



Langtidsholdbarhed af beton i marint miljø:
Undersøgelse af danske broer

1. Prøveudtagning
2. Chloridindtrængning
3. Mikroskopi og SEM-EDX



Undersøgelsesfartøj



Kerneudboring onder vand



Udtagne betonkerner

Prøve-numre	Bro	Byggeår	Kote [m]	Udtagnings-dato	Ekspone-ringstid	Bindertype
V1-V4	Vejlefjordbroen	1975-1980	-1,0	18-01-2012	Ca. 34 år	Slaggecement (Aquafirm) fra Tyskland
A1-A4	Alssundbroen	1978-1981	-1,5	17-01-2012	Ca. 31 år	A/L/S-cement fra AaP
F1-F4	Farøbroen	1980-1985	-1,5	03-02-2012	Ca. 30 år	Lavalkali-cement fra AaP + 23% FA fra Danaske
28J-30J	Øresundsbroen	1993-2000	-2,0	08-10-2010	Ca. 12 år	Lavalkali-cement fra Cementa + 4% MS fra Elkem



Kerner fra Vejlefjordbroen



Kerner fra Alssundbroen



Kerner fra Farøbroen

Chloridanalyser

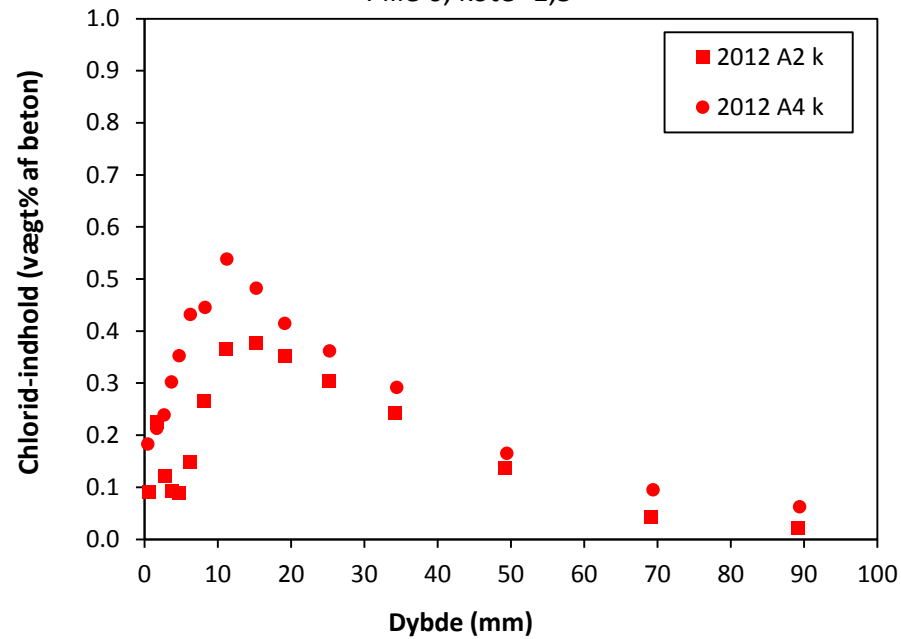


Alssundbroen - chloridprofiler

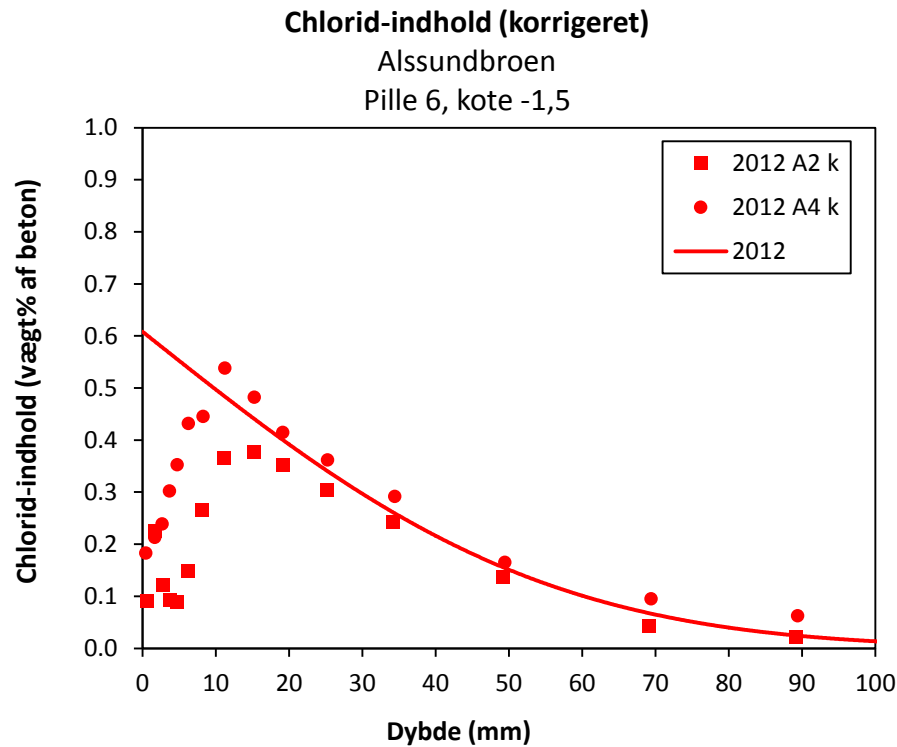
Chlorid-indhold (korrigeret)

Alssundbroen

Pille 6, kote -1,5



Alssundbroen - chloridindtrængningsparametre



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

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

År

2012

Enhed

Exp.tid

31

år

D_a

0,95

$\times 10^{-12} \text{ m}^2/\text{s}$

C_s

0,608

vægt% Cl af BE

C_i

0,001

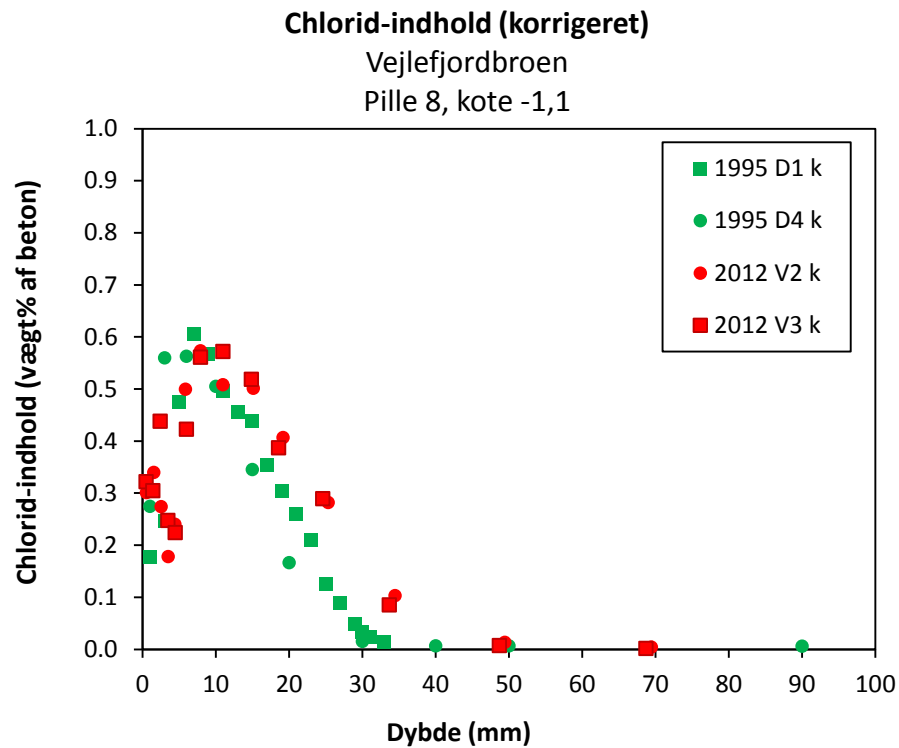
vægt% Cl af BE

$K_{0,05}$

13,5

$\text{mm}/\text{år}^{1/2}$

Vejlefjordbroen - chloridprofiler

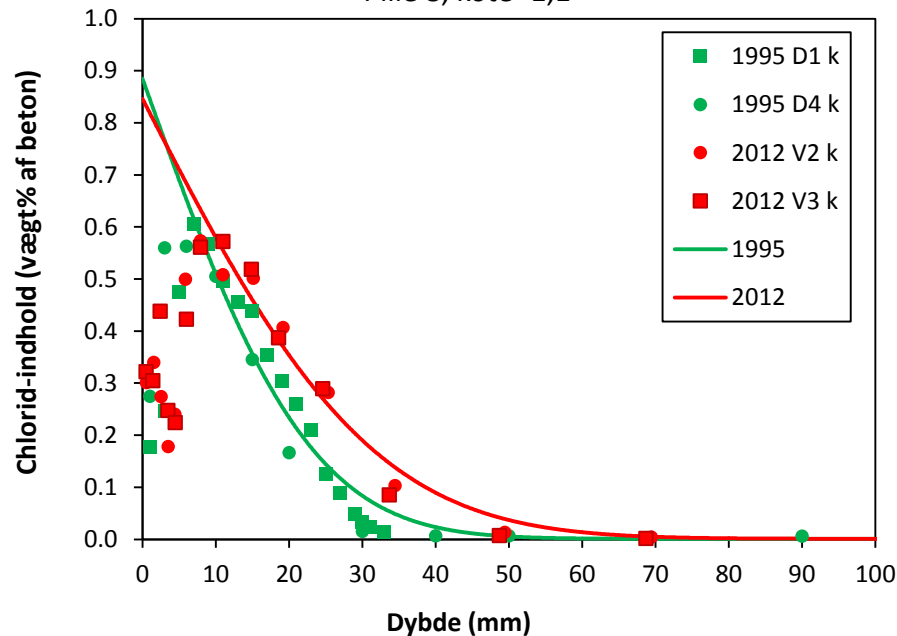


Vejlefjordbroen - chloridindtrængningsparametre

Chlorid-indhold (korrigeret)

Vejlefjordbroen

Pille 8, kote -1,1

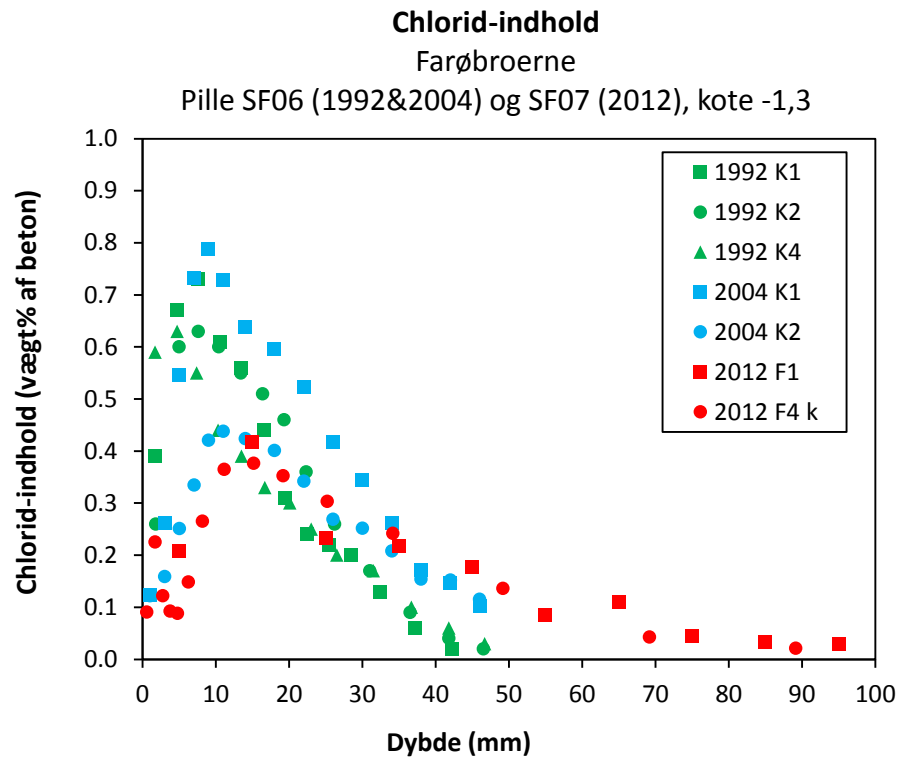


$$C(x, t) = C_s - (C_s - C_i) \cdot \operatorname{erf}\left(\frac{x}{\sqrt{4 \cdot D_a \cdot t}}\right)$$

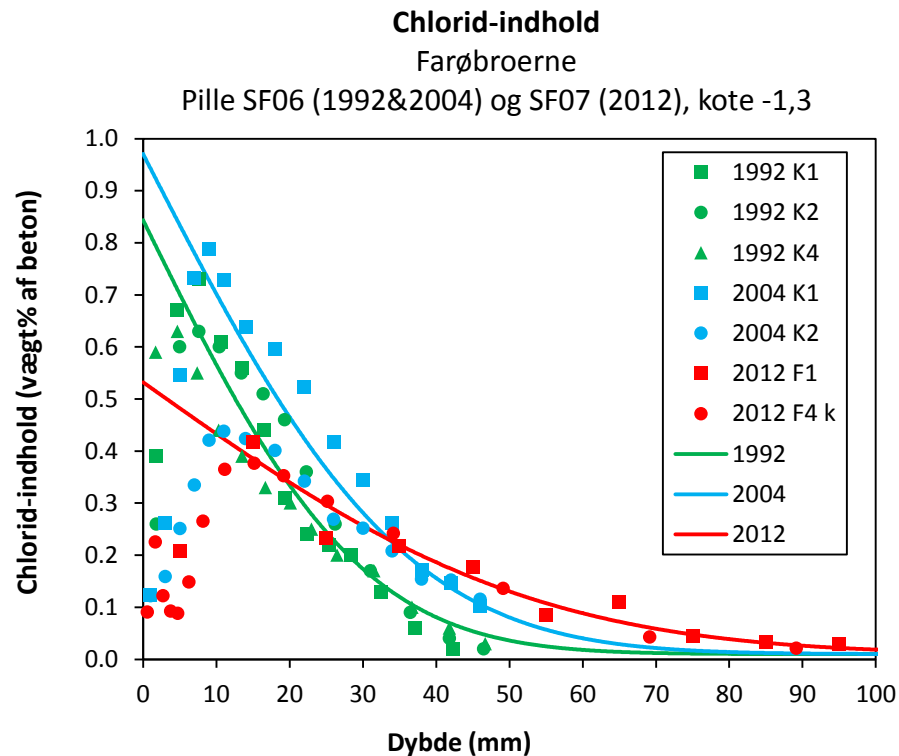
$$K_{0,05} = 2\sqrt{D_a} \cdot \operatorname{erf}^{-1}\left(\frac{C_s - 0,05}{C_s - C_i}\right)$$

År	1995	2012	Enhed
Exp.tid	17	34	år
D_a	0,30	0,28	$\times 10^{-12} \text{ m}^2/\text{s}$
C_s	0,885	0,846	vægt% Cl af BE
C_i	0,001	0,001	vægt% Cl af BE
$K_{0,05}$	8,3	8,0	$\text{mm}/\text{år}^{1/2}$

Farøbroen - chloridprofiler



Farøbroen - chloridindtrængningsparametre

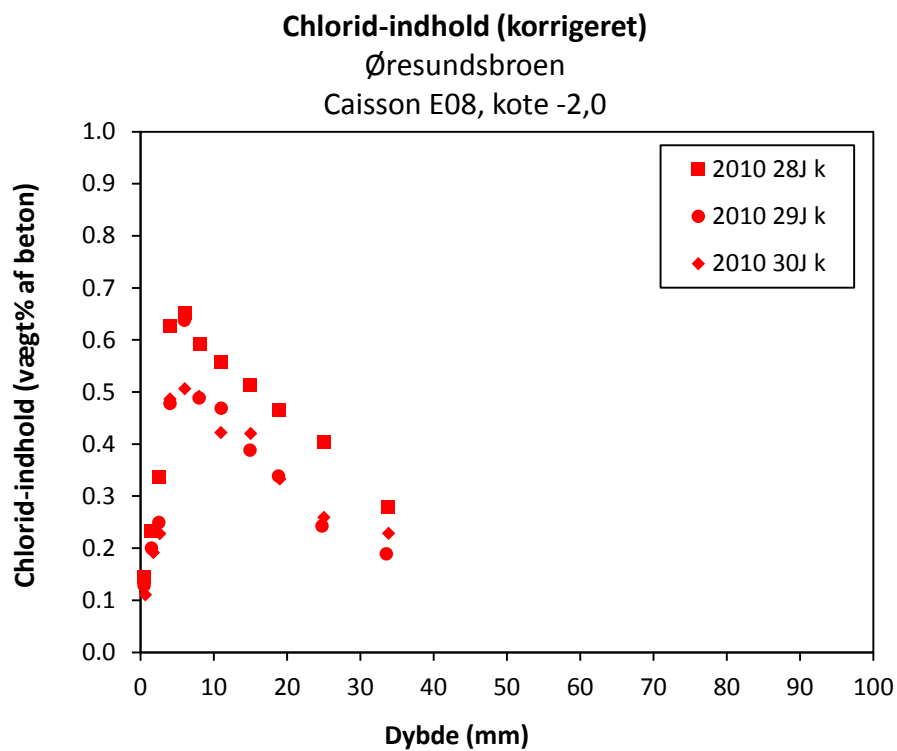


$$C(x, t) = C_s - (C_s - C_i) \cdot \operatorname{erf}\left(\frac{x}{\sqrt{4 \cdot D_a \cdot t}}\right)$$

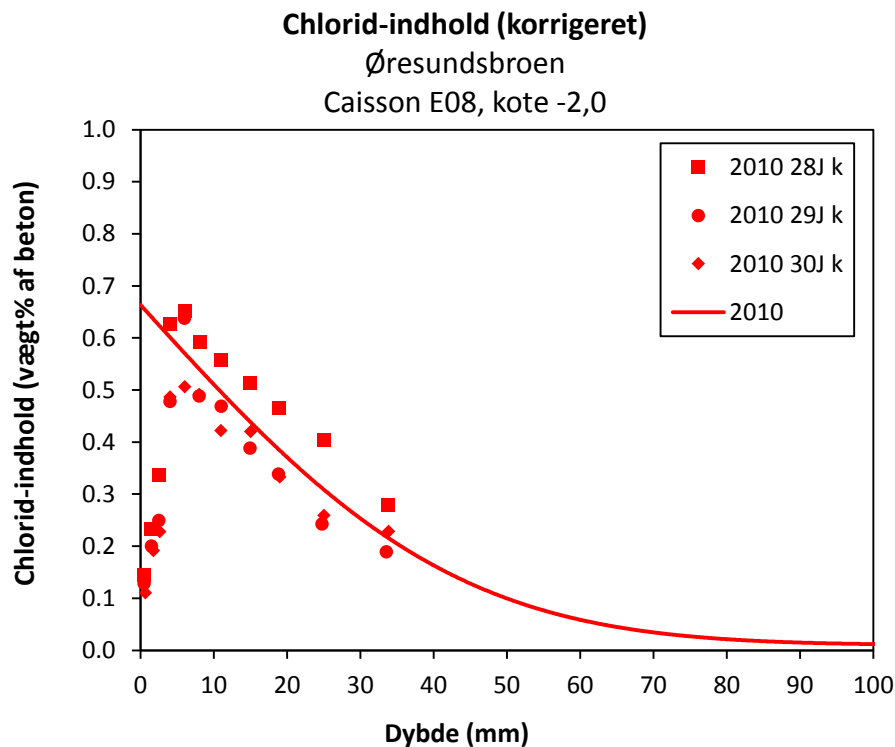
$$K_{0,05} = 2\sqrt{D_a} \cdot \operatorname{erf}^{-1}\left(\frac{C_s - 0,05}{C_s - C_i}\right)$$

År	1992	2004	2012	Enhed
Exp.tid	10,7	22,4	30	år
D_a	0,80	0,55	0,92	$\times 10^{-12} \text{ m}^2/\text{s}$
C_s	0,844	0,971	0,532	vægt% Cl af BE
C_i	0,010	0,010	0,010	vægt% Cl af BE
$K_{0,05}$	14,0	12,0	13,5	$\text{mm}/\text{år}^{1/2}$

Øresundsbroen - chloridprofiler



Øresundsbroen - chloridindtrængningsparametre



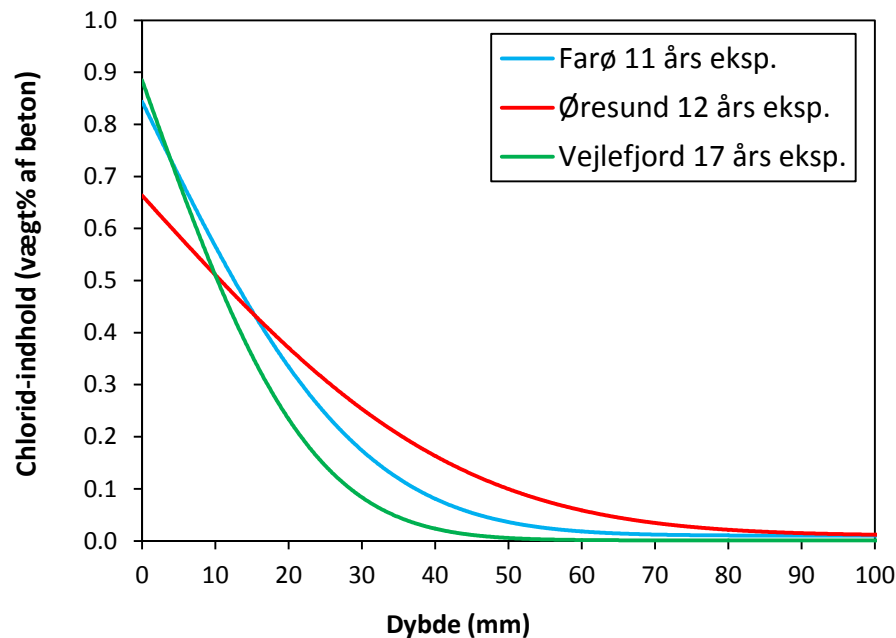
$$C(x, t) = C_s - (C_s - C_i) \cdot \operatorname{erf}\left(\frac{x}{\sqrt{4 \cdot D_a \cdot t}}\right)$$

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

År	2010	Enhed
Exp.tid	12	år
D_a	1,50	$\times 10^{-12} \text{ m}^2/\text{s}$
C_s	0,663	vægt% Cl af BE
C_i	0,010	vægt% Cl af BE
$K_{0,05}$	18,2	$\text{mm}/\text{år}^{1/2}$

Chloridindtrængning efter 11-17 år – 3 broer

Chloridprofiler
3 broer, kote -1 til -2



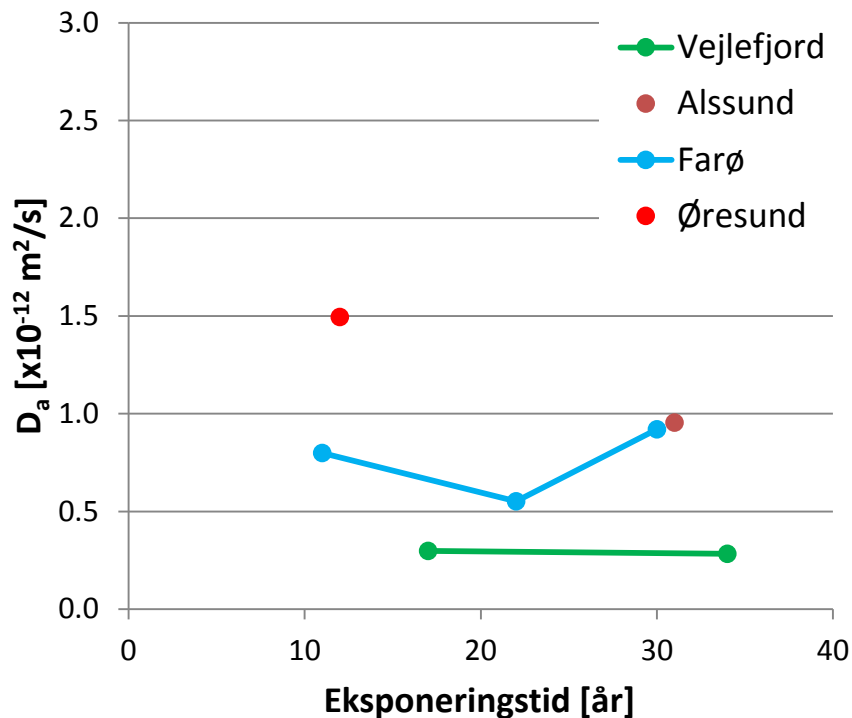
$$C(x, t) = C_s - (C_s - C_i) \cdot \operatorname{erf}\left(\frac{x}{\sqrt{4 \cdot D_a \cdot t}}\right)$$

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

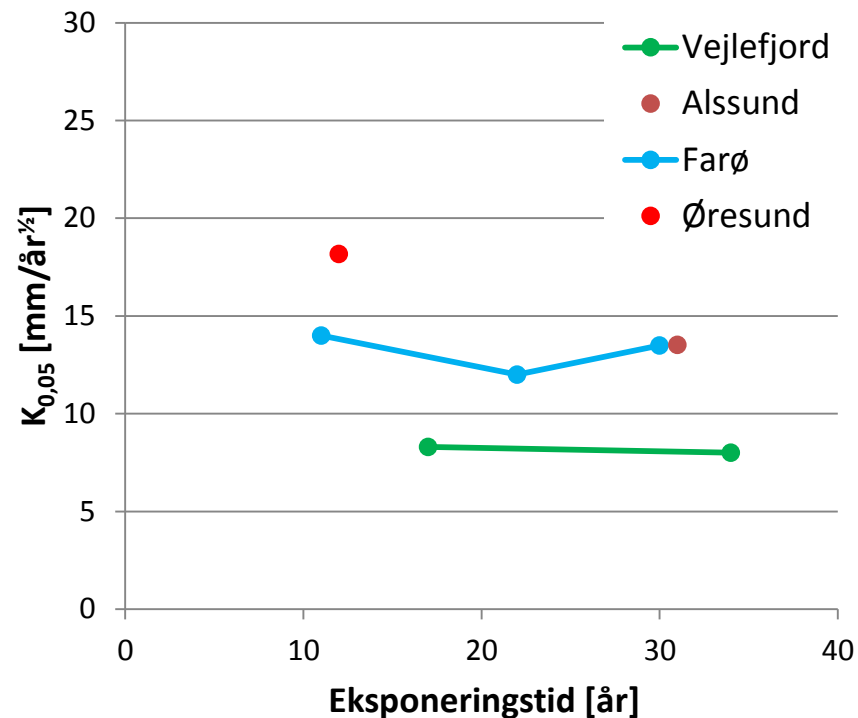
	Farø	Øresund	Vejlefjord	Enhed
Exp.tid	11	12	17	år
D _a	0,80	1,50	0,30	x10 ⁻¹² m ² /s
C _s	0,844	0,663	0,885	vægt% Cl af BE
C _i	0,010	0,010	0,001	vægt% Cl af BE
K _{0,05}	14,0	18,2	8,3	mm/år ^½

Chloridindtrængningsparametre – 4 broer

Diffusionskoefficienten D_a



Indtrængningsparameteren $K_{0,05}$



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

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

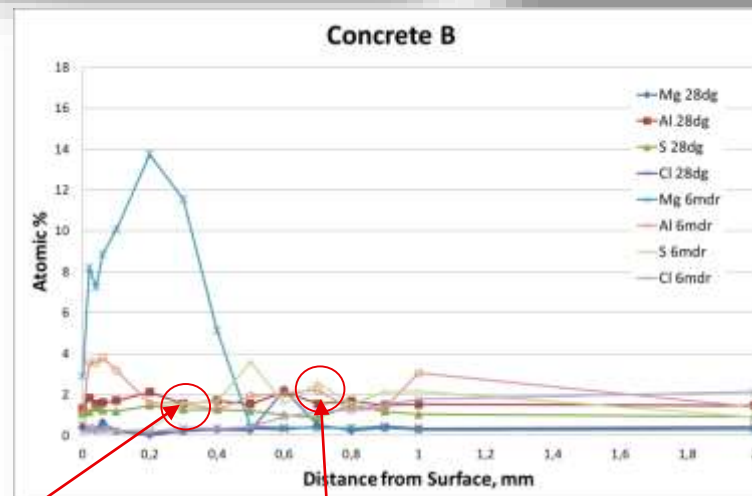
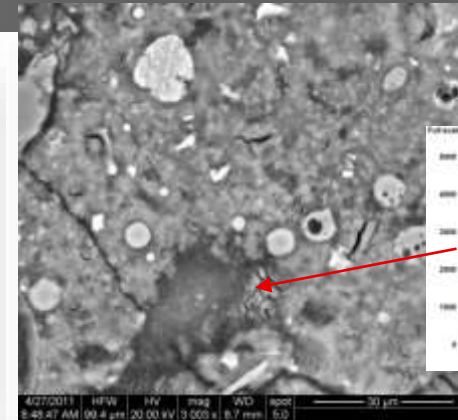
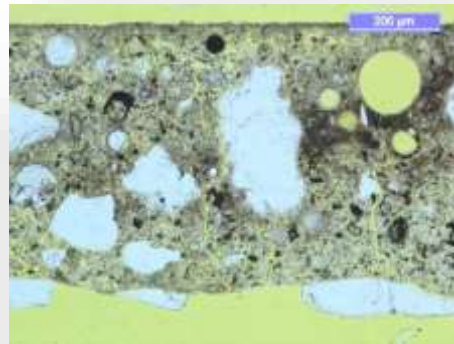
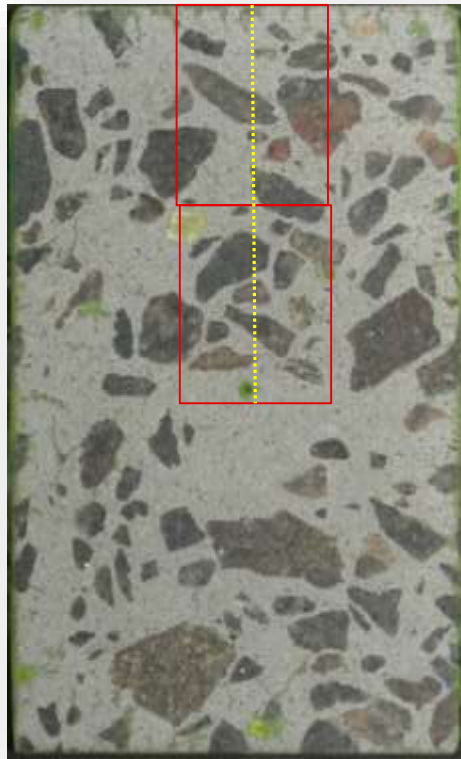
Der ses ikke en tidsafhængig diffusionskoefficient som f.eks.

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

i de to tilfælde, hvor der efter de første 10 års eksponering er målt til mere en 1 termin



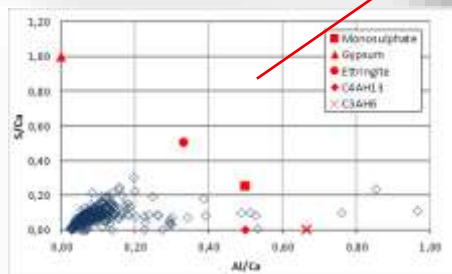
Mikroskopi og SEM-EDX



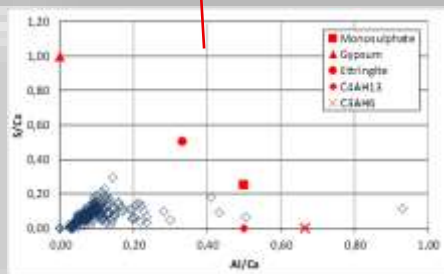
Macro-analysis: Crack pattern, homogeneity...

Micro-analysis - OPM: Paste porosity, leaching, carbonation, precipitates, micro-cracks ...

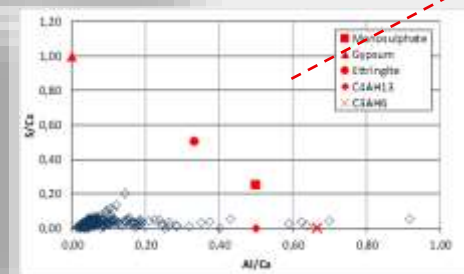
SEM-EDX: Structural analysis, chemical trends, phase identification, phase analysis ...



Depth: 0,3mm



Depth: 0,7mm



Depth: 23mm

Fremgangsmåde ved SEM-EDX-målingerne

- I hvert dybdeniveau udføres 300 punktanalyser, som er fordelt over 3 analysefelter (fig. 1), som hver består af 10x10 punkter fordelt over et areal svarende til billedarealet ved ca. 1500x forstørrelse (fig. 2).
- De tre felter fordeles på tværs af prøven, og placeres så vidt muligt uden om tilslag og luftporer.

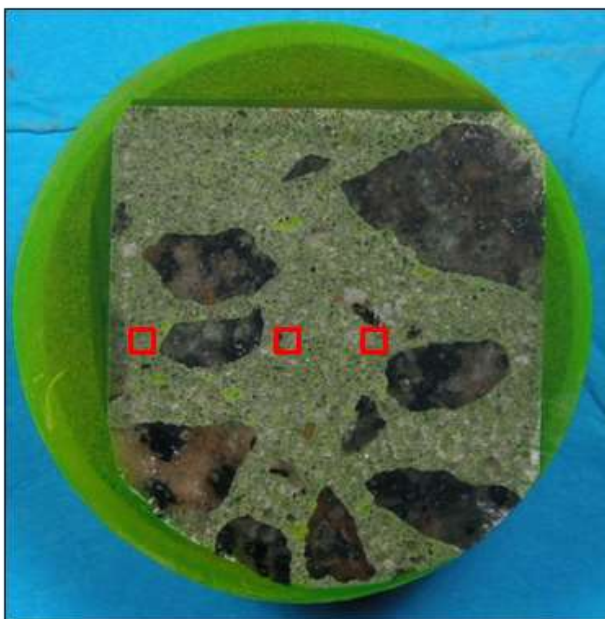


Fig. 1: Eksempel på fordeling af de 3 analysefelter i et bestemt niveau

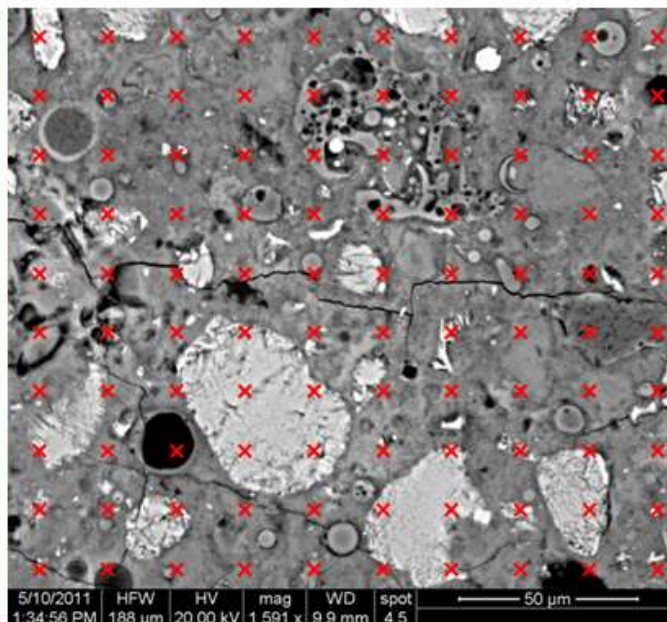


Fig. 2: Eksempel på et analysefelt, som består af 10x10 punkter.

Bro	Bygget	Udtagningsdato	Udtagningssted	Kote/Niveau	Prøvenr.	Cement	Tyndslib		Polerprøve		Chlorid	
						Type	Top	Bund	Top	Bund	Dybde	Mass%
Gl Lillebælt	1929-35	sep-10	Pille 3 vandfyldt celle 17	Gulv	Niras 640	PC	-	-	0-45	100-140	0-30	0,29
Gl Lillebælt	1929-35	dec-10	Pille 3 vandfyldt celle 19	4	Niras 607	PC	-	-	-	50-100	0-30	0,42
Gl Lillebælt	1929-35	dec-10	Pille 3 vandfyldt celle 19	4	Niras 608	PC	-	-	-	40-75	0-30	0,40
Gl Lillebælt	1929-35	dec-10	Pille 3 vandfyldt celle 18	4	Niras 626	PC	-	-	0-45	-	0-30	0,35
Gl Lillebælt	1929-35	dec-10	Pille 3 vandfyldt celle 18	4	Niras 627	PC	-	-	0-45	45-90	0-30	0,41
Gl Lillebælt	1929-35	dec-10	Pille 3 vandfyldt celle 18	4	Niras 628	PC	-	-	0-45	-	0-30	0,41
Gl Lillebælt	1929-35	dec-10	Pille 3 vandfyldt celle 18	4	Niras 629	PC	-	-	-	30-75	0-30	0,41
Vejlefjord	1975-80	okt-96	Pille 8, sydside	+35	Niras 681-1	PC	x	x	-	-		
Vejlefjord	1975-80	okt-96	Pille 8, sydside	-149	Niras 681-3	Slagge	x	x	-	-		
Vejlefjord	1975-80	okt-96	Pille 8, sydside	-265	Niras 681-4	Slagge	x	x	-	-		
Vejlefjord	1975-80	dec-95	Pille 13, vestside	+1,3m	Niras 660-1 (4)	Slagge	x	x	-	-		
Vejlefjord	1975-80	dec-95	Pille 13, vestside	+1,4m	Niras 660-2 (15)	Slagge	x	x	-	-		
Gl Lillebælt	1929-35	okt-11	Pille 4, vandfyldt celle 20-22	4V_05	LB-1	PC	-	-			0-200	
Gl Lillebælt	1929-35	okt-11	Pille 4, vandfyldt celle 17-19	4V_06	LB-2	PC	A,B	C	A,B	C	-	
Gl Lillebælt	1929-35	okt-11	Pille 4, tør, celle 18	4T-01	LB-3	PC	A,B	C	A,B	C	-	
Gl Lillebælt	1929-35	okt-11	Pille 4, tør, celle 17	4T-02	LB-4	PC	A	C	A	C	0-200	
Gl Lillebælt	1929-35	okt-11	Pille 4, tør, celle 1-2	4T_03	LB-5	PC	A,B	C	A,B	C	-	
Gl Lillebælt	1929-35	okt-11	Pille 4, tør, celle 3-1	4T_04	LB-6	PC	A	-	A	-	0-200	
Gl Lillebælt	1929-35	okt-11	Pille 4, vandfyldt celle 5	4V_03	LB-7	PC	-	C	-	C	0-200	
Gl Lillebælt	1929-35	okt-11	Pille 4, vandfyldt celle 5	4V_04	LB-8	PC	A,B	C	A,B	C	-	
Gl Lillebælt	1929-35	okt-11	Pille 4, tør	1	LB-9	PC	A	-	A	-	10-12, 20-22, 36-38	
Alssundbroen	1978-81	jan-12	Piller, under vand	-1,5m	A3	PC (LavAlk)	A	-	A,B	-		
Vejlefjordbroen	1975-80	jan-12	Piller, under vand	-1m	V1	Slagge, lav CH	A	-	A,B	-		
Farøbroen	1980-85	feb-12	Piller, under vand	-1,5m	F3	PC (LavAlk)+23%FA	A	-	A,B	-		
Stormstrømsbroen	1933-37	jan-12	Piller, under vand	-7.3 til -7.5	Rambøll 7UV	PC, 1:2:3			0-45			
Stormstrømsbroen	1933-37	jan-12	Piller, under vand	-6.1 til -6.7	Rambøll 12UV V	PC, 1:2:3			0-45			
Stormstrømsbroen	1933-37	jan-12	Piller, under vand	-1.1	Rambøll 33UV top	PC, 1:2:3			0-45			
Øresundsbroen	1998 (juli)	nov-10	Pille, over vand		F16 (7090)	SE lavAlk+MS			A			
Øresundsbroen	1998 (juli)	nov-10	Pille, over vand		F17 (7090)	SE lavAlk+MS			A			
Øresundsbroen	1997 (nov)	nov-10	Pille, over vand		H23 (7090)	SE lavAlk+MS			A			
Øresundsbroen	1997 (juli)	nov-10	Pille, under vand	-2m	J28 (7090)	SE lavAlk+MS			A			

Young concrete: Femern trial concrete (28 maturity age, 6 & 24 months)

- A Portland low alkali sulfate resistant cement (CEM I 42,5 N) w/c=0.40.
- B CEM I 42,5 N with 15% fly ash, w/c=0.40.
- C CEM I 42,5 N with 25% fly ash, w/c=0.40.
- D CEM I 42,5 N with 25% fly ash, SCC, w/c=0.40.
- E CEM I 42,5 N with 4% silica fume, w/c=0.40.
- F CEM I 42,5 N with 12% fly ash and 4% silica fume, w/c=0.40.
- G CEM I 42,5 N with 12% fly ash and 4% silica fume, no air entrainment, w/c=0.40.
- H CEM I 42,5 N with 12% fly ash and 4% silica fume, w/c=0.45.
- I CEM I 42,5 N with 12% fly ash and 4% silica fume, w/c=0.35.
- J CEM I 42,5 N with 12% fly ash and 4% silica fume, SCC, w/c=0.40.
- K Traditional slag cement (CEM III/B), w/c=0.40.
- L CEM III/B, no air entrainment, w/c=0.40.
- M CEM III/B, SCC, w/c=0.40.
- N 70 % slag mixed with 30% rapid cement (CEM I 52,5 N) w/c=0.40.
- O CEM I 42,5 N with 4% silica fume with super absorbing polymers, w/c=0.40.

Basis cement (CEM II, 52.5 – containing <5% LF and FA)

Rapid hardening cement (CEM I 52.5 LA/MS)

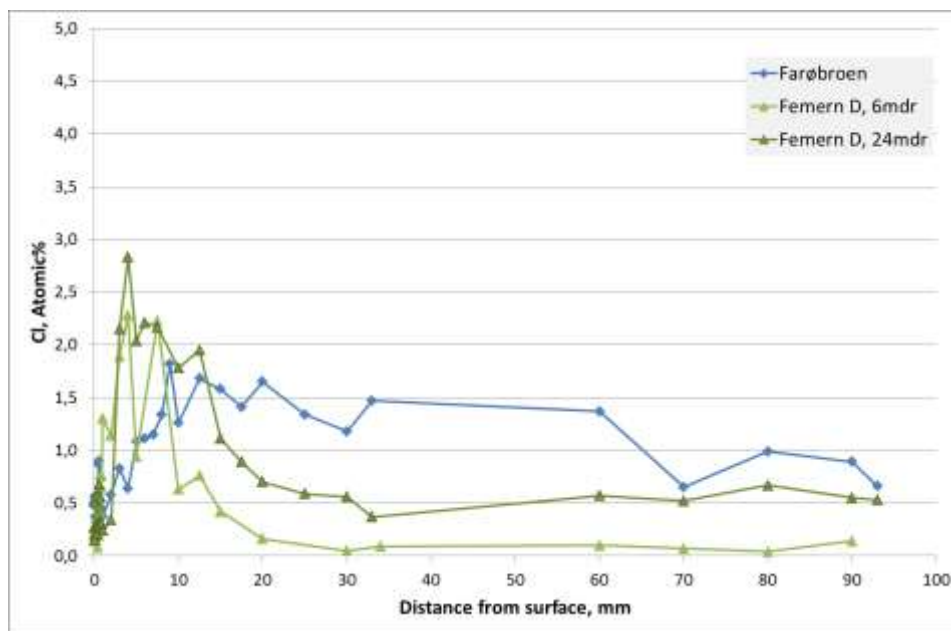
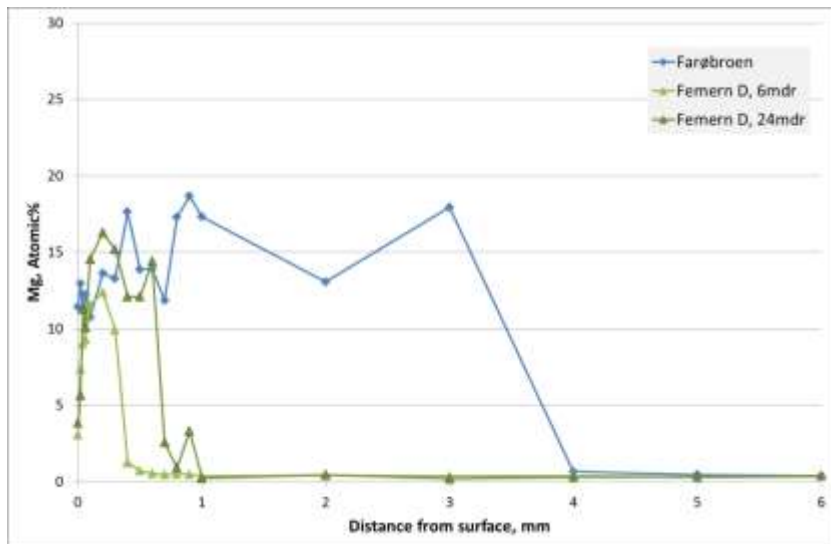
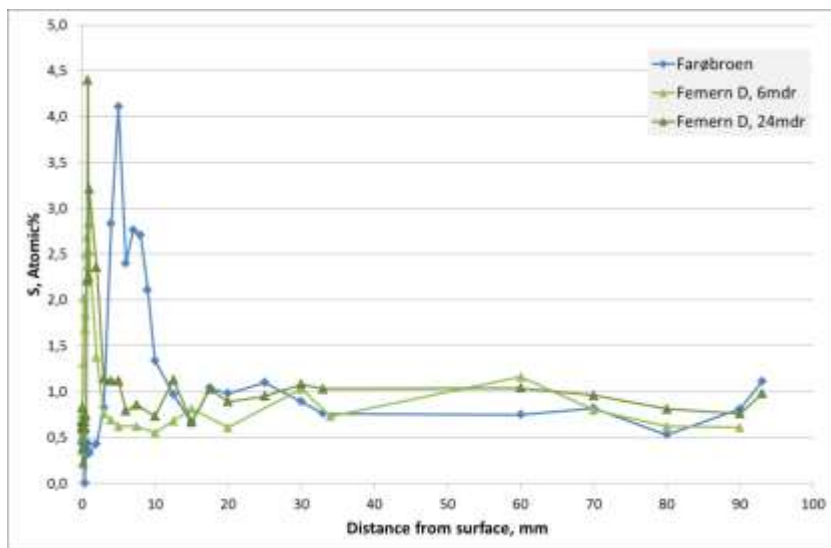
Rapid hardening cement (CEM I 52.5 LA/MS) with 30% fly ash

Rød – 28 døgn, 6 mdr, 2 år

Sort – kun 28 døgn

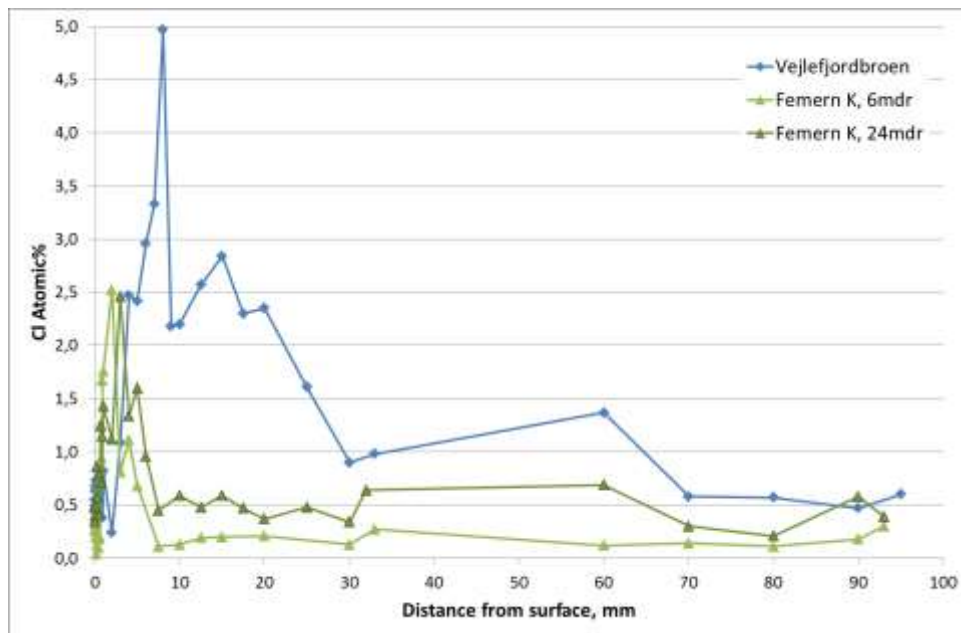
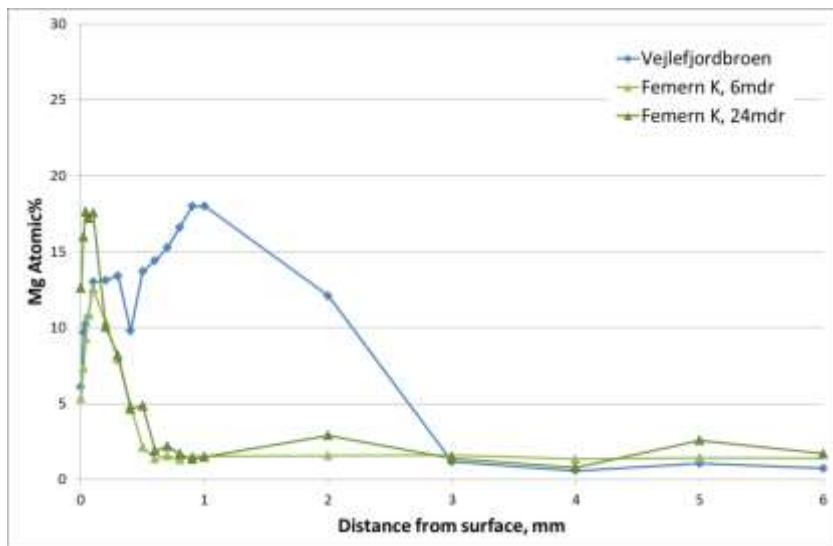
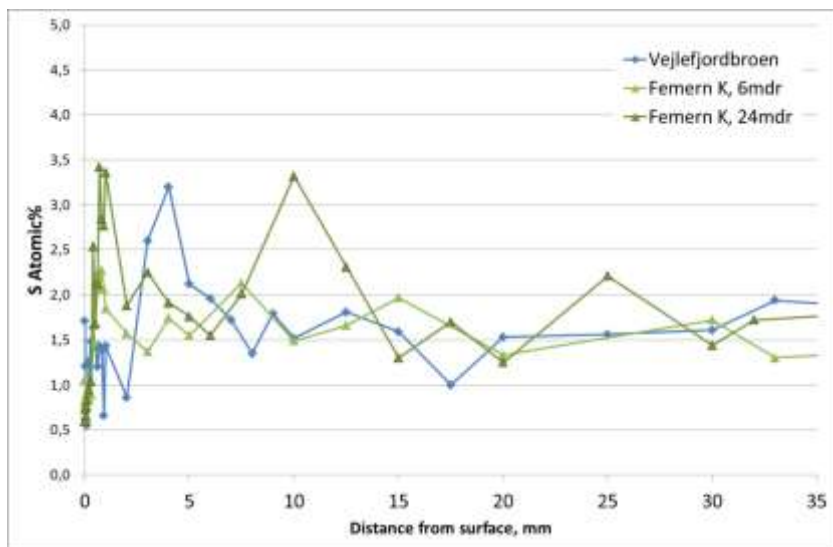
Farøbroen og Femern D – SEM-EDX

Tidsmæssig variation af S, Mg og Cl

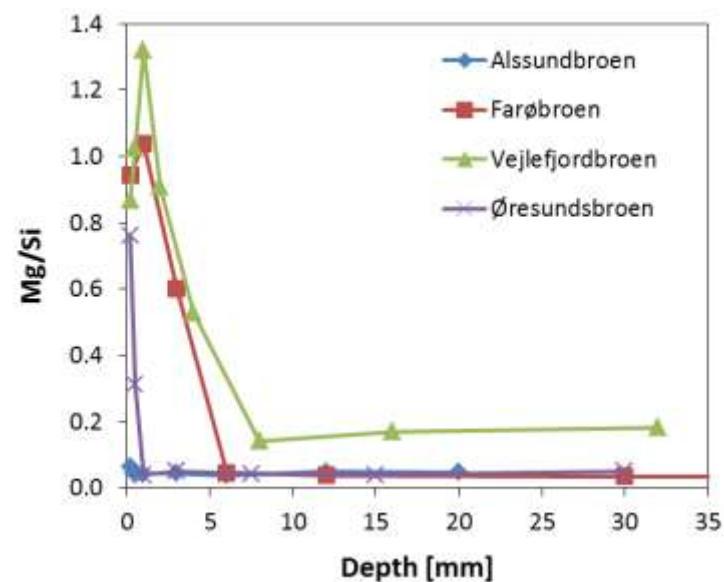
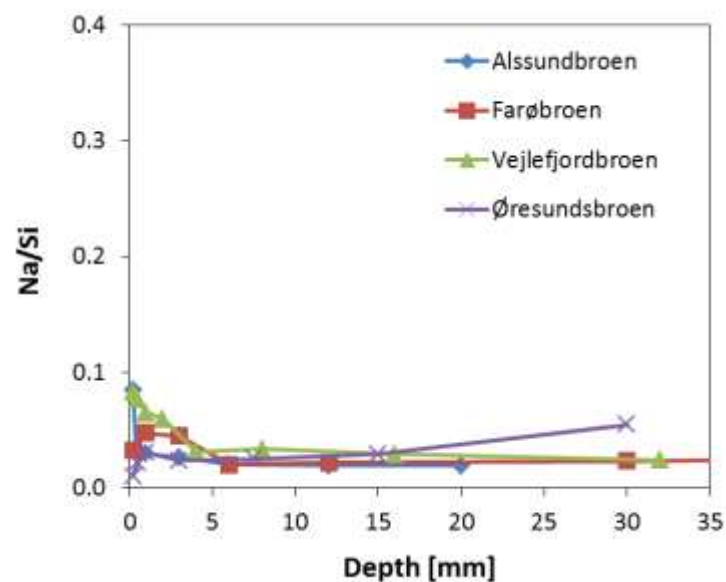
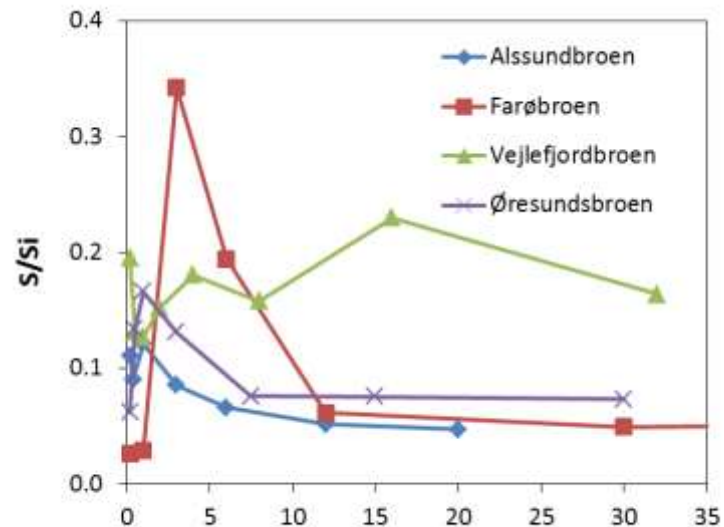
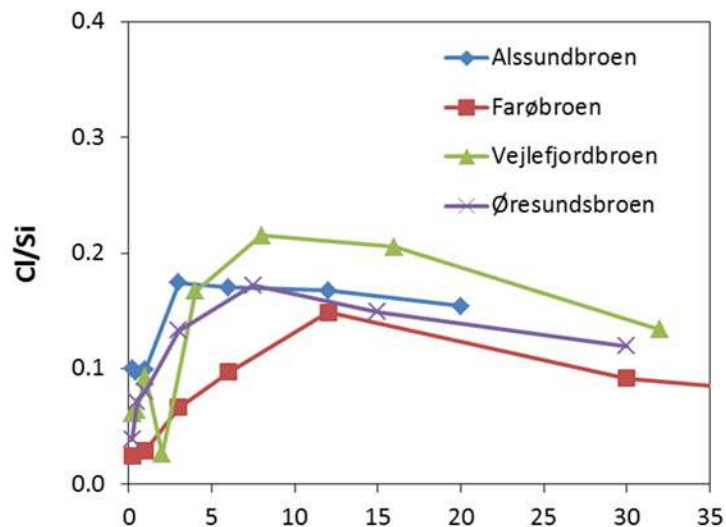


Vejlefjordbroen og Femern K – SEM-EDX

Tidsmæssig variation af S, Mg og Cl



Grundstofprofiler i 4 broer – SEM-EDX



Farebroen

Pillar, cote -150, south

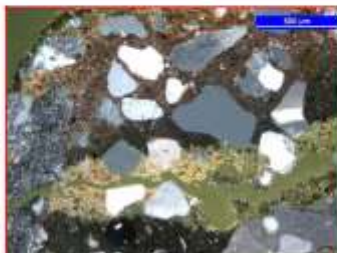
Age: 1980-85



Info
Cement type:
Fly ash:
Microsilica:
Slag:
W/C, apparent:
Air %:

Lavak
X
-
-
0.40
3-4

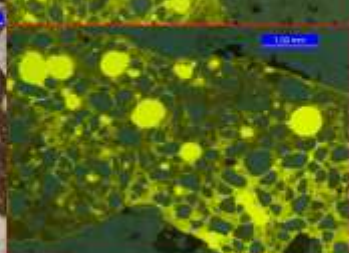
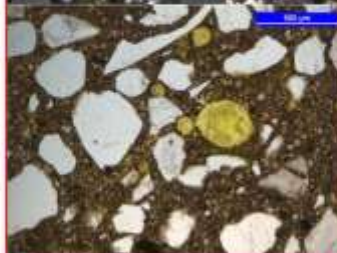
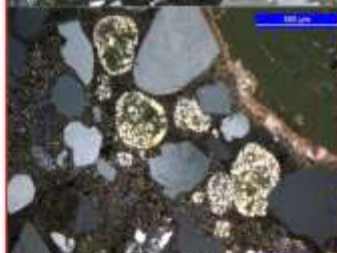
Comments
Core taken in 2012
Cement type: Lavakalk
Section No: 7206-F3



Micro-observations

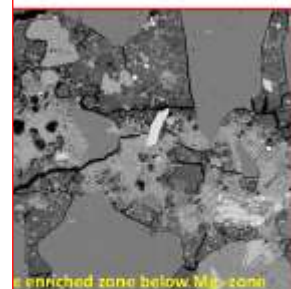
Micro-structural zoning through concrete:

1. Surface is uneven and scaled. A thin calcite crust is occasionally observed, as well as a paste damaged by biological growth.
2. 0-3mm: Partially carbonated paste with bands of black paste. Massive ettringite and thaumasite-like phases are observed in air voids. Paste is highly cracked.
3. 3-10mm: Porous, black paste ettringite and thaumasite-like phases in air voids.
4. Internal paste contains a relatively high amount of CH. Observed in air voids too. Many small autogenous cracks in paste.

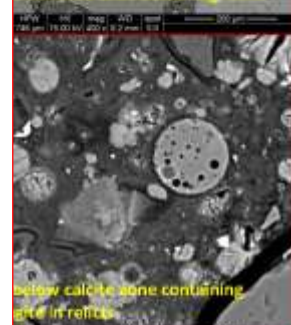


0, south

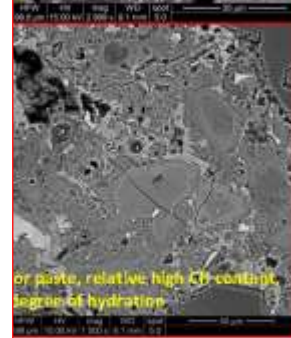
Age: 1980-85



enriched zone below Mg-zone



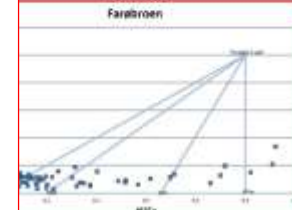
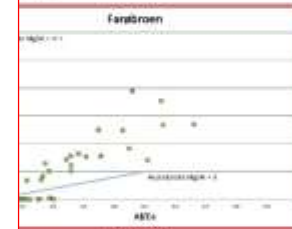
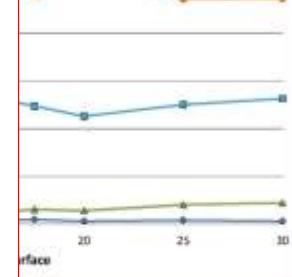
below calcite zone containing
gels in refills



or paste, relative high CH content
begin of hydration

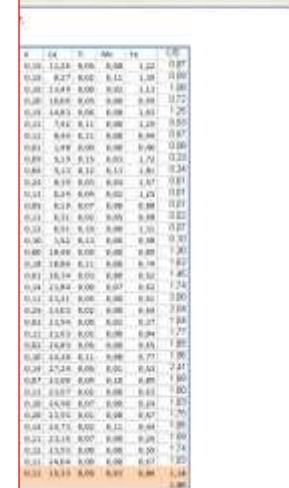
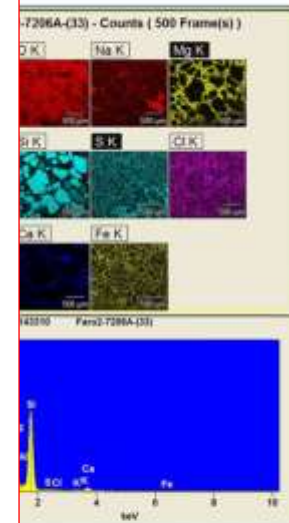
0, south

Age: 1980-85

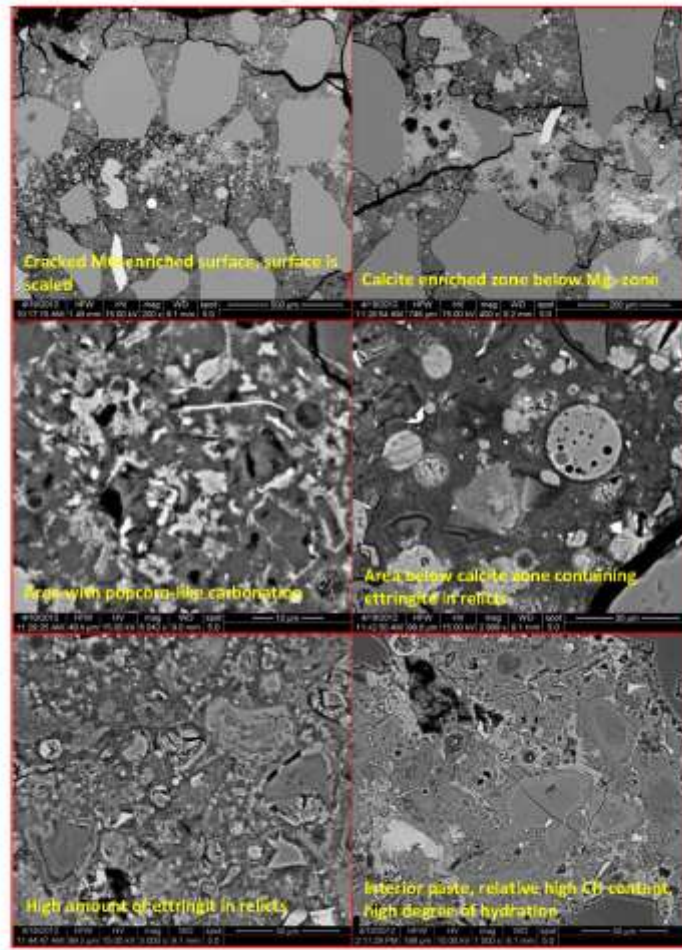


0, south

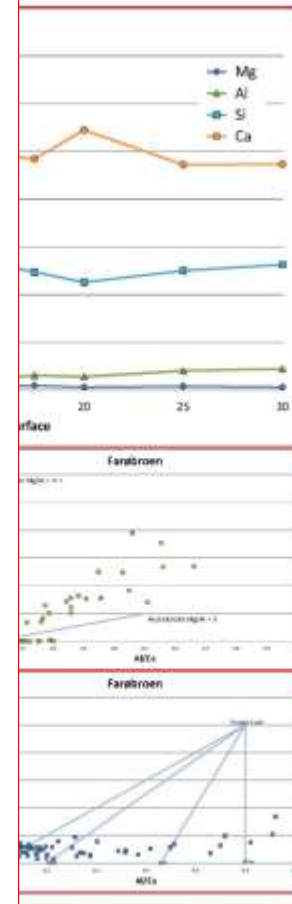
Age: 1980-85



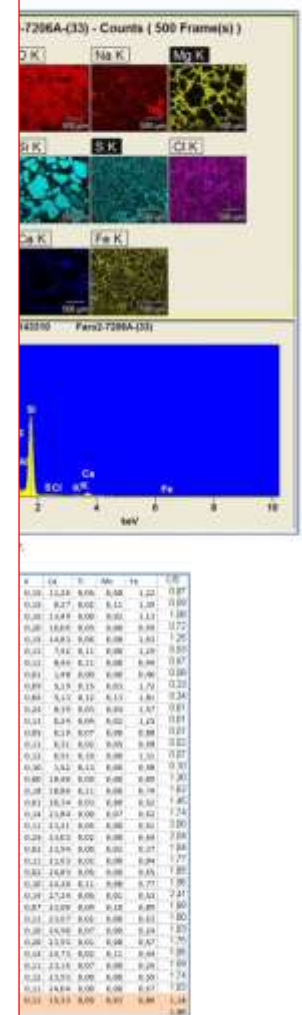
Farebroen Pillar, cote -150, south Age: 1980-85



0, south Age: 1980-85

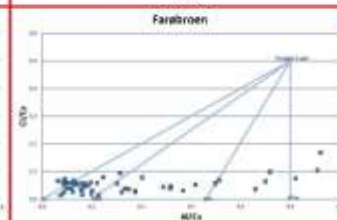
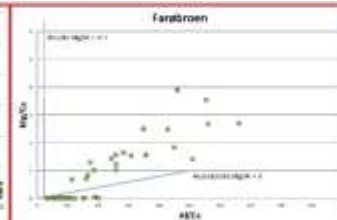
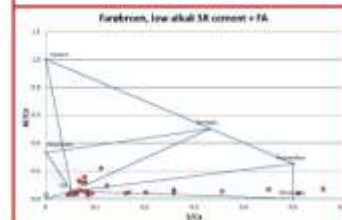
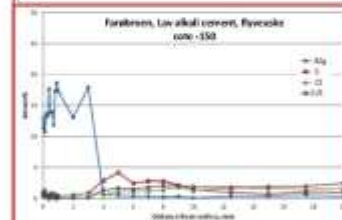
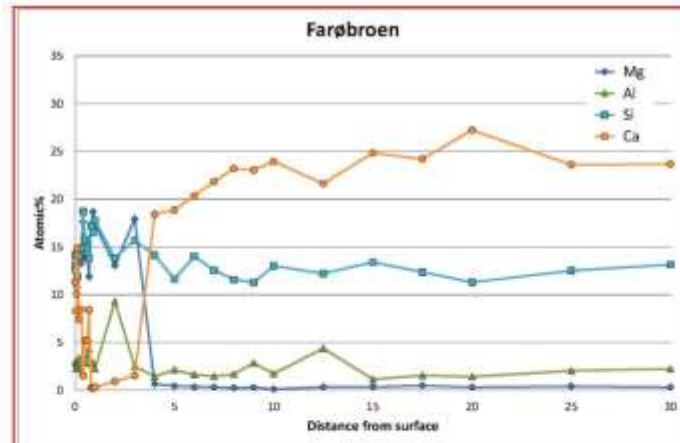


0, south Age: 1980-85

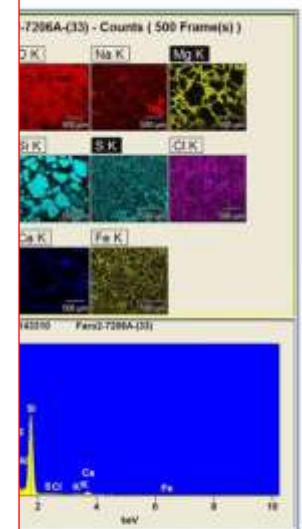


Mikroskopi og SEM-EDX – dataark 3

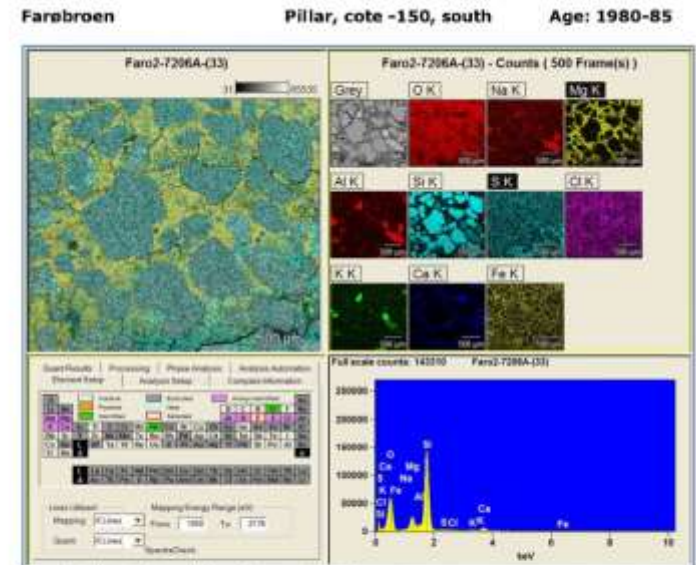
Farøbroen Pillar, cote -150, south Age: 1980-85



0, south Age: 1980-85



#	Si	O	Na	Fe	Ca
0.00	0.00	0.00	0.00	0.00	0.00
0.01	0.01	0.01	0.01	0.01	0.01
0.02	0.02	0.02	0.02	0.02	0.02
0.03	0.03	0.03	0.03	0.03	0.03
0.04	0.04	0.04	0.04	0.04	0.04
0.05	0.05	0.05	0.05	0.05	0.05
0.06	0.06	0.06	0.06	0.06	0.06
0.07	0.07	0.07	0.07	0.07	0.07
0.08	0.08	0.08	0.08	0.08	0.08
0.09	0.09	0.09	0.09	0.09	0.09
0.10	0.10	0.10	0.10	0.10	0.10
0.11	0.11	0.11	0.11	0.11	0.11
0.12	0.12	0.12	0.12	0.12	0.12
0.13	0.13	0.13	0.13	0.13	0.13
0.14	0.14	0.14	0.14	0.14	0.14
0.15	0.15	0.15	0.15	0.15	0.15
0.16	0.16	0.16	0.16	0.16	0.16
0.17	0.17	0.17	0.17	0.17	0.17
0.18	0.18	0.18	0.18	0.18	0.18
0.19	0.19	0.19	0.19	0.19	0.19
0.20	0.20	0.20	0.20	0.20	0.20
0.21	0.21	0.21	0.21	0.21	0.21
0.22	0.22	0.22	0.22	0.22	0.22
0.23	0.23	0.23	0.23	0.23	0.23
0.24	0.24	0.24	0.24	0.24	0.24
0.25	0.25	0.25	0.25	0.25	0.25
0.26	0.26	0.26	0.26	0.26	0.26
0.27	0.27	0.27	0.27	0.27	0.27
0.28	0.28	0.28	0.28	0.28	0.28
0.29	0.29	0.29	0.29	0.29	0.29
0.30	0.30	0.30	0.30	0.30	0.30
0.31	0.31	0.31	0.31	0.31	0.31
0.32	0.32	0.32	0.32	0.32	0.32
0.33	0.33	0.33	0.33	0.33	0.33
0.34	0.34	0.34	0.34	0.34	0.34
0.35	0.35	0.35	0.35	0.35	0.35
0.36	0.36	0.36	0.36	0.36	0.36
0.37	0.37	0.37	0.37	0.37	0.37
0.38	0.38	0.38	0.38	0.38	0.38
0.39	0.39	0.39	0.39	0.39	0.39
0.40	0.40	0.40	0.40	0.40	0.40
0.41	0.41	0.41	0.41	0.41	0.41
0.42	0.42	0.42	0.42	0.42	0.42
0.43	0.43	0.43	0.43	0.43	0.43
0.44	0.44	0.44	0.44	0.44	0.44
0.45	0.45	0.45	0.45	0.45	0.45
0.46	0.46	0.46	0.46	0.46	0.46
0.47	0.47	0.47	0.47	0.47	0.47
0.48	0.48	0.48	0.48	0.48	0.48
0.49	0.49	0.49	0.49	0.49	0.49
0.50	0.50	0.50	0.50	0.50	0.50
0.51	0.51	0.51	0.51	0.51	0.51
0.52	0.52	0.52	0.52	0.52	0.52
0.53	0.53	0.53	0.53	0.53	0.53
0.54	0.54	0.54	0.54	0.54	0.54
0.55	0.55	0.55	0.55	0.55	0.55
0.56	0.56	0.56	0.56	0.56	0.56
0.57	0.57	0.57	0.57	0.57	0.57
0.58	0.58	0.58	0.58	0.58	0.58
0.59	0.59	0.59	0.59	0.59	0.59
0.60	0.60	0.60	0.60	0.60	0.60
0.61	0.61	0.61	0.61	0.61	0.61
0.62	0.62	0.62	0.62	0.62	0.62
0.63	0.63	0.63	0.63	0.63	0.63
0.64	0.64	0.64	0.64	0.64	0.64
0.65	0.65	0.65	0.65	0.65	0.65
0.66	0.66	0.66	0.66	0.66	0.66
0.67	0.67	0.67	0.67	0.67	0.67
0.68	0.68	0.68	0.68	0.68	0.68
0.69	0.69	0.69	0.69	0.69	0.69
0.70	0.70	0.70	0.70	0.70	0.70
0.71	0.71	0.71	0.71	0.71	0.71
0.72	0.72	0.72	0.72	0.72	0.72
0.73	0.73	0.73	0.73	0.73	0.73
0.74	0.74	0.74	0.74	0.74	0.74
0.75	0.75	0.75	0.75	0.75	0.75
0.76	0.76	0.76	0.76	0.76	0.76
0.77	0.77	0.77	0.77	0.77	0.77
0.78	0.78	0.78	0.78	0.78	0.78
0.79	0.79	0.79	0.79	0.79	0.79
0.80	0.80	0.80	0.80	0.80	0.80
0.81	0.81	0.81	0.81	0.81	0.81
0.82	0.82	0.82	0.82	0.82	0.82
0.83	0.83	0.83	0.83	0.83	0.83
0.84	0.84	0.84	0.84	0.84	0.84
0.85	0.85	0.85	0.85	0.85	0.85
0.86	0.86	0.86	0.86	0.86	0.86
0.87	0.87	0.87	0.87	0.87	0.87
0.88	0.88	0.88	0.88	0.88	0.88
0.89	0.89	0.89	0.89	0.89	0.89
0.90	0.90	0.90	0.90	0.90	0.90
0.91	0.91	0.91	0.91	0.91	0.91
0.92	0.92	0.92	0.92	0.92	0.92
0.93	0.93	0.93	0.93	0.93	0.93
0.94	0.94	0.94	0.94	0.94	0.94
0.95	0.95	0.95	0.95	0.95	0.95
0.96	0.96	0.96	0.96	0.96	0.96
0.97	0.97	0.97	0.97	0.97	0.97
0.98	0.98	0.98	0.98	0.98	0.98
0.99	0.99	0.99	0.99	0.99	0.99
1.00	1.00	1.00	1.00	1.00	1.00



Phase distribution through the surface region of the concrete.

[illegible]