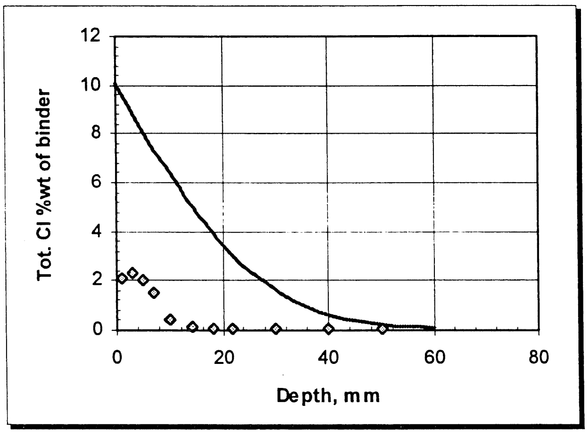


H2 sub 100 yrs no change DCl or Cs

B

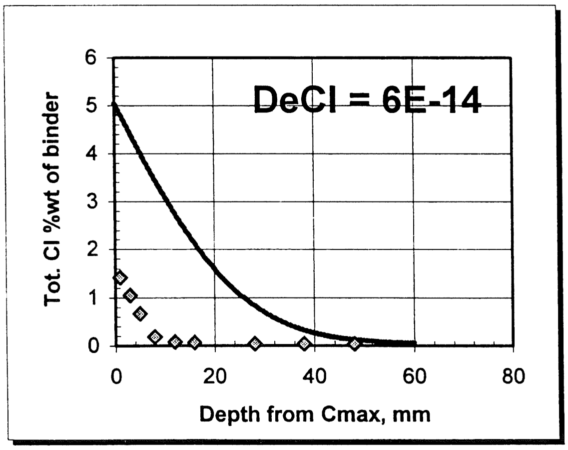


H2 splash 100 yrs DCl 50 % reduction, Cs = 10 %

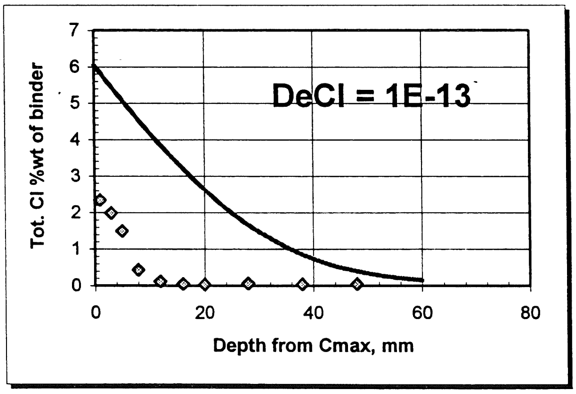


H2 sub 100 yrs DCl 50 % reduction, Cs = 10 %

C



H2 splash 100 yrs diffusion zone, extrapolation of trend



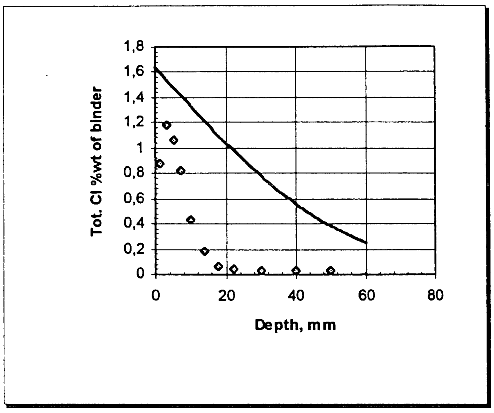
H2 sub 100 yrs diffusion zone, extrapolation of trend

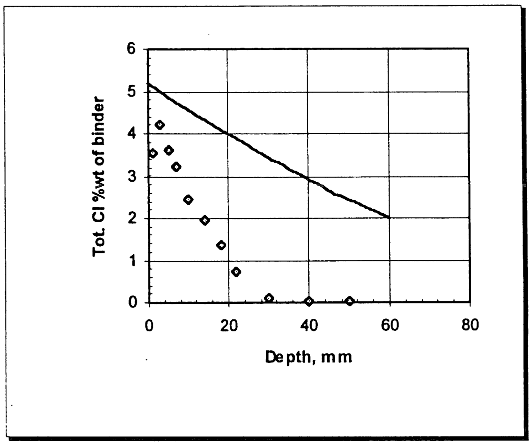
100 years prediction H2 SRPC 10% SF w/c 0.30

Appendix B. Prediction of total chloride profiles after 100 years of marine exposure.

Splash zone | **Submerged zone**

A

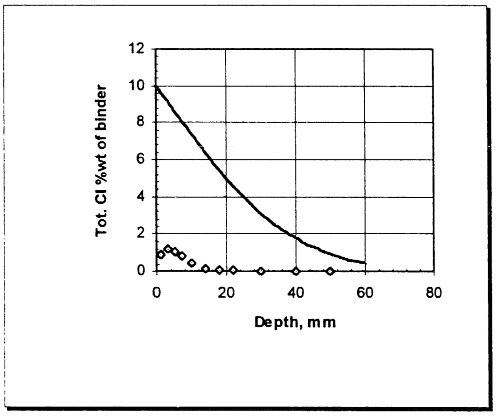


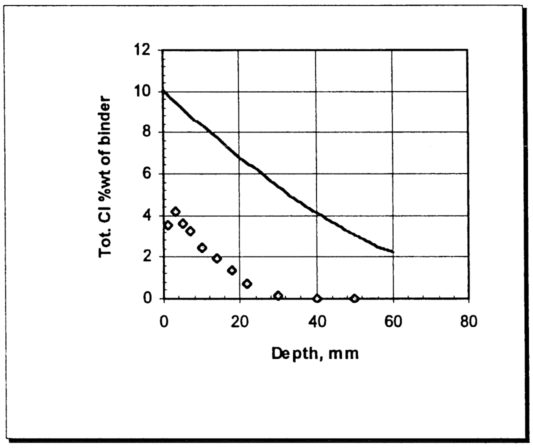


12-35 splash 100 yrs no change DCl or Cs

12-35 sub 100 yrs no change DCl or Cs

B

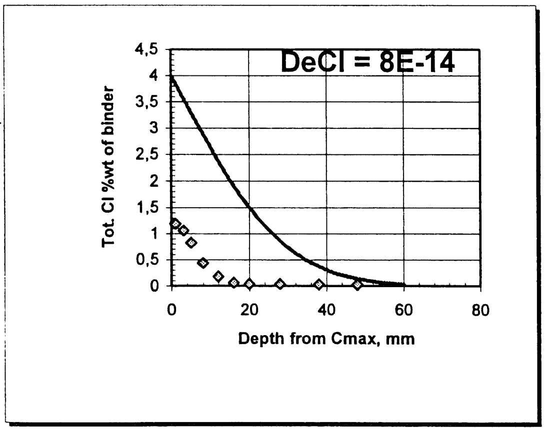


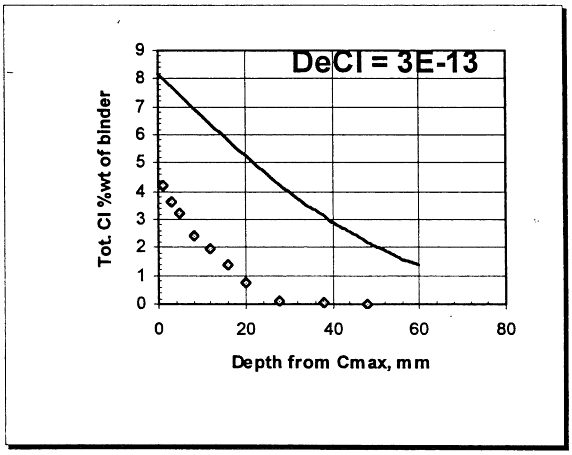


12-35 splash 100 yrs DCl 50 % reduction, Cs = 10 %

12-35 sub 100 yrs DCl 50 % reduction, Cs = 10 %

C





12-35splash 100yrs diffusion zone, extrapolation of trend

12-35sub 100yrs diffusion zone, extrapolation of trend

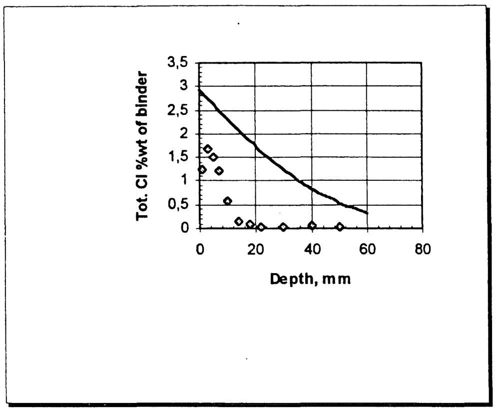
100 years prediction 12-35 SRPC 5%SF 10%FA w/c 0.35

Appendix B. Prediction of total chloride profiles after 100 years of marine exposure.

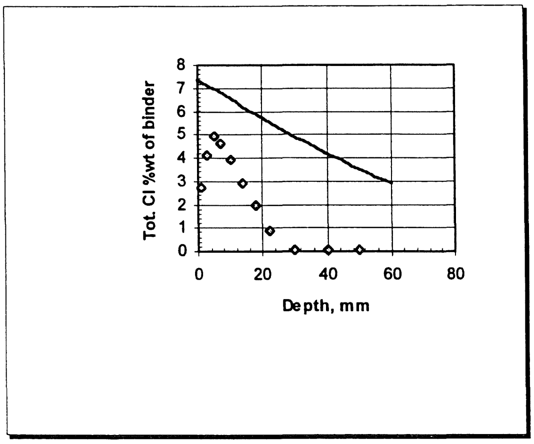
Splash zone

Submerged zone

A

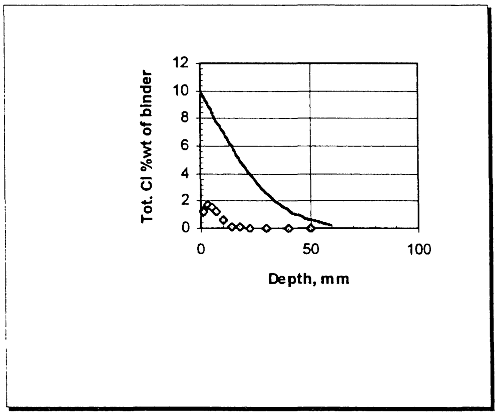


10-40 splash 100 yrs no change DCl or Cs

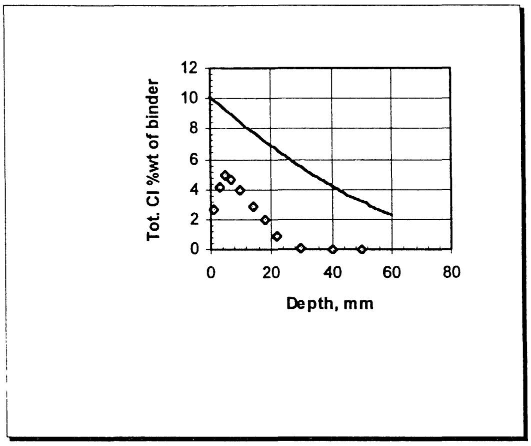


10-40 sub 100 yrs no change DCl or Cs

B

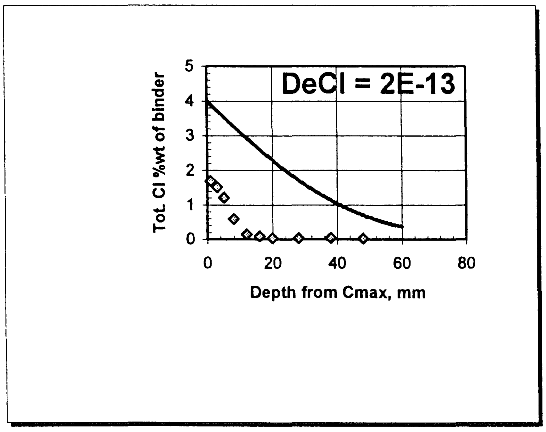


10-40 splash 100 yrs DCl 50 % reduction, Cs = 10 %

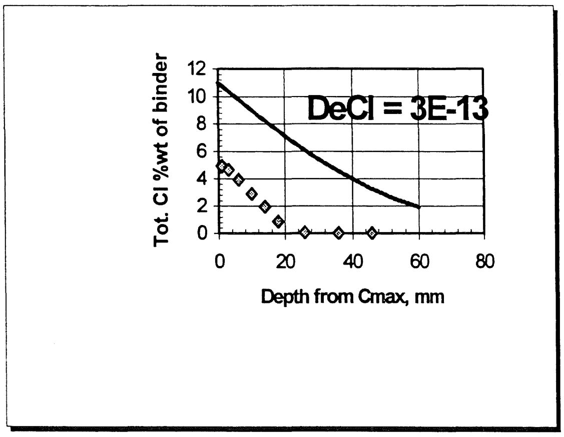


10-40 sub 100 yrs DCl 50 % reduction, Cs = 10 %

C



10-40splash 100yrs diffusion zone, extrapolation of trend



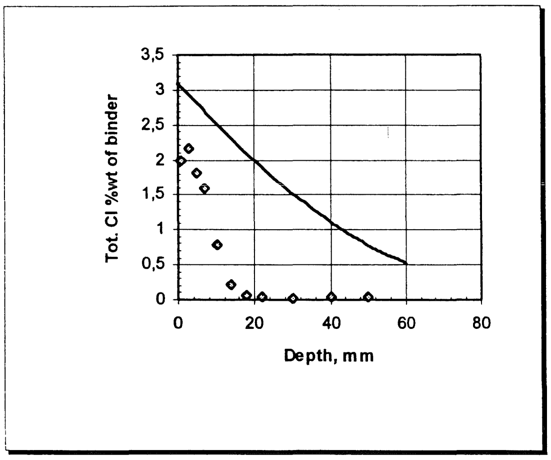
10-40sub 100yrs diffusion zone, extrapolation of trend

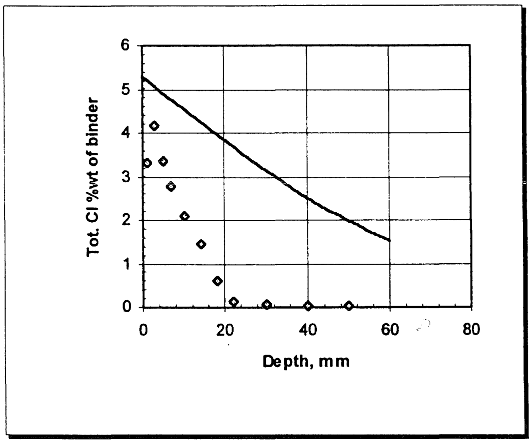
100 years prediction 10-40 SRPC 5%SF 17%FA w/c 0.40

Appendix B. Prediction of total chloride profiles after 100 years of marine exposure.

Splash zone | **Submerged zone**

A

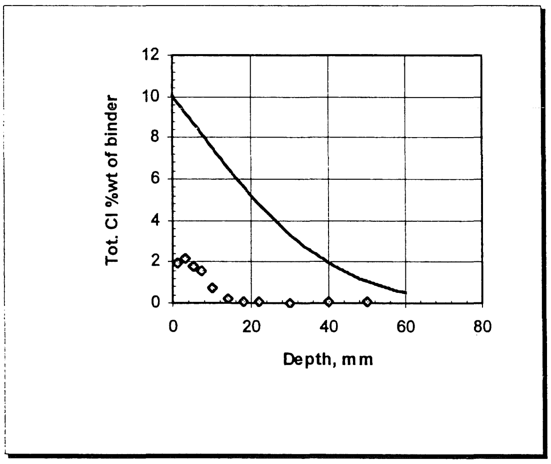


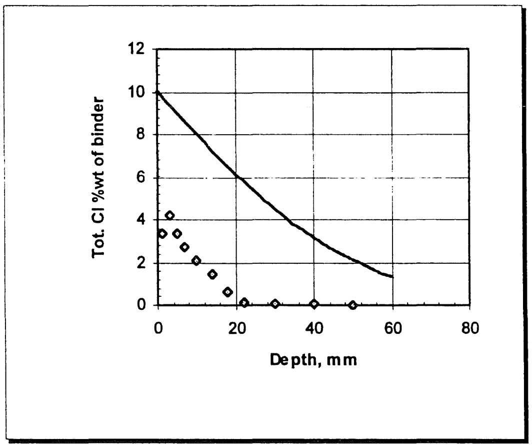


H8 splash 100 yrs no change DCl or Cs

H8 sub 100 yrs no change DCl or Cs

B

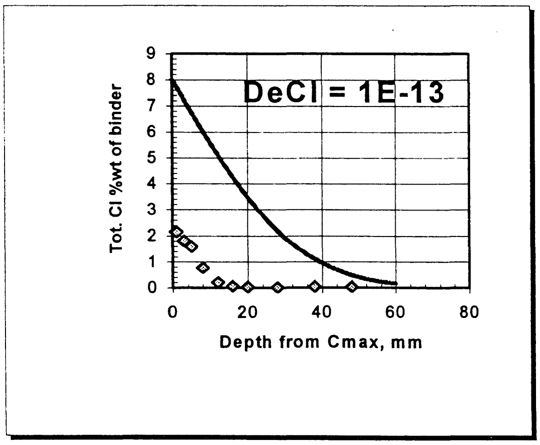


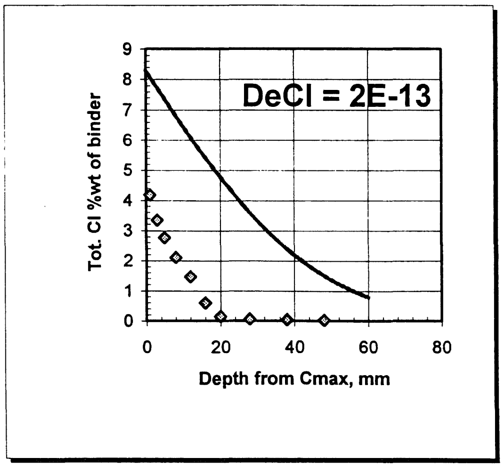


H8 splash 100 yrs DCl 50 % reduction, Cs = 10 %

H8 sub 100 yrs DCl 50 % reduction, Cs = 10 %

C





H8 splash 100 yrs diffusion zone, extrapolation of trend

H8 sub 100 yrs diffusion zone, extrapolation of trend

100 years prediction H8 SRPC 20% FA w/c 0.30

Appendix B. Prediction of total chloride profiles after 100 years of marine exposure.