
# Langtidsholdbarhed af beton i marint miljø: Undersøgelse af danske broer

# Disposition

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

CONCRETE EXPERTCENTRE

# Broer


Vejlefjordbroen 1975-80


Alssundbroen 1978-81


Farøbroerne 1980-85


Øresundsbroen 1993-2000

# Undersøgelsesfartøj


CONCRETE EXPERTCENTRE

# Kerneudboring under 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 |

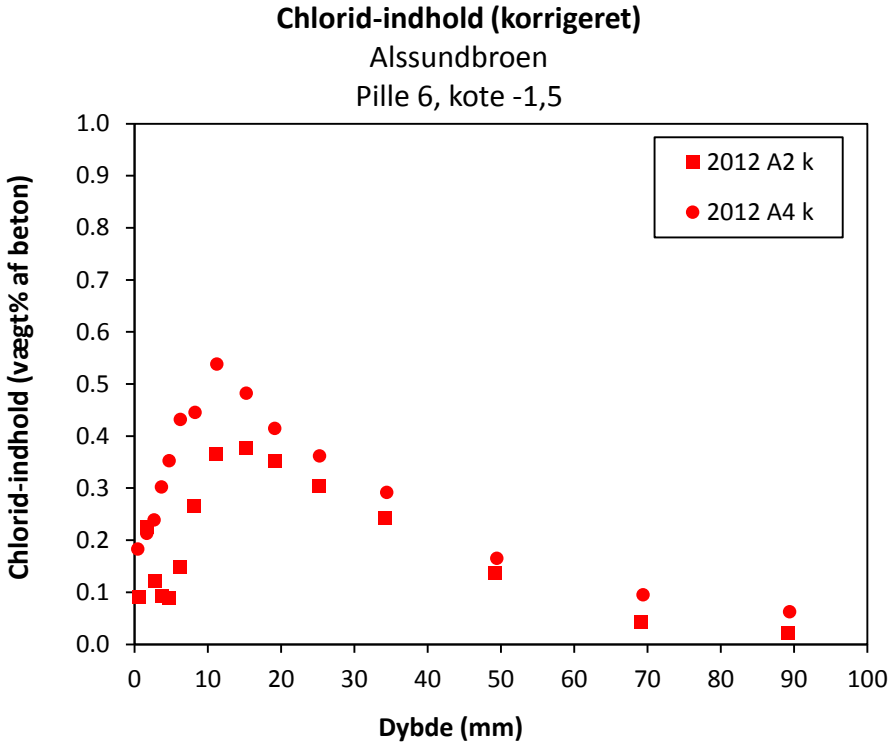
*Kerner fra Vejlefjordbroen*

*Kerner fra Alssundbroen*

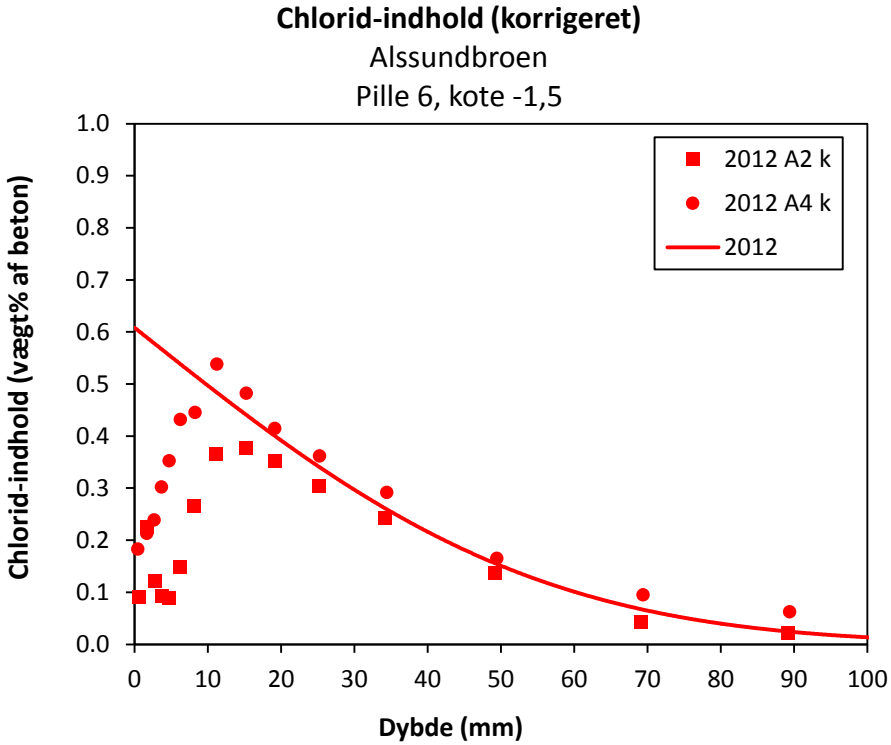
*Kerner fra Farøbroen*

# Chloridanalyser

# Alssundbroen - chloridprofiler



# Alssundbroen - chloridindtrængningsparametre

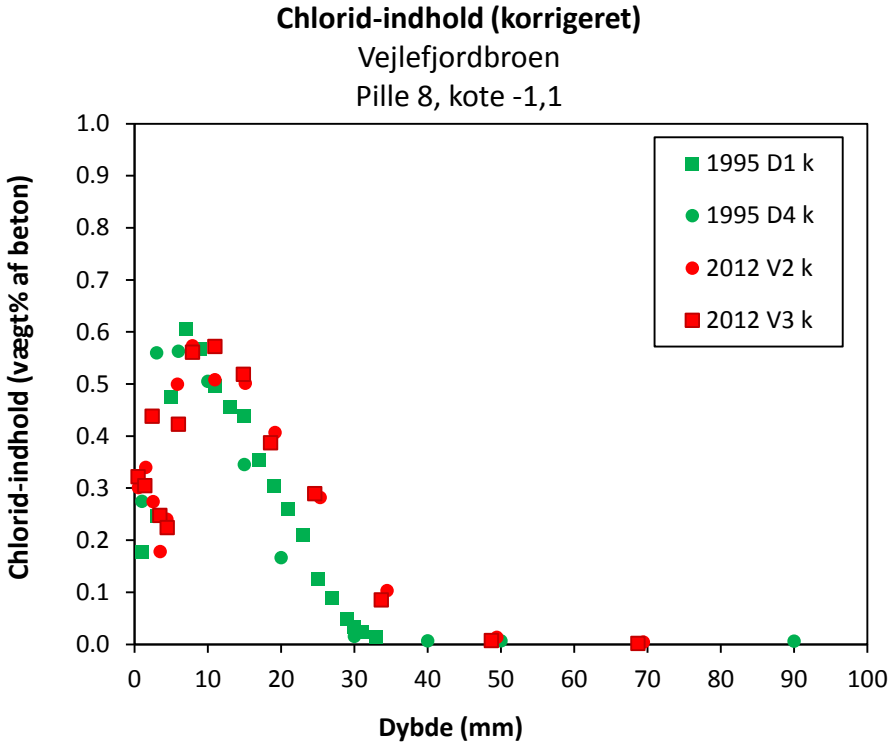



$$C(x,t) = C_s - (C_s - C_i) \cdot erf\left(\frac{x}{\sqrt{4 \cdot D_a \cdot t}}\right)$$

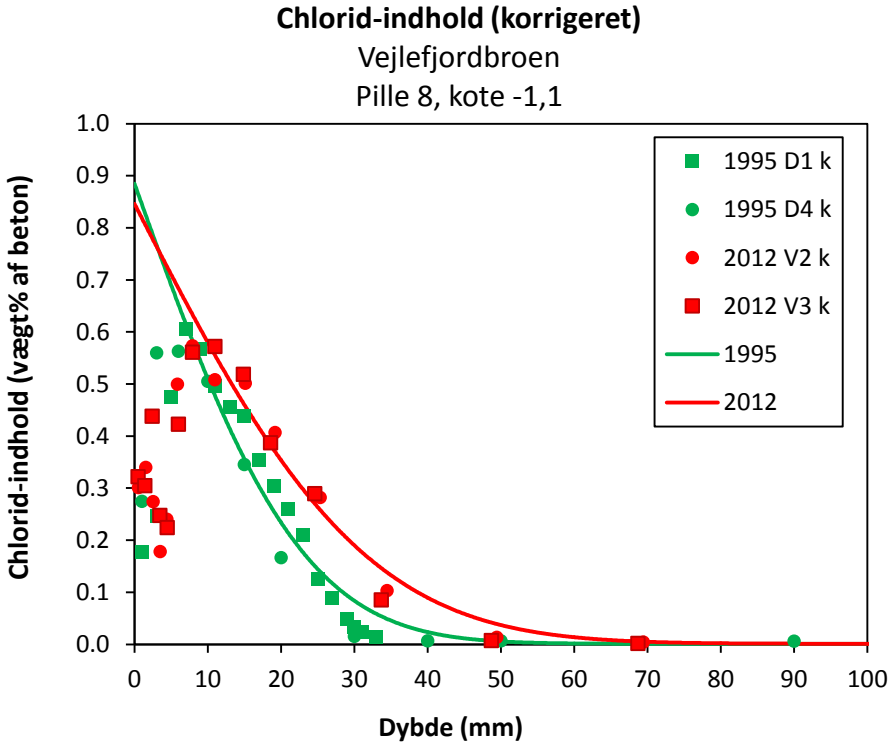
$$K_{0,05} = 2\sqrt{D_a} \cdot erf^{-1}\left(\frac{C_s - 0{,}05}{C_s - C_i}\right)$$

| År | 2012 | Enhed |
|---|---|---|
| Exp.tid | 31 | år |
| $D_a$ | 0,95 | x$10^{-12}$ m$^2$/s |
| $C_s$ | 0,608 | vægt% Cl af BE |
| $C_i$ | 0,001 | vægt% Cl af BE |
| $K_{0,05}$ | 13,5 | mm/år$^{½}$ |

# Vejlefjordbroen - chloridprofiler



# Vejlefjordbroen - chloridindtrængningsparametre

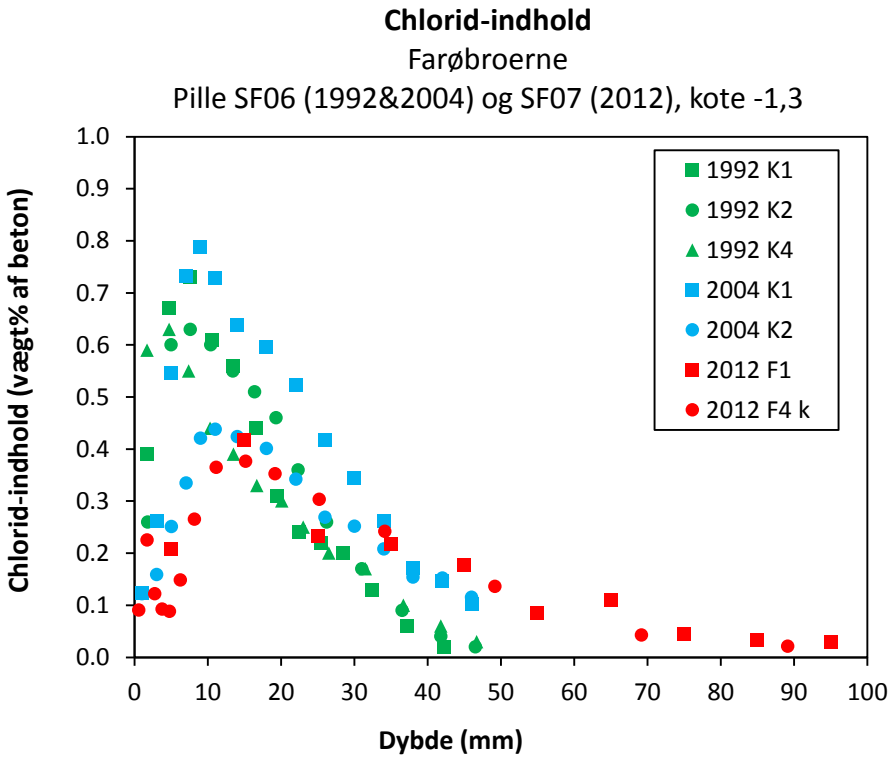



$$C(x,t) = C_s - (C_s - C_i) \cdot erf\left(\frac{x}{\sqrt{4 \cdot D_a \cdot t}}\right)$$

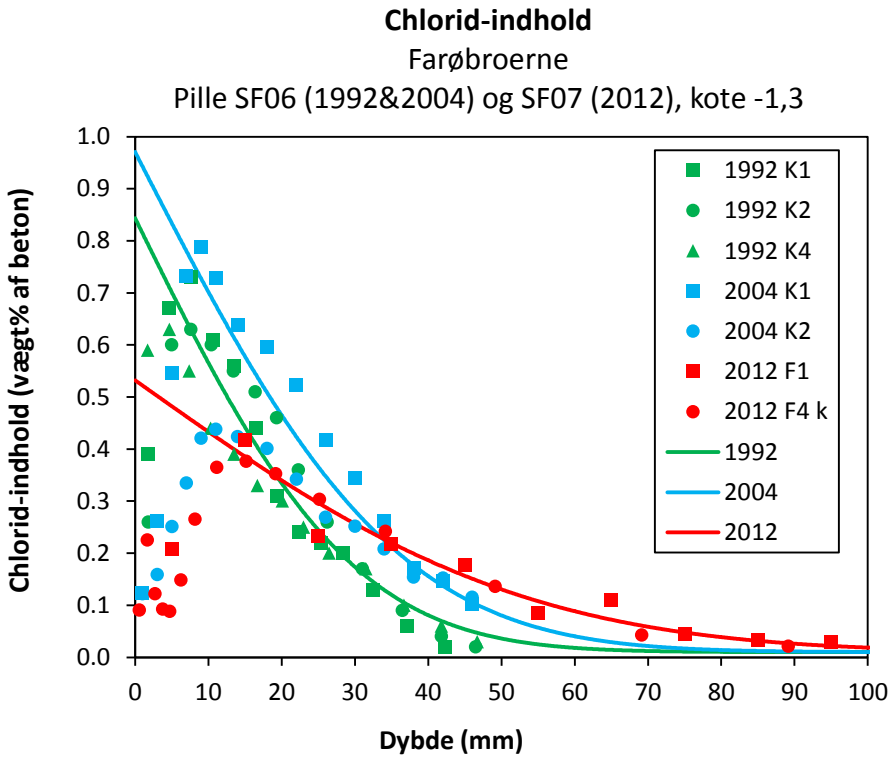
$$K_{0,05} = 2\sqrt{D_a} \cdot erf^{-1}\left(\frac{C_s - 0{,}05}{C_s - C_i}\right)$$

| År | 1995 | 2012 | Enhed |
|---|---|---|---|
| Exp.tid | 17 | 34 | år |
| $D_a$ | 0,30 | 0,28 | x$10^{-12}$ m$^2$/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 | mm/år$^{½}$ |

# Farøbroen - chloridprofiler



# Farøbroen - chloridindtrængningsparametre

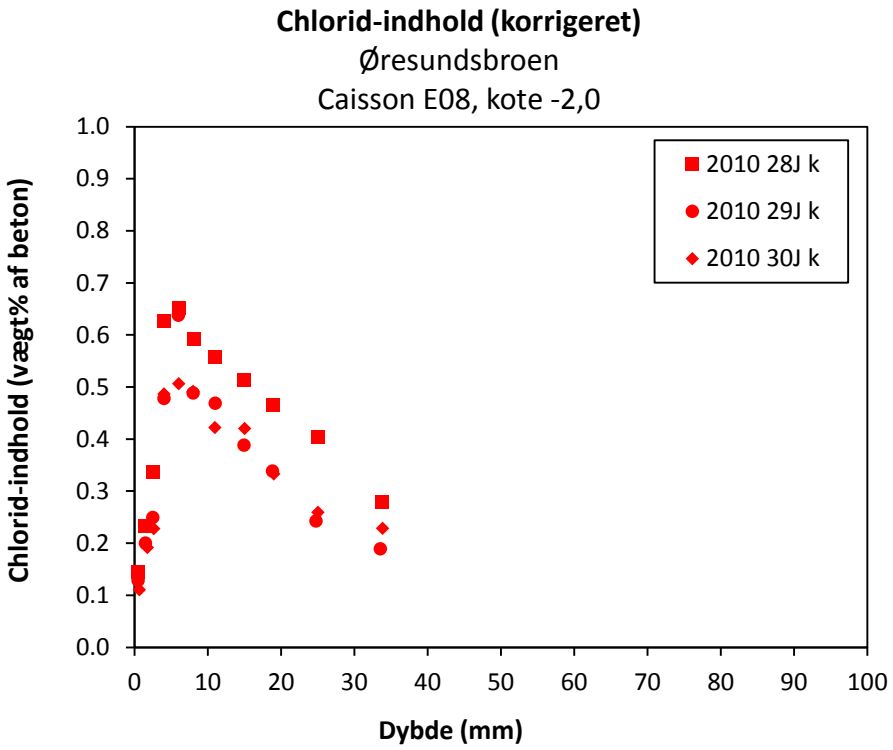



$$C(x,t) = C_s - (C_s - C_i) \cdot erf\left(\frac{x}{\sqrt{4 \cdot D_a \cdot t}}\right)$$

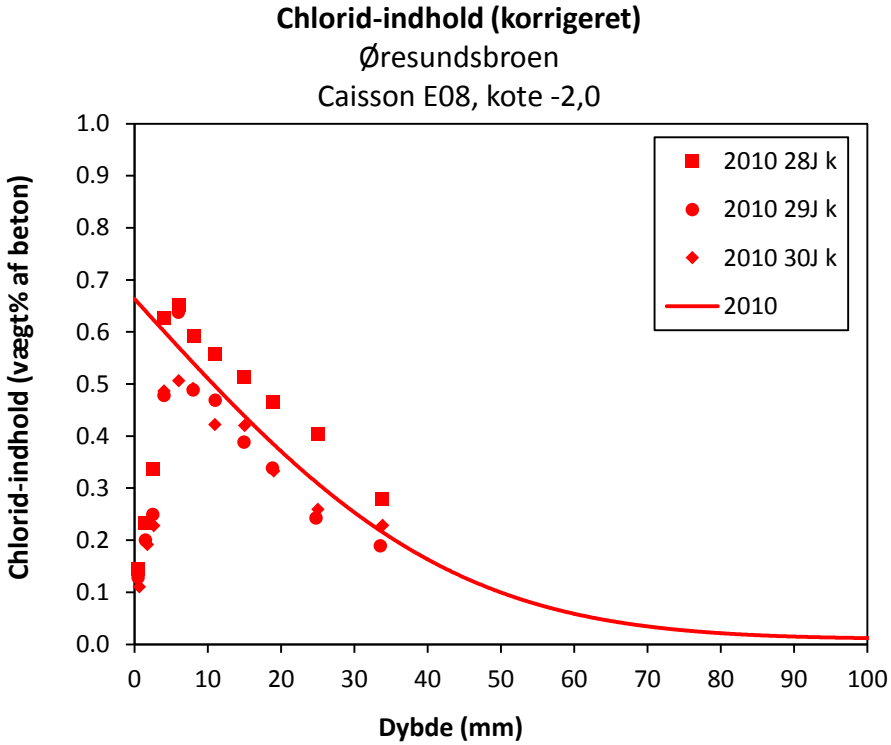
$$K_{0,05} = 2\sqrt{D_a} \cdot erf^{-1}\left(\frac{C_s - 0{,}05}{C_s - C_i}\right)$$

| År | 1992 | 2004 | 2012 | Enhed |
|---|---|---|---|---|
| Exp.tid | 10,7 | 22,4 | 30 | år |
| $D_a$ | 0,80 | 0,55 | 0,92 | x$10^{-12}$ m$^2$/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 | mm/år$^{½}$ |

# Øresundsbroen - chloridprofiler



# Øresundsbroen - chloridindtrængningsparametre



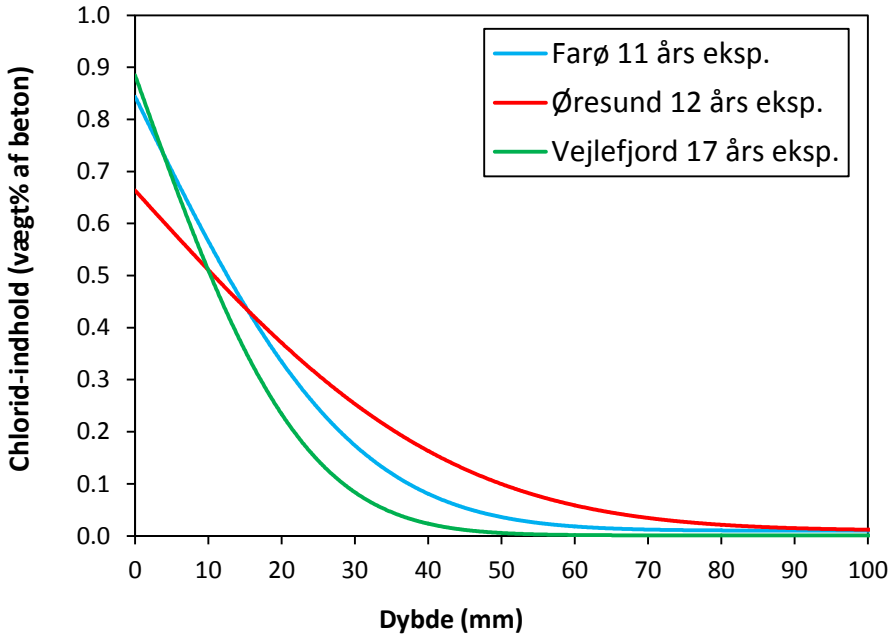

$$C(x,t) = C_s - (C_s - C_i) \cdot erf\left(\frac{x}{\sqrt{4 \cdot D_a \cdot t}}\right)$$

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

| År | 2010 | Enhed |
|---|---|---|
| Exp.tid | 12 | år |
| $D_a$ | 1,50 | x$10^{-12}$ m$^2$/s |
| $C_s$ | 0,663 | vægt% Cl af BE |
| $C_i$ | 0,010 | vægt% Cl af BE |
| $K_{0,05}$ | 18,2 | mm/år$^{½}$ |

# Chloridindtrængning efter 11-17 år – 3 broer

**Chloridprofiler**
3 broer, kote -1 til -2

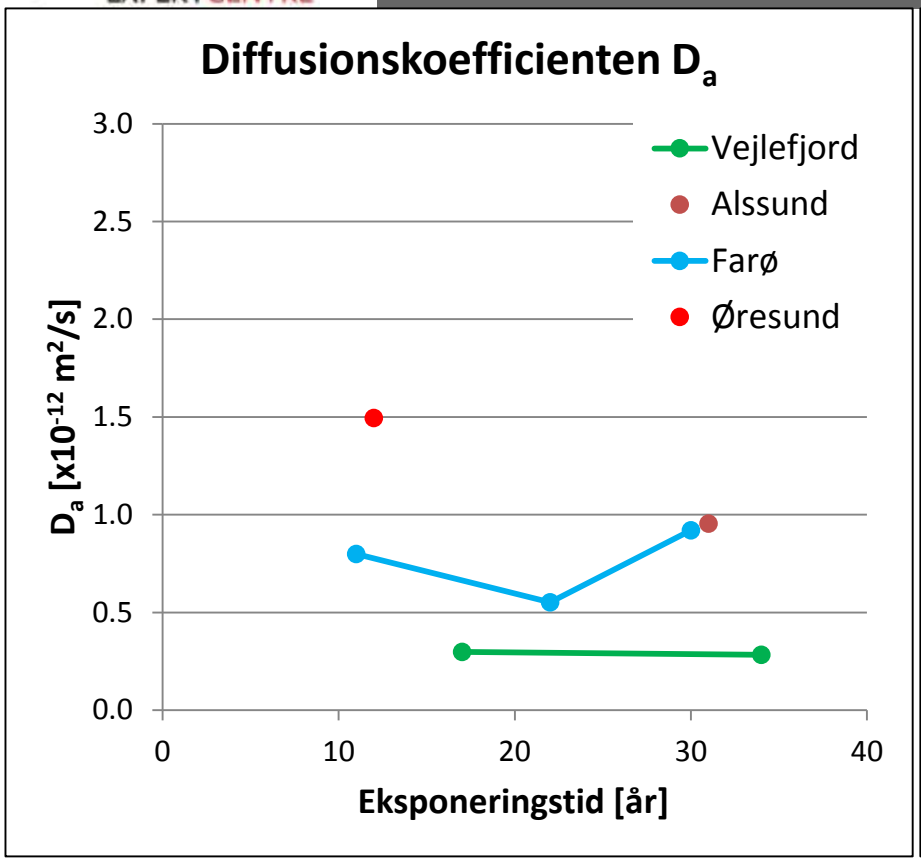


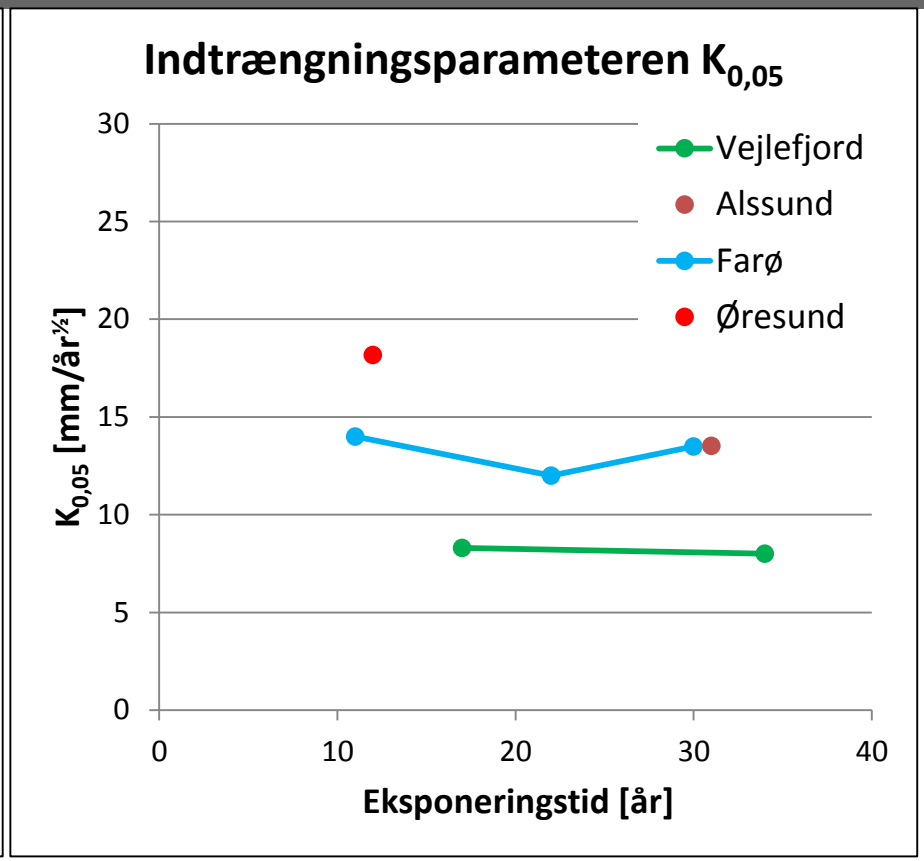

$$C(x,t) = C_s - (C_s - C_i) \cdot erf\left(\frac{x}{\sqrt{4 \cdot D_a \cdot t}}\right)$$

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

| | Farø | Øresund | Vejlefjord | Enhed |
|---|---|---|---|---|
| Exp.tid | 11 | 12 | 17 | år |
| $D_a$ | 0,80 | 1,50 | 0,30 | x$10^{-12}$ 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




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

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

Der ses ikke en tidsafhængig diffusionskoefficient som f.eks.

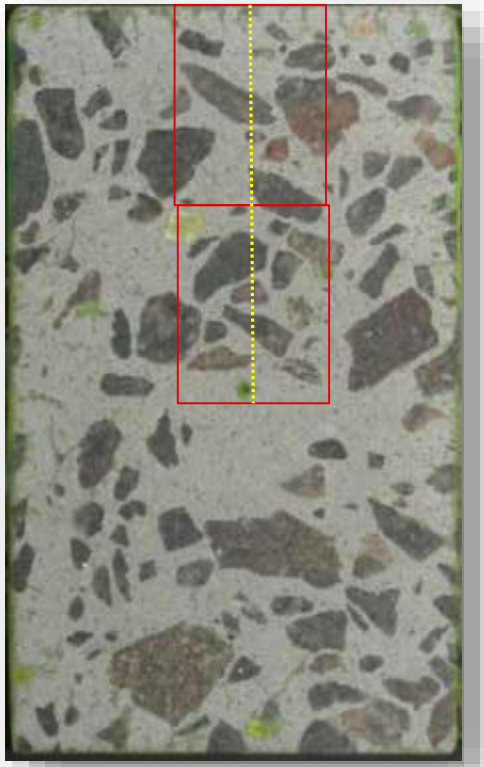
$$D_a(t) = D_{aex}\left(\frac{t_{ex}}{t}\right)^{\alpha}$$

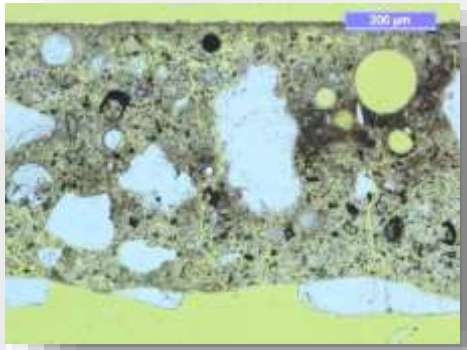
i de to tilfælde, hvor der efter de første 10 års eksponering er målt til mere en 1 termin

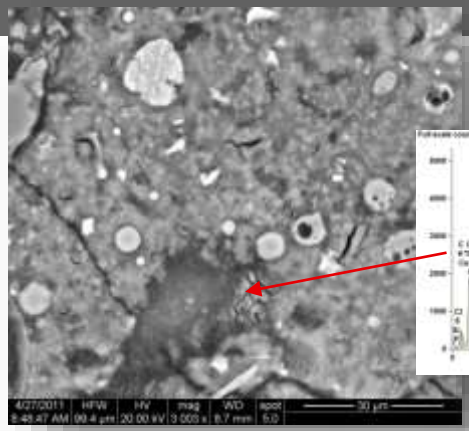
CONCRETE EXPERTCENTRE

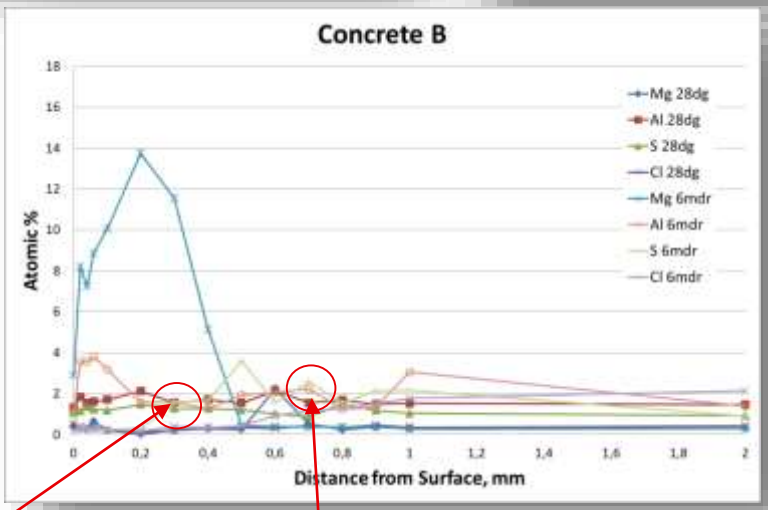
# Mikroskopi og SEM-EDX


# Mikroskopi og SEM-EDX





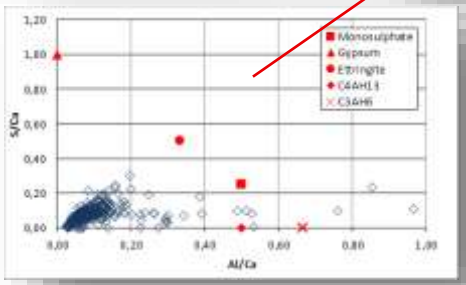




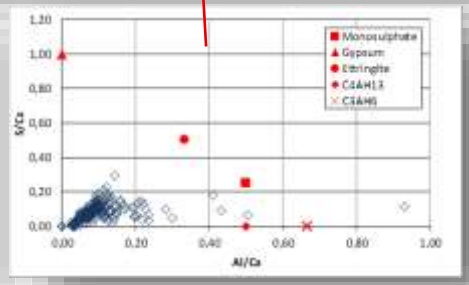

Macro-analysis: Crack pattern, homogeneity…

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

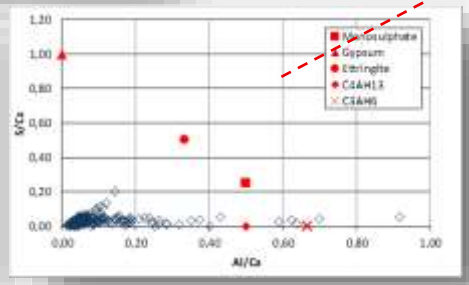
SEM-EDX: Structural analysis, chemical trends, phase identification, phase analysis …




Depth: 0,3mm




Depth: 0,7mm




Depth: 23mm

# Fasesammensætning ved SEM-EDX

**Fremgangsmåde ved SEM-EDX-målingerne**

- I hvert dybdeniveau udføres 300 punktanalyser, som er fordelt over 3 analyse-felter (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.

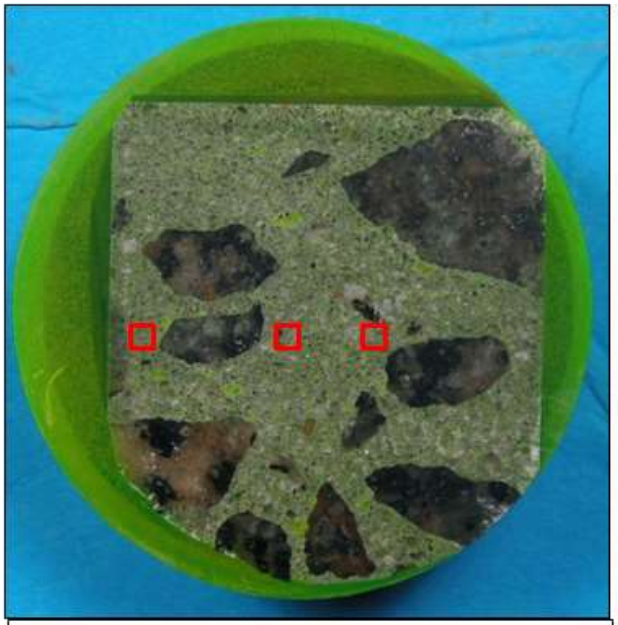


Fig. 1: Eksempel på fordeling af de 3 analysefelter i et bestemt niveau

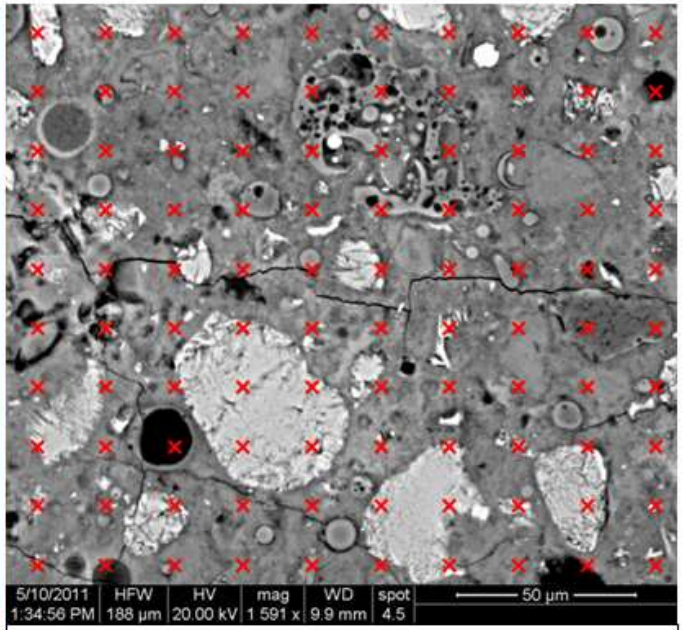



Fig. 2: Eksempel på et analysefelt, som består af 10x10 punkter.

# Mikroskopi og SEM-EDX – gamle broer

| 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 | | | |

# Mikroskopi og SEM-EDX – ung beton

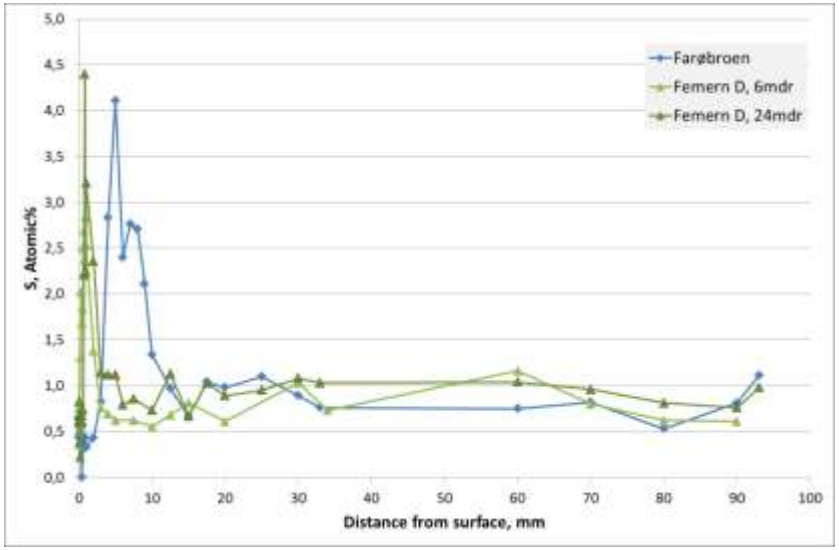
Young concrete: Femern trial concrete (28 maturity age, 6 & 24 months)

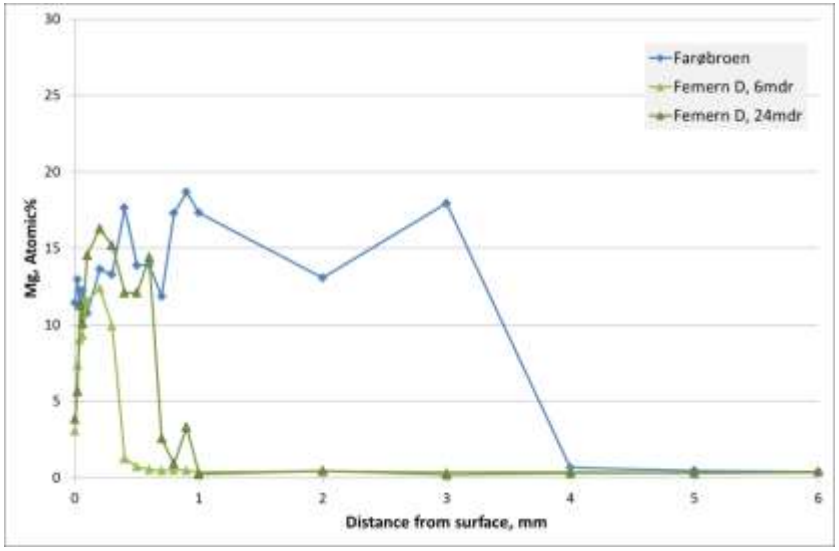
| | |
|---|---|
| A | Portland low alkali sulfate resistant cement (CEM I 42,5 N) w/c=0.40. |
| B | CEM I 42,5 N with 15% fly ash, w/c=0.40. |
| C | CEM I 42,5 N with 25% fly ash, w/c=0.40. |
| D | CEM I 42,5 N with 25% fly ash, SCC, w/c=0.40. |
| E | CEM I 42,5 N with 4% silica fume, w/c=0.40. |
| F | 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

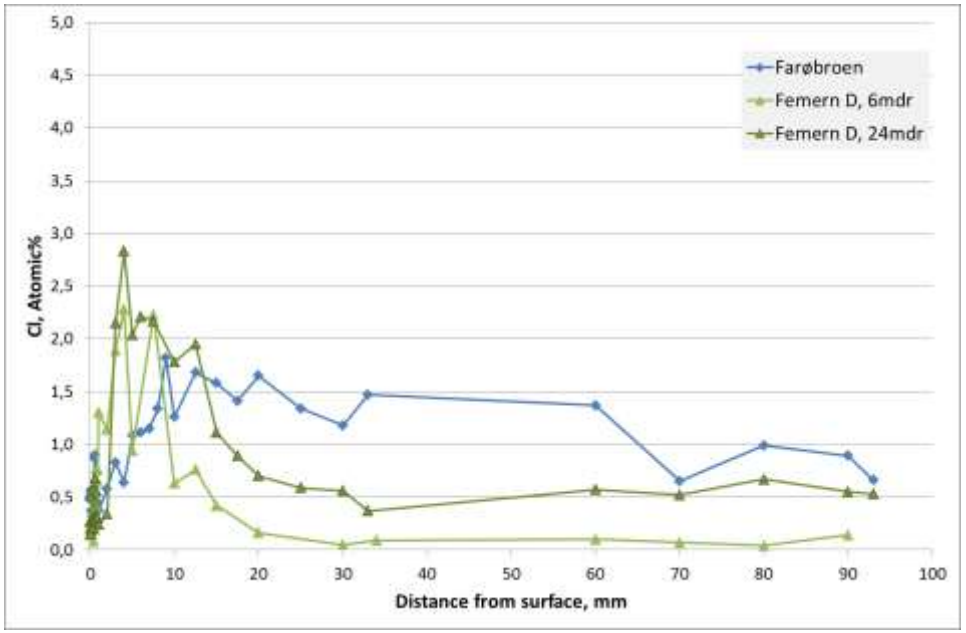
Rød – 28 døgn, 6 mdr, 2 år
Sort – kun 28 døgn

# Farøbroen og Femern D – SEM-EDX

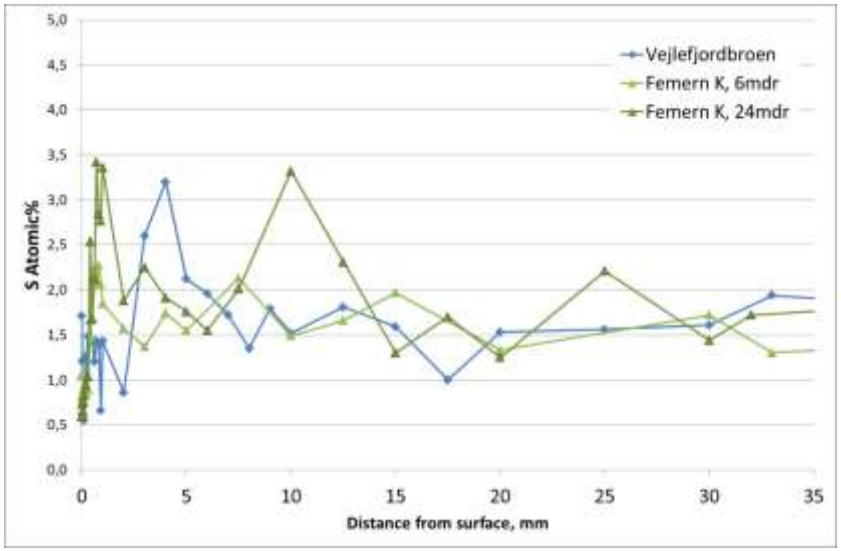


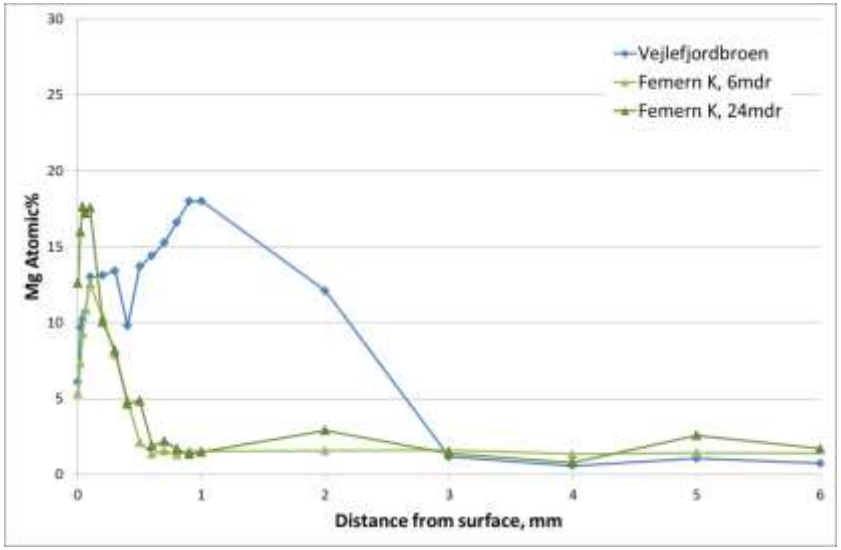




Tidsmæssig variation af S, Mg og Cl

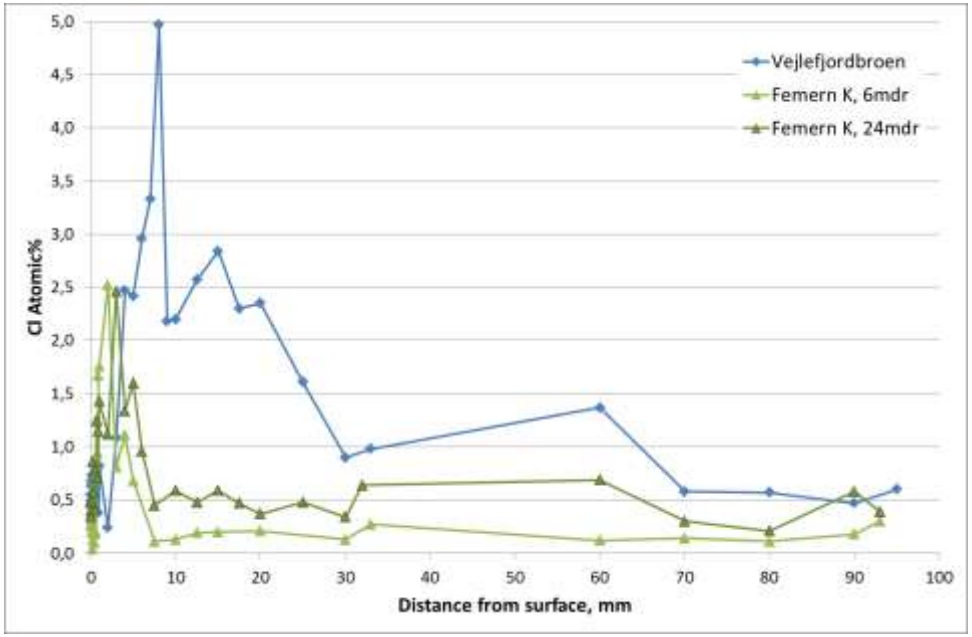


# Vejlefjordbroen og Femern K – SEM-EDX

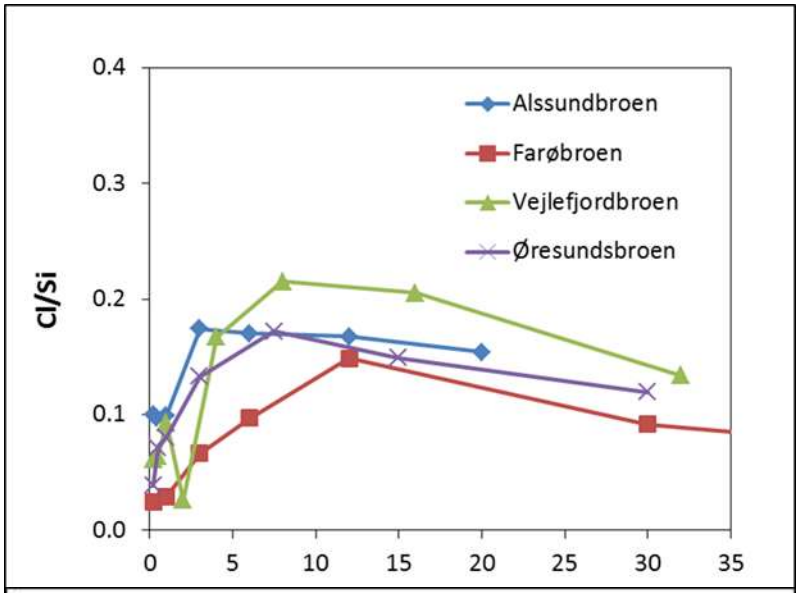


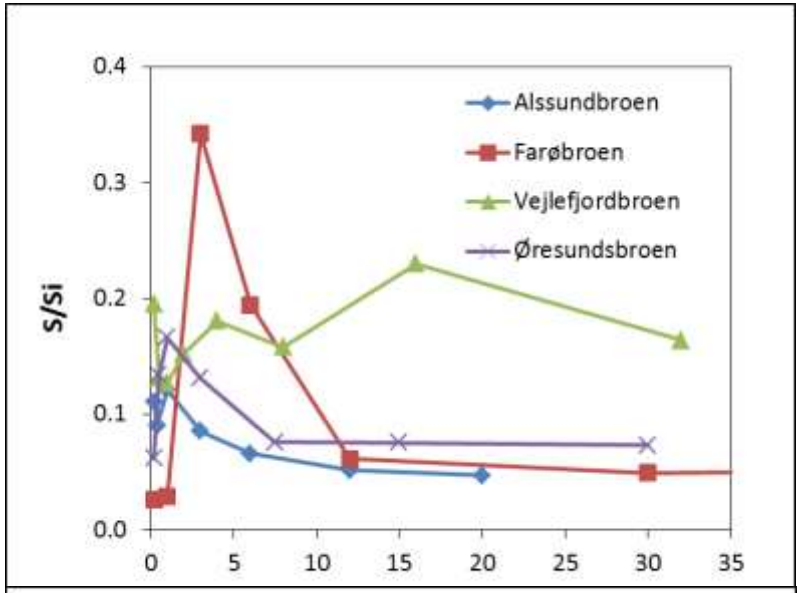



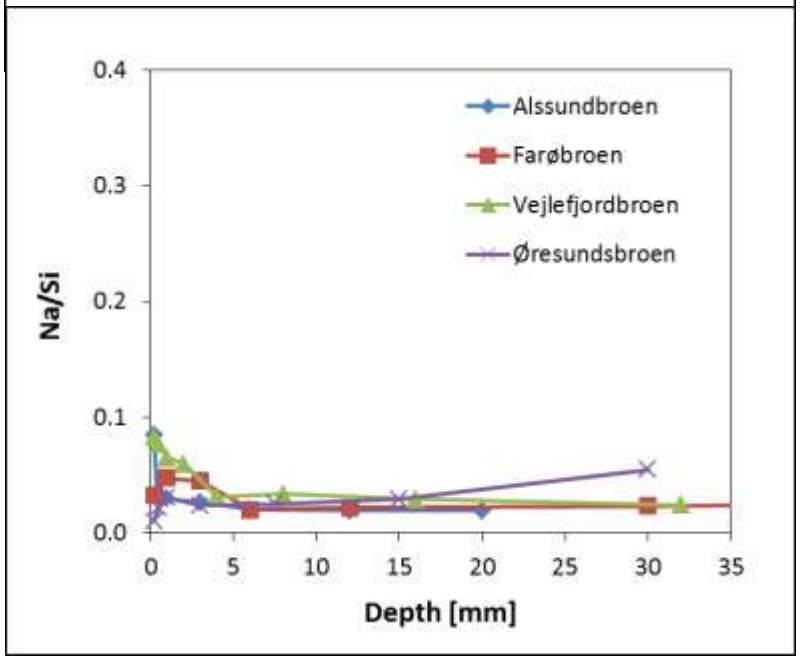

Tidsmæssig variation af S, Mg og Cl

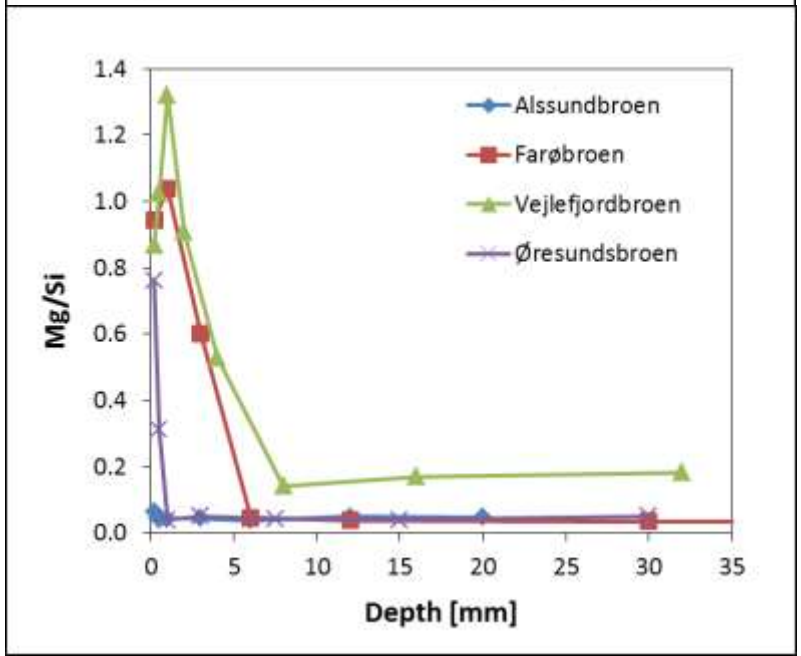


# Grundstofprofiler i 4 broer – SEM-EDX



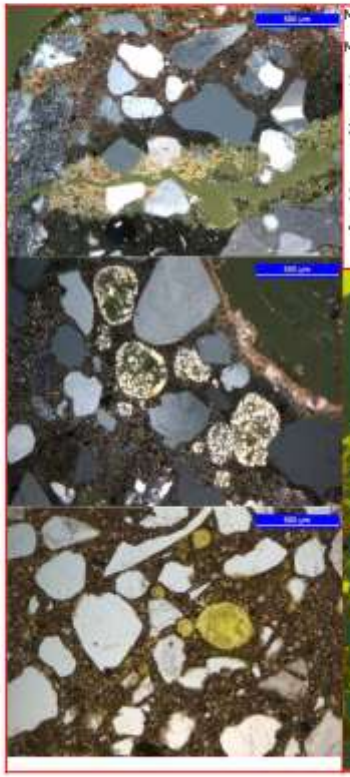



# Mikroskopi og SEM-EDX – dataark 1

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

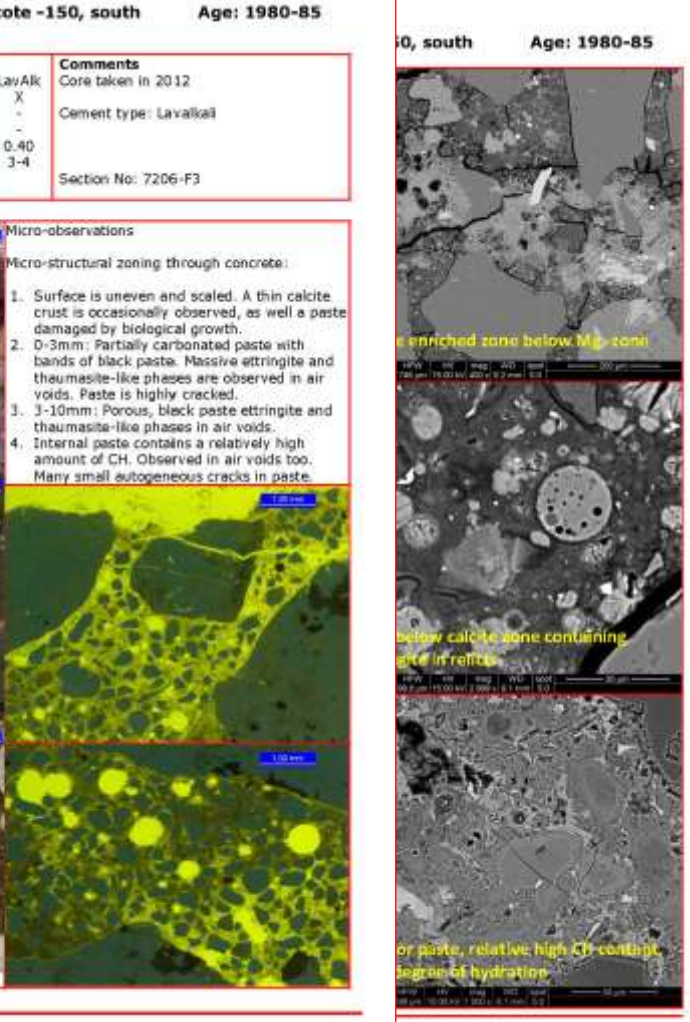
| Info | | Comments |
|---|---|---|
| Cement type | LavAlk | Core taken in 2012 |
| Fly ash | X | |
| Microsilica | - | Cement type: Lavalkali |
| Slag | - | |
| W/C, apparent | 0.40 | |
| Air % | 3-4 | |
| | | Section No: 7206-F3 |

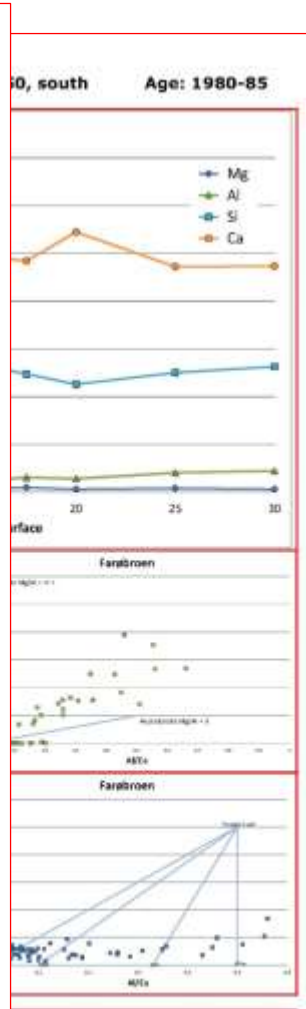


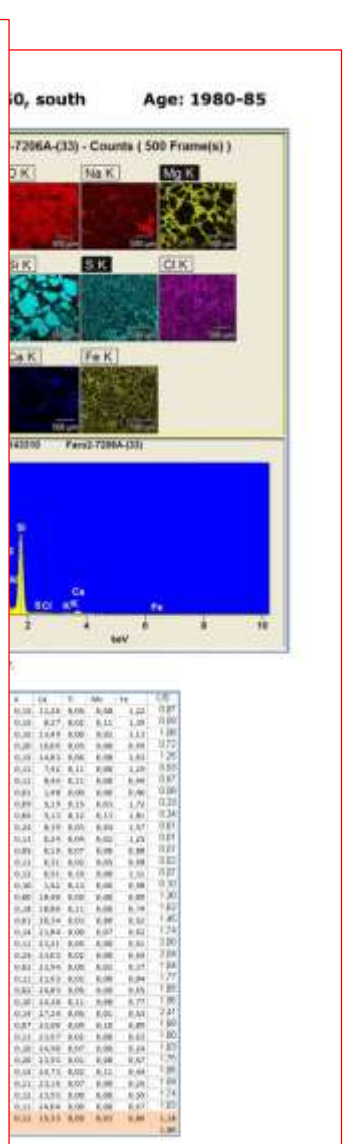
Micro-observations

Micro-structural zoning through concrete:

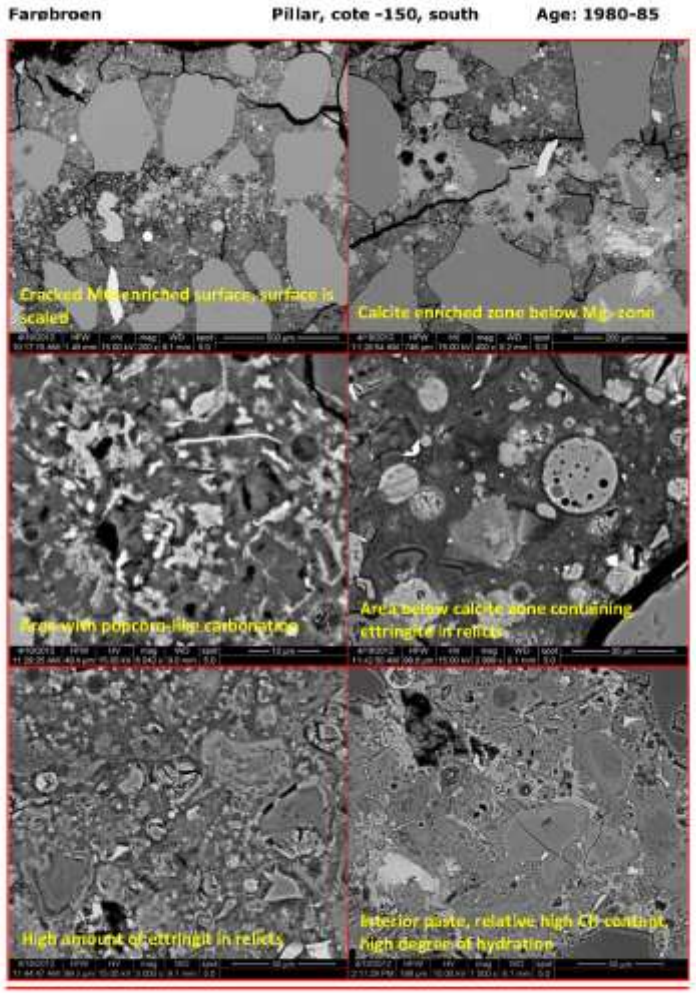
1. Surface is uneven and scaled. A thin calcite crust is occasionally observed, as well a paste damaged by biological growth.
2. 0-3mm: Partially carbonated paste with bands of black paste. Massive ettringite and thaumasite-like phases are observed in air voids. Paste is highly cracked.
3. 3-10mm: Porous, 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 autogeneous cracks in paste.

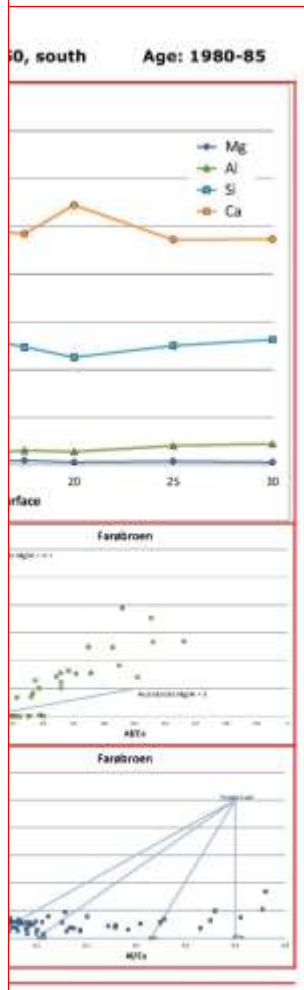


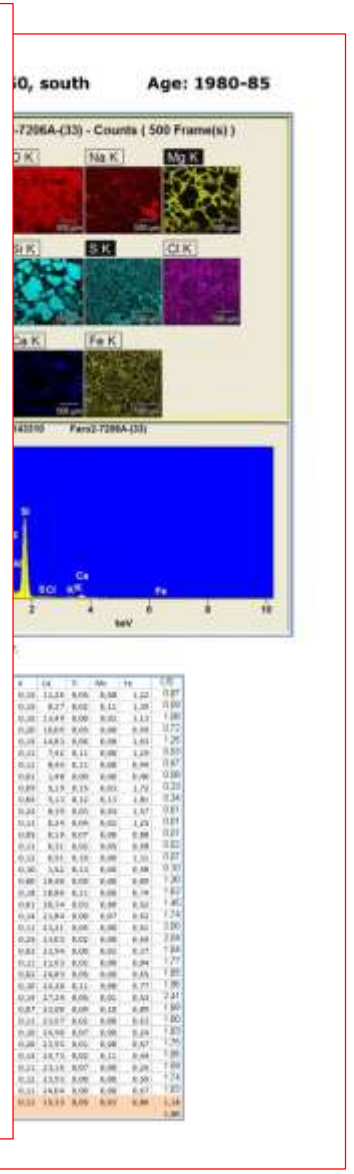



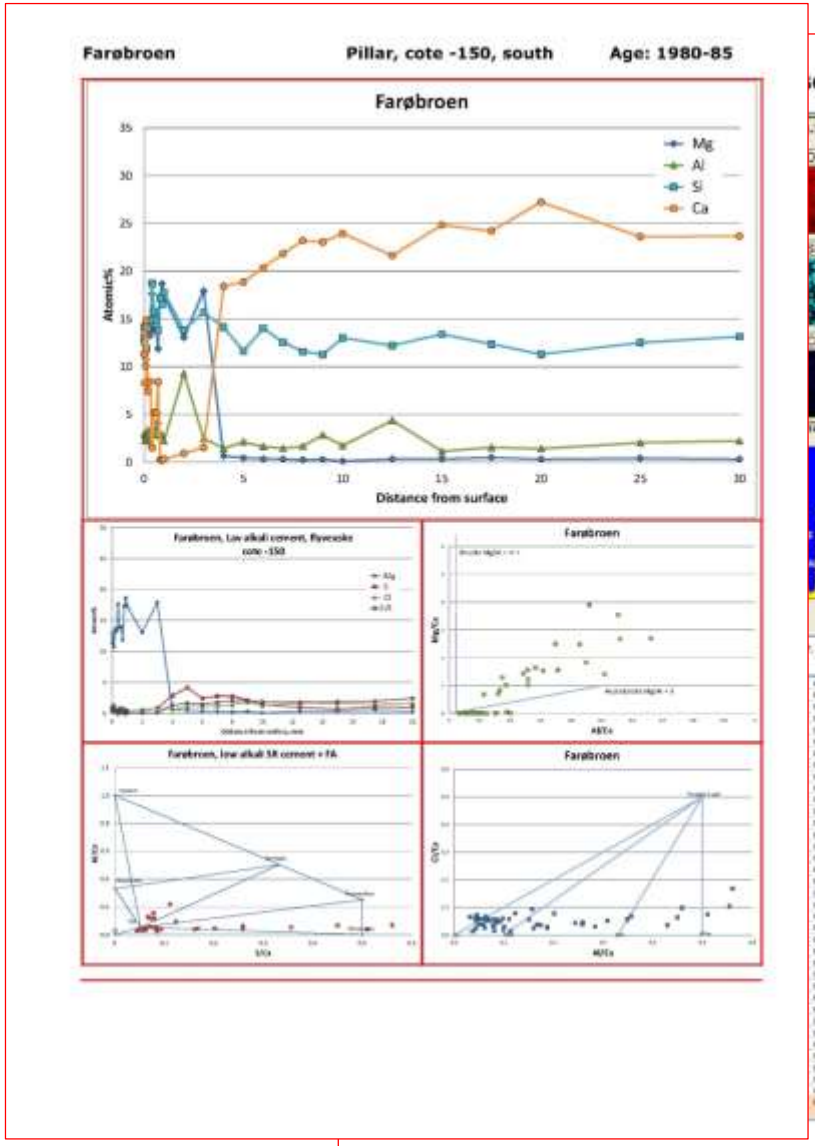
# Mikroskopi og SEM-EDX – dataark 2



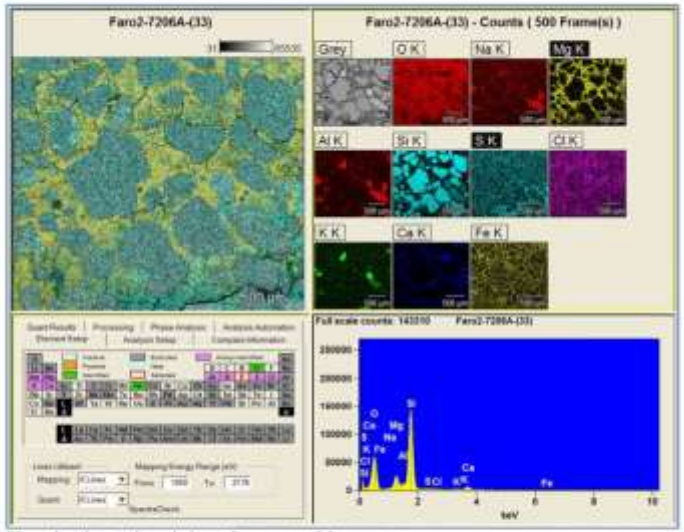



# Mikroskopi og SEM-EDX – dataark 3



# Mikroskopi og SEM-EDX – dataark 4

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




*Phase distribution through the surface region of the concrete.*