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NTNU  
Norwegian University of  
Science and Technology

# Anvendelse af marine feltdata til forudsigelse af kloridindtrængning i beton

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# Indhold

I. — Intro

- II. Indsamling af kloriddata og vurdering af, hvordan det bør anvendes
- III. Kvadratrods metode til bestemmelse af videre kloridindtrængning
- IV. Anvendelse af Machine Learning til forudsigelse af kloridindtrængning i designstadiet



# Indsamling af kloriddata og vurdering af hvordan det bør anvendes

Paper II: Correlating the development of chloride profiles and microstructural changes in marine concrete up to ten years  
& Paper IV: When and how should chloride profiles be calibrated for paste fraction?



# Fokus fokus fokus

Mixture proportions of concrete exposed at the Fehmarn Belt Exposure Site [kg/m<sup>3</sup>].

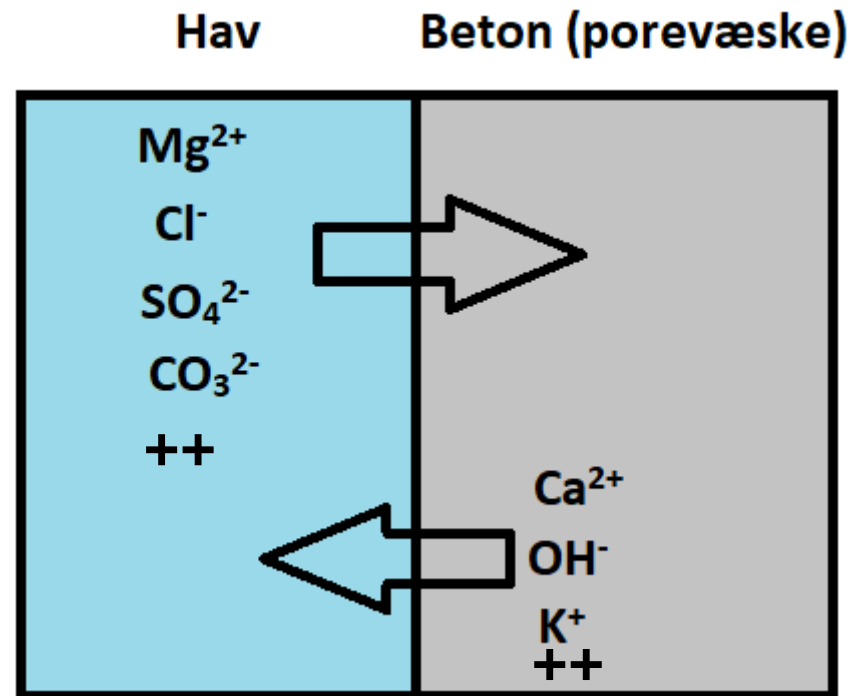
Concrete ID in thesis		PC	15FA	25FA	25FA_SCC	4SF	12FA4SF	12FA4SF_ noAEA	12FA4SF_ high_wc	12FA4SF_ low_wc	12FA4SF_ SCC	SG	SG_noAEA	SG_SCC	SG_rapid
Original concrete ID		A	B	C	D	E	F	G	H	I	J	K	L	M	N
Group I		x	x	x		x	x					x			
Group II								x	x	x			x		x
Group III					x						x			x	
Powder composition [wt.%]	CEM I 42.5N -SR5	100	85	75	75	96	84	84	84	84	84				
	CEM I 52.5N														30
	CEM III <sup>a)</sup>											100	100	100	
	FA		15	25	25		12	12	12	12	12				
	SF					4	4	4	4	4	4				
	GGBS														70
	w/(c+2SF+0.5FA+GGBS)	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.45	0.35	0.40	0.40	0.40	0.40	0.40

a) GGBS content: 67% by wt.

FA = Fly Ash, SF = Silica Fume, GGBS = Ground Granulated Blast-furnace Slag



# Transport af ioner til/fra beton



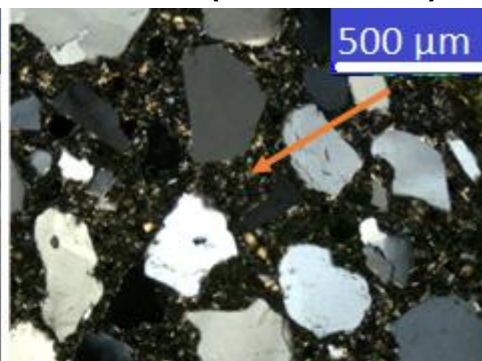
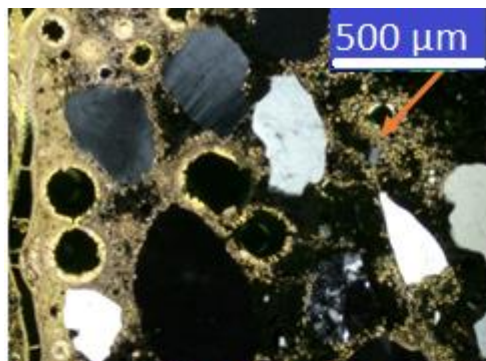
# "Microstructurally Changed Zone"

Surface

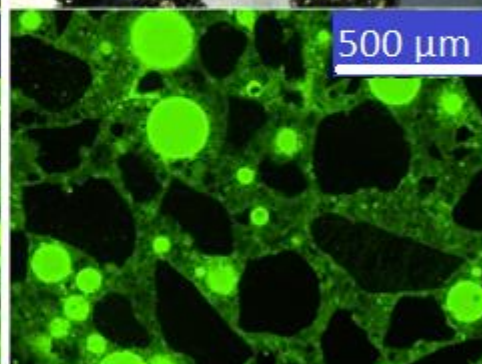
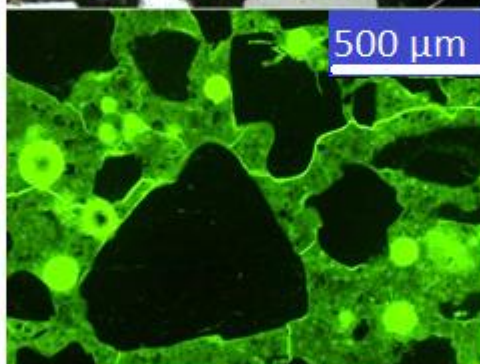
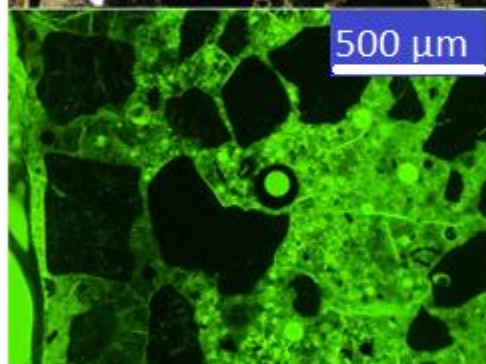
Opaline

Bulk ("normal")

Light mode:  
Cross polarized



Fluorescence

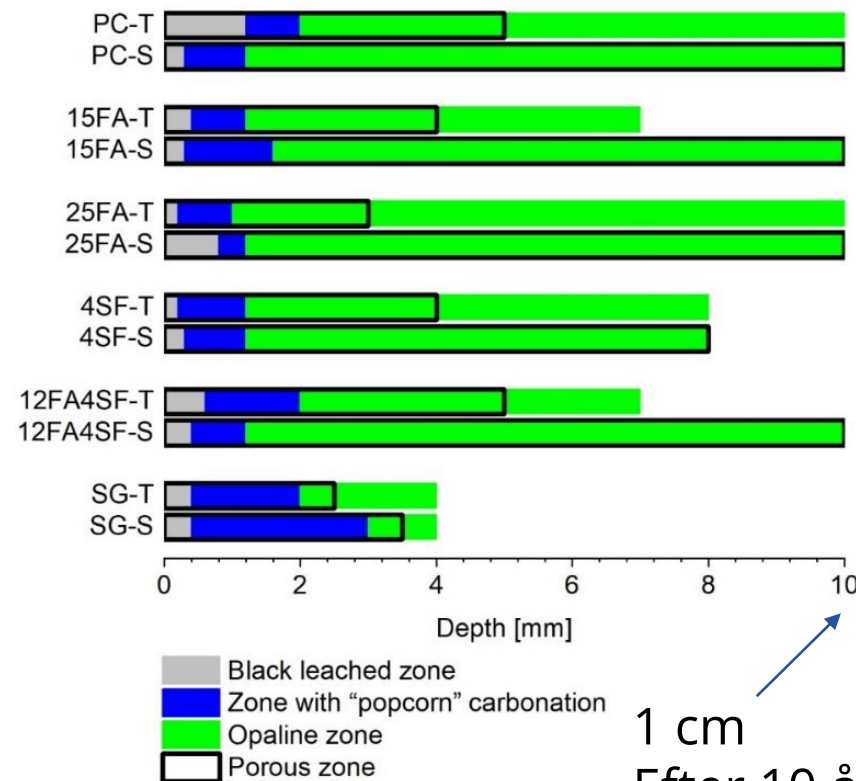


Surface zone (Typical <1 mm depth): intermixed leached paste and popcorn carbonation (marked with arrow), high porosity.

Opaline zone (Typical of 2–10 mm depth): no visible CH, with increased porosity and micro-cracking.

Bulk (Typical of >10 mm depth): visible CH (marked with arrow) and apparent w/c of 0.40.

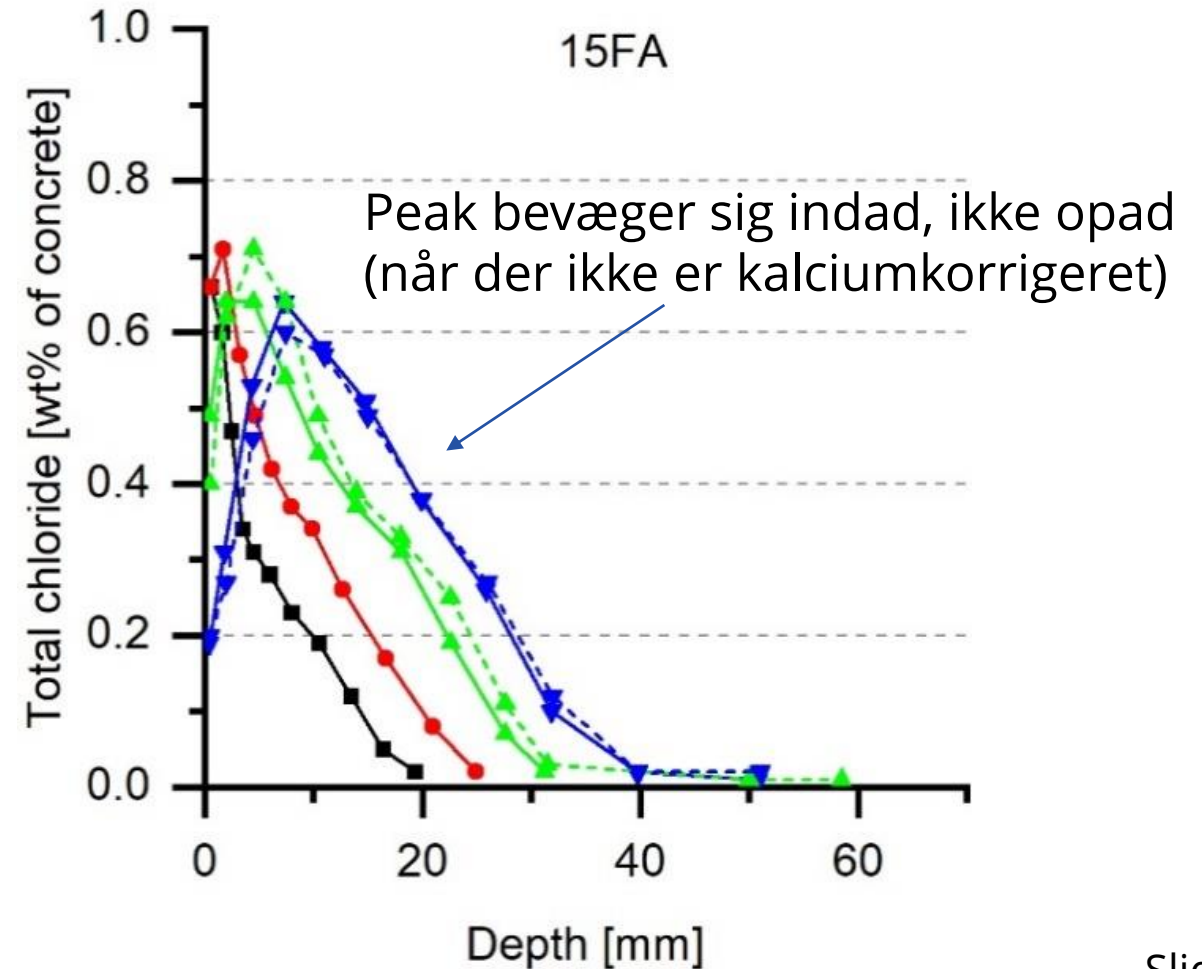
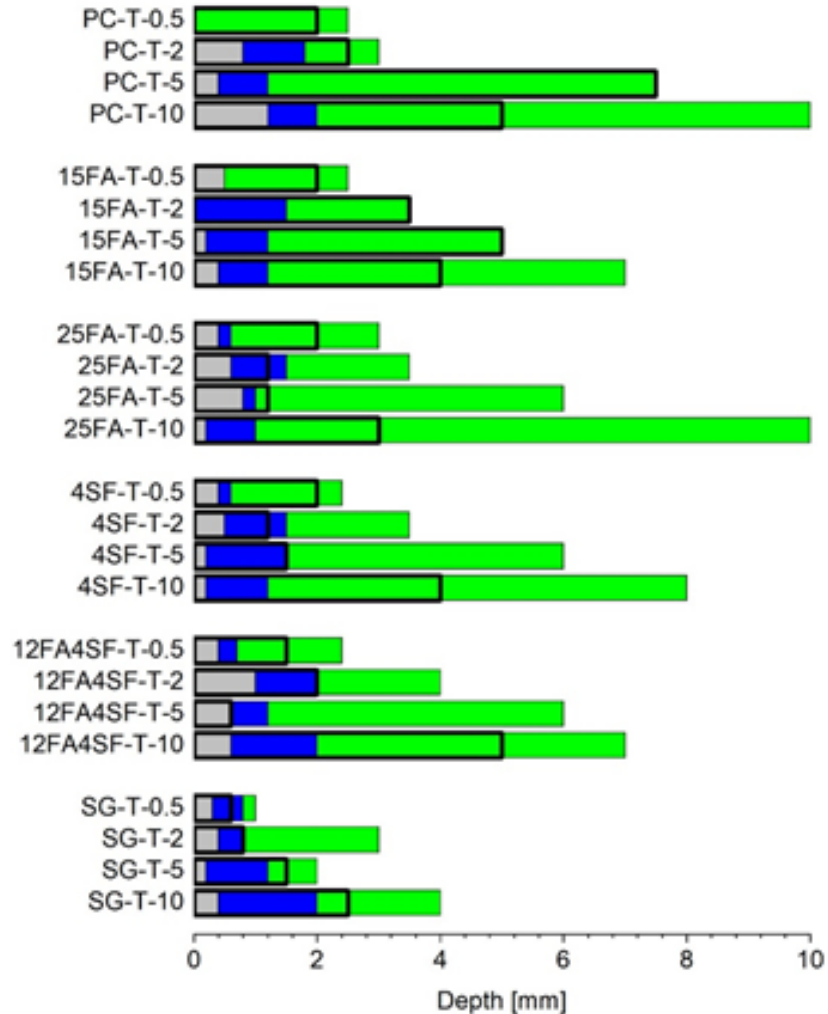
## Microstructurally Changed Zone



1 cm  
After 10 år

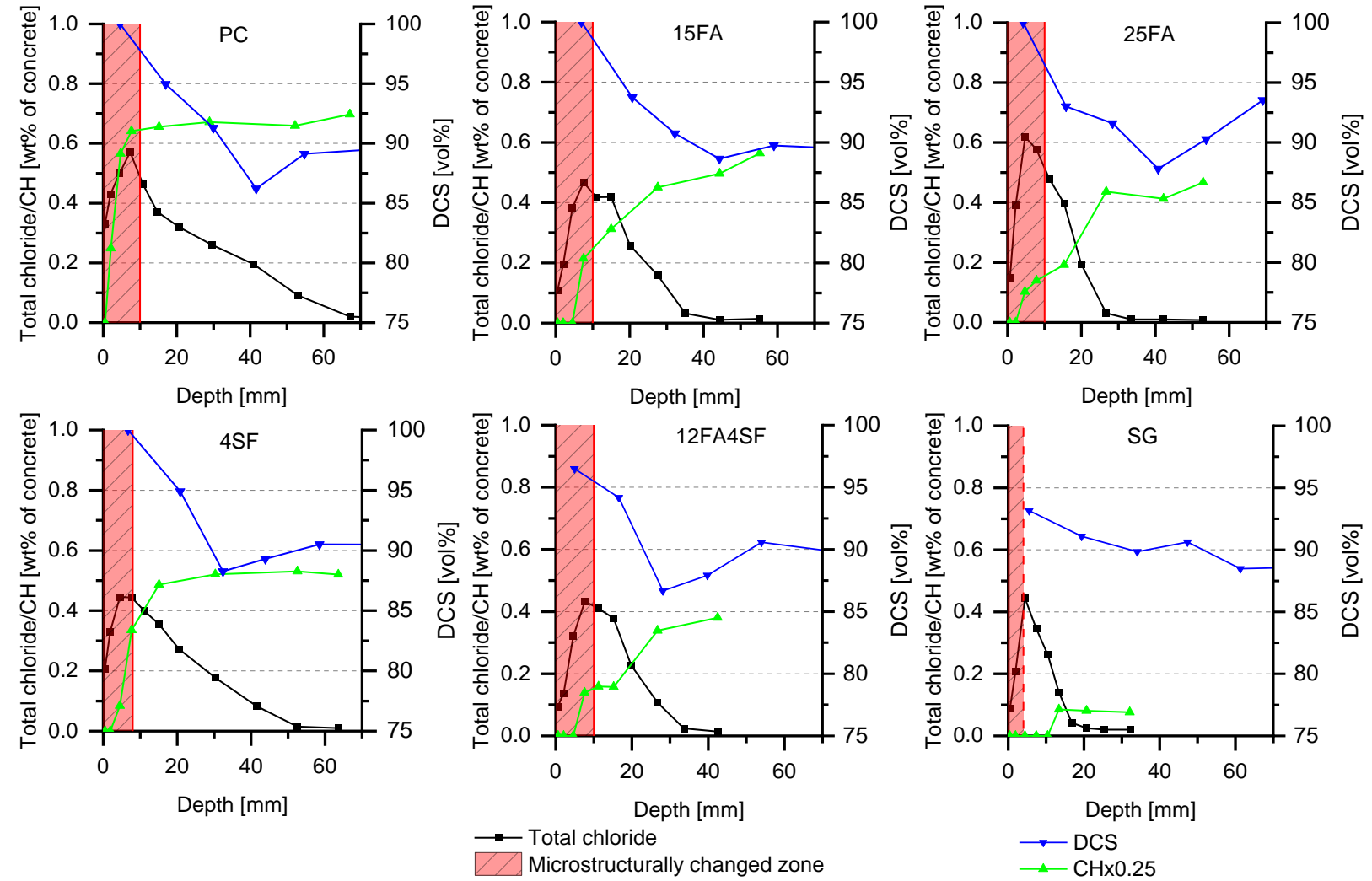


# Både MCZ og klorider bevæger sig indad over tid





# Kloridprofiler vs. MCZ vs. portlandit vs. Vandmætningsgrad (10år)

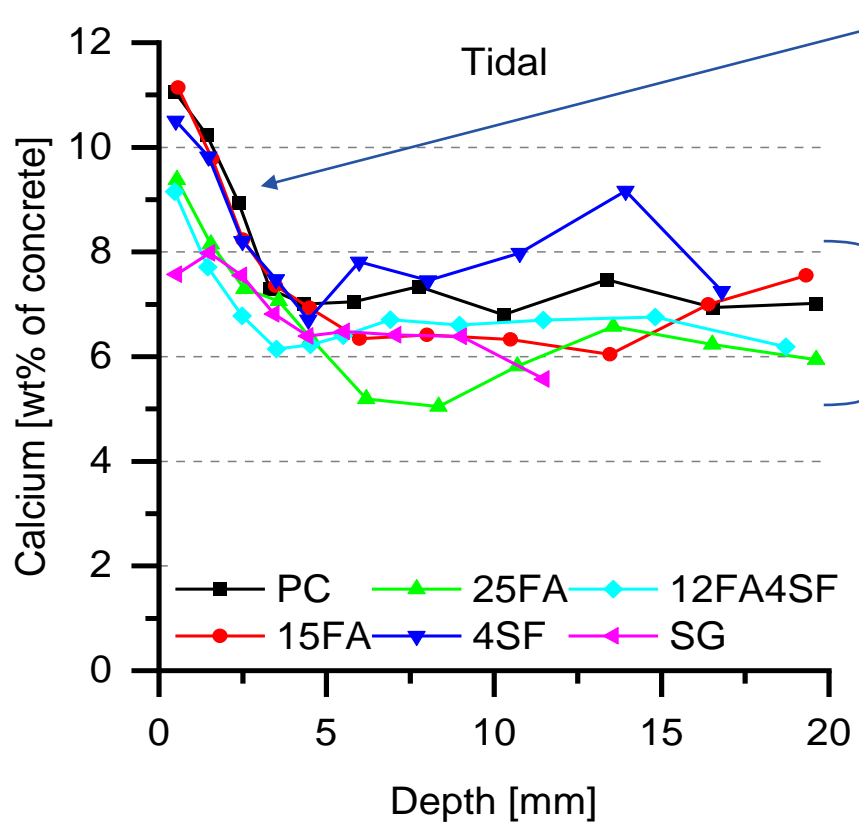






# Kalciumkalibrering (konvertering fra klorid/beton til klorid/binder)

Klorid trænger ind gennem pasta, ikke sten.

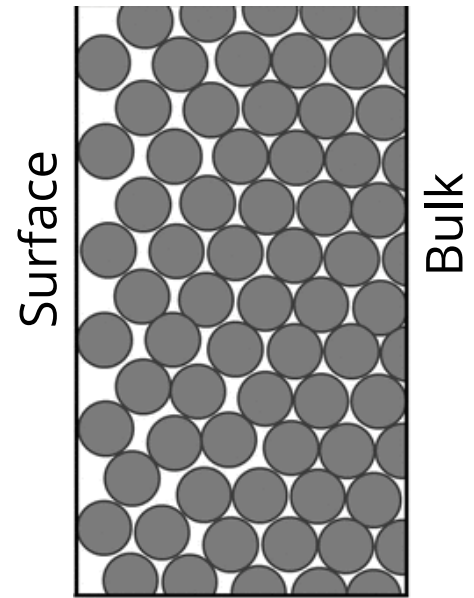


After 1/2 year of marine exposure

Systematisk variation (væg-effekt)

$$Kalibreret\ klorid\ indhold = \frac{wt\%Cl_{m\ddot{a}lt}}{wt\%Ca_{m\ddot{a}lt}} \times wt\%Ca_{teoretisk}$$

Usystematisk variation



Nie, Zhijie, et al. "Minicolumn test of remaining GAC performance for taste and odor removal: Theoretical analysis." Journal of Environmental Engineering 146.1 (2020): 04019097.

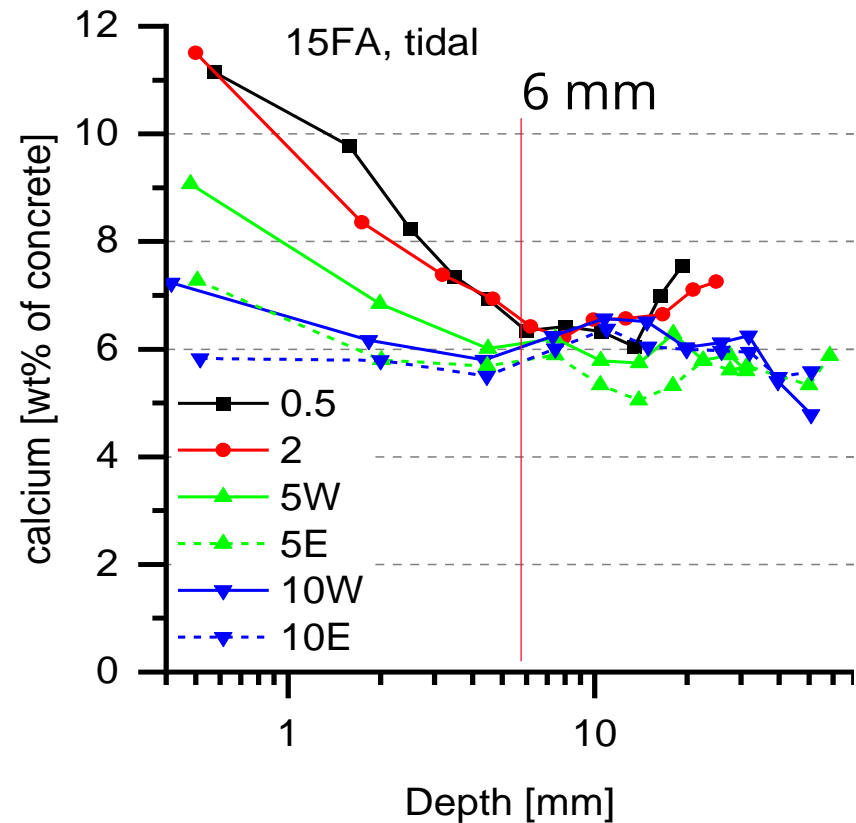


# Kalcium kalibrering calibration impact

$$\text{Kalibreret klorid indhold} = \frac{\text{wt}\%Cl_{\text{målt}}}{\text{wt}\%Ca_{\text{målt}}} \times \text{wt}\%Ca_{\text{teoretisk}}$$

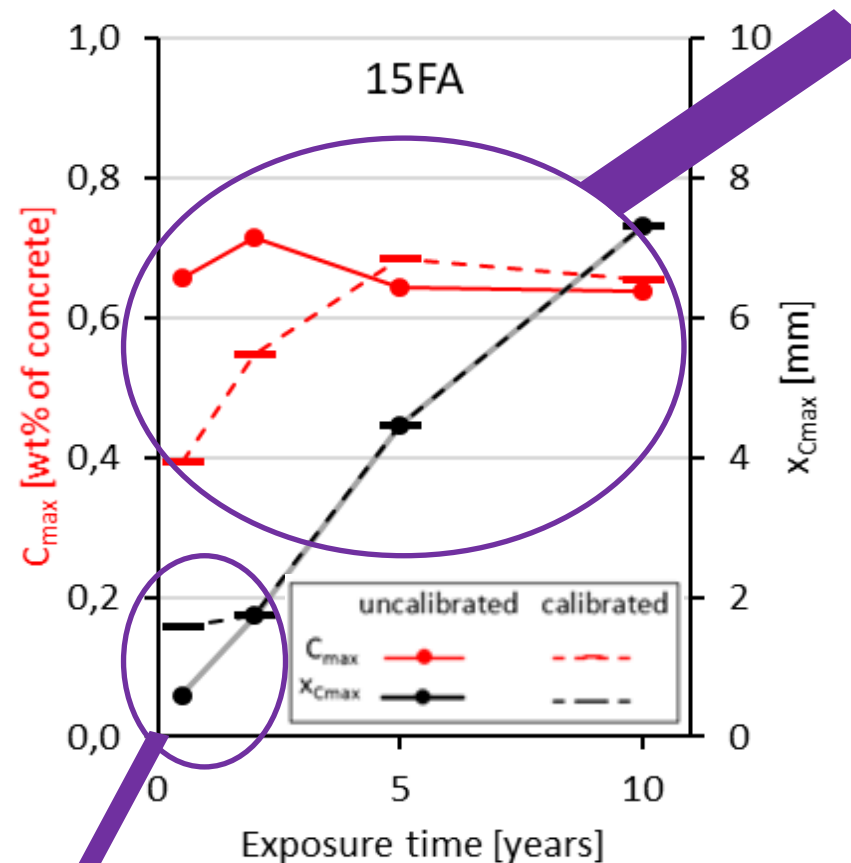
Leaching udgør problem

→



Efter ½, 2, 5 og 10 års marin eksponering

- Kalibreret maksimal kloridkoncentration ( $C_{\text{max}}$ ) stiger over tid (målt kalcium falder)



- Indflydelse på peak position



# Anbefaling vedrørende brug af data

- Ignorerer data influeret af mikrostrukturelle ændringer  
(I praksis maximum kloridkoncentration og alt tættere på overfladen)

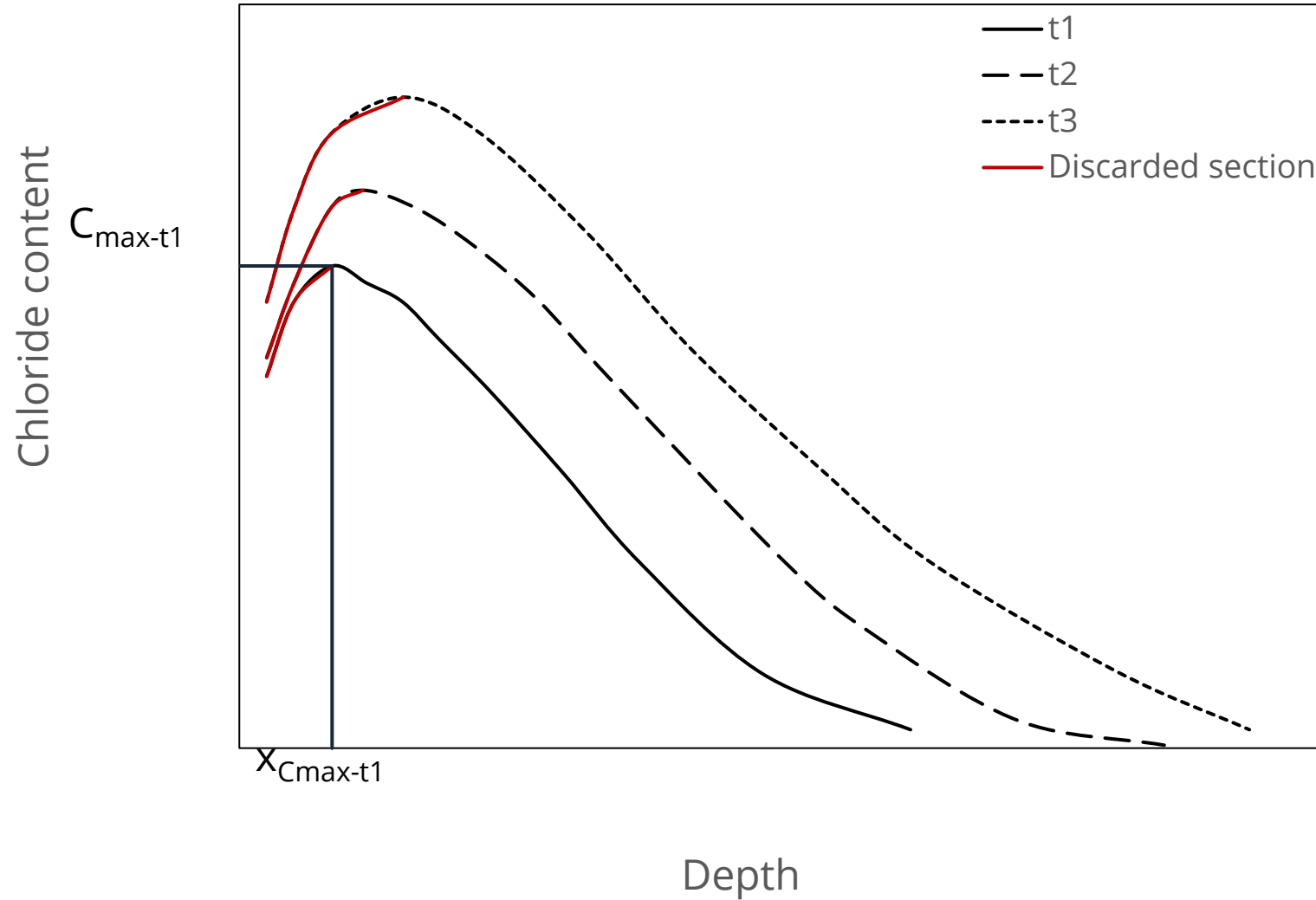


# Kvadratrodsmetoden

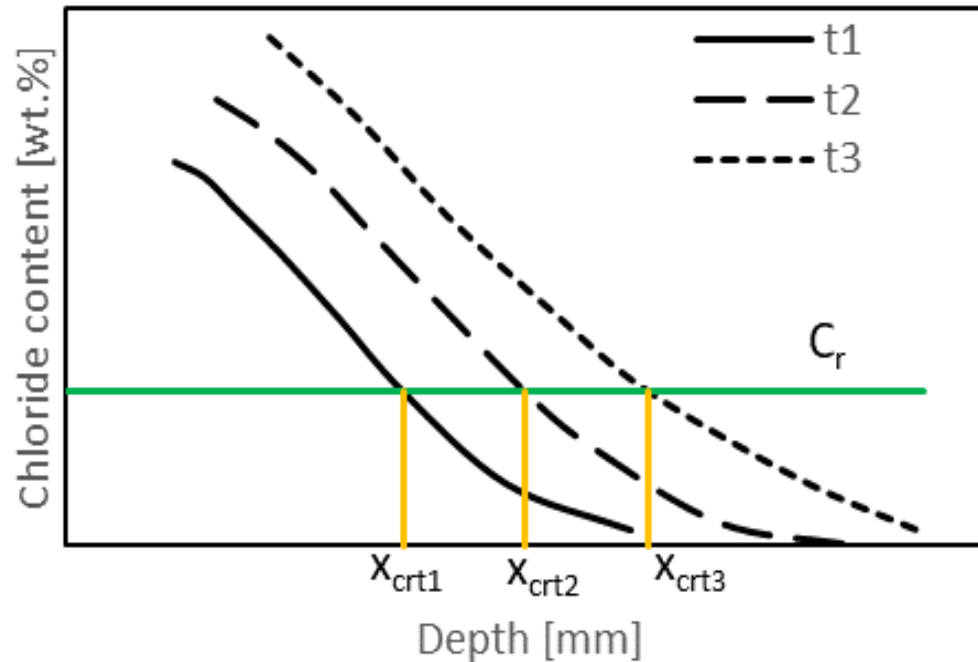
Paper I: The square root method for chloride ingress prediction – Applicability and limitations



# Metodebeskrivelse - step 1



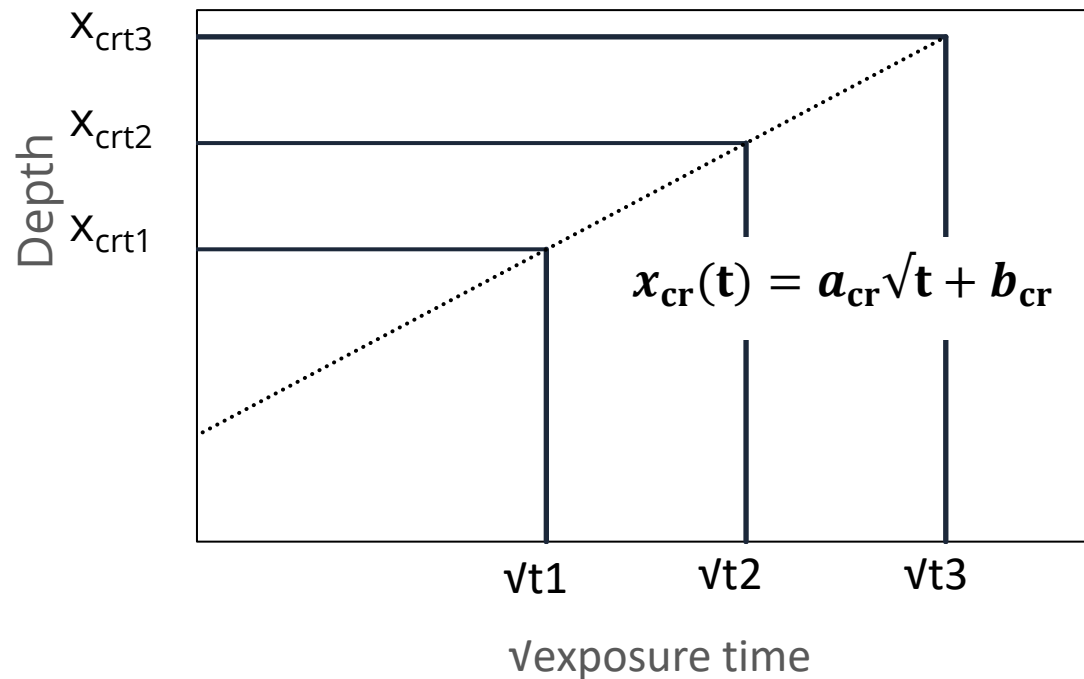
# Metodebeskrivelse – step 2



## Step 2

- Udvalg en referencekoncentration ( $C_r$ ),  
 $C_r < C_{\max-t1}$ .
- For hver kloridprofil identificeres indtrængningsdybden ( $x_{Cr}$ ) for  $C_r$ .

# Metodebeskrivelse – step 3

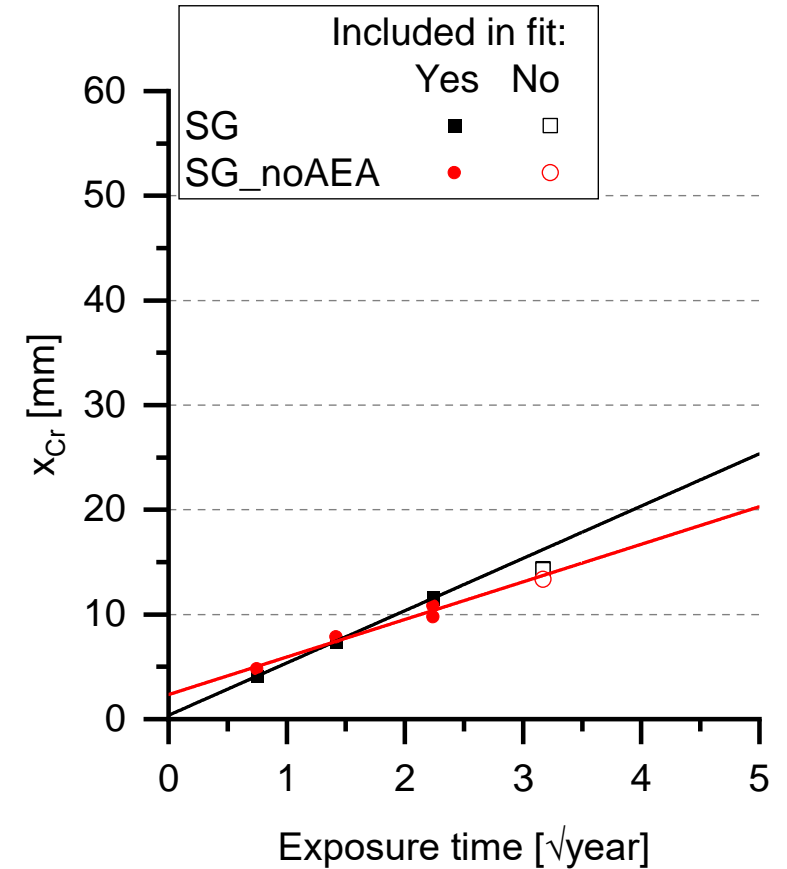
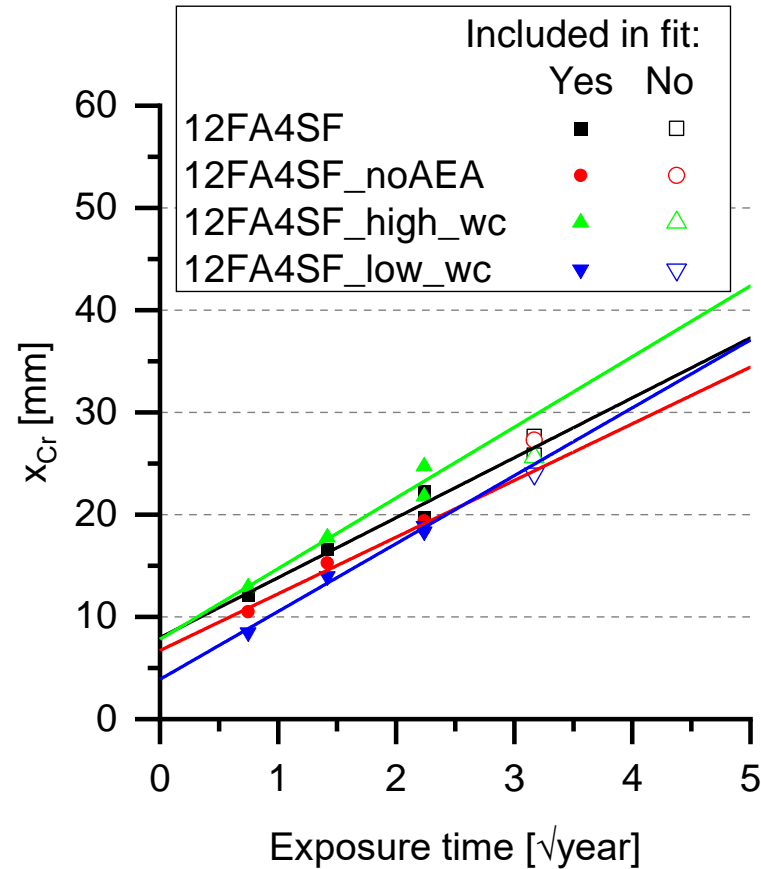
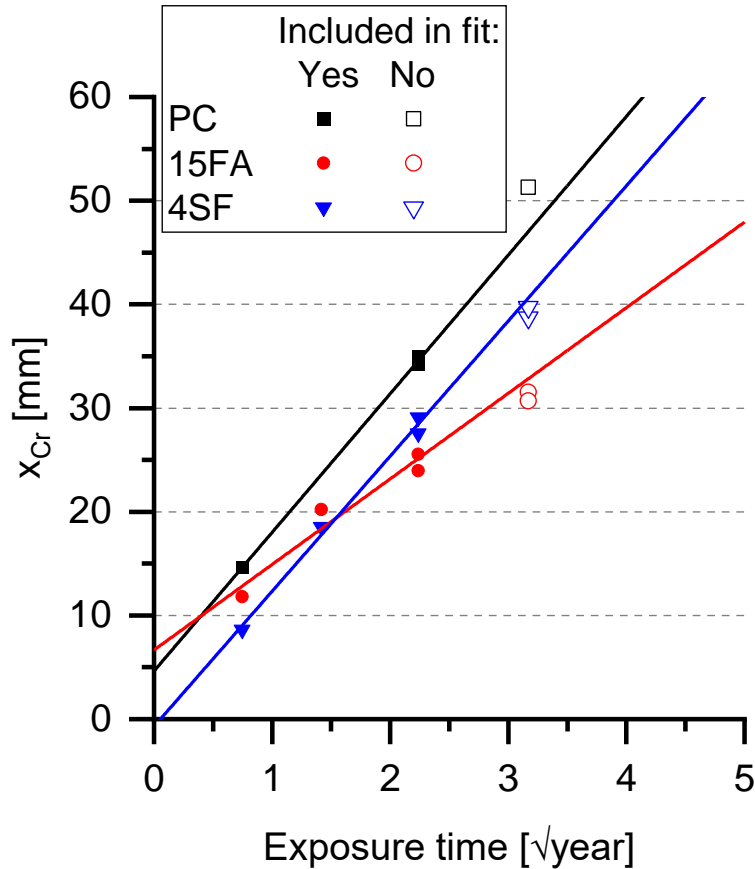


## Step 3

- Plot  $x_{\text{Cr}}$  mod kvadratroden af tiden og bestem hældningen ( $a_{\text{Cr}}$ ) og skæringen ( $b_{\text{Cr}}$ ) ved lineær regression.
- Dybden af referencekoncentrationen ( $x_{\text{Cr}}$ ) som funktion af tiden kan nu beskrives:

$$x_{\text{Cr}}(t) = a_{\text{Cr}}\sqrt{t} + b_{\text{Cr}}$$

# Eksempler på forudsigelse af videre kloridindtrængning



+ God forudsigelse af videre kloridindtrængning ( $R^2$  på 0,96 for 237 rette linier)

- Ikke brugbar for design scenarie.





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# Videre forskning (efter PhD)



Efterfølgende slides er fjernet, da resultaterne endnu ikke er offentliggjort.



# References

Poulsen, S. L. and H. E. Sørensen (2014). Chloride ingress in old Danish bridges. Proceedings 2nd International Congress on Durability of Concrete (ICDC), New Delhi, India.

Poulsen, S. L., H. E. Sørensen and U. Jönsson (2018). Chloride ingress in concrete blocks at the Rødbyhavn marine exposure site - Status after 5 years. 4th International Conference on Service Life Design for Infrastructures (SLD4). Delft, The Netherlands: 192-203.

Danner, T., U. Hjorth Jakobsen and M. R. Geiker (2019). Mineralogical Sequence of Self-Healing Products in Cracked Marine Concrete. *Minerals* **9**(5): 284:

Y. Cao, C. Gehlen, U. Angst, L. Wang, Z. Wang, Y. Yao, Critical chloride content in reinforced concrete—An updated review considering Chinese experience, *Cement and Concrete Research* 117 2019 58-68. <https://doi.org/10.1016/j.cemconres.2018.11.020>.

U.H. Jakobsen, K. De Weerd, M.R. Geiker, Elemental zonation in marine concrete, *Cement and Concrete Research* 85 2016 12-27

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Georget et al, in review



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# Thanks for listening!

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