Performance based design of concrete – durability

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Performance based service life design: durability of concrete

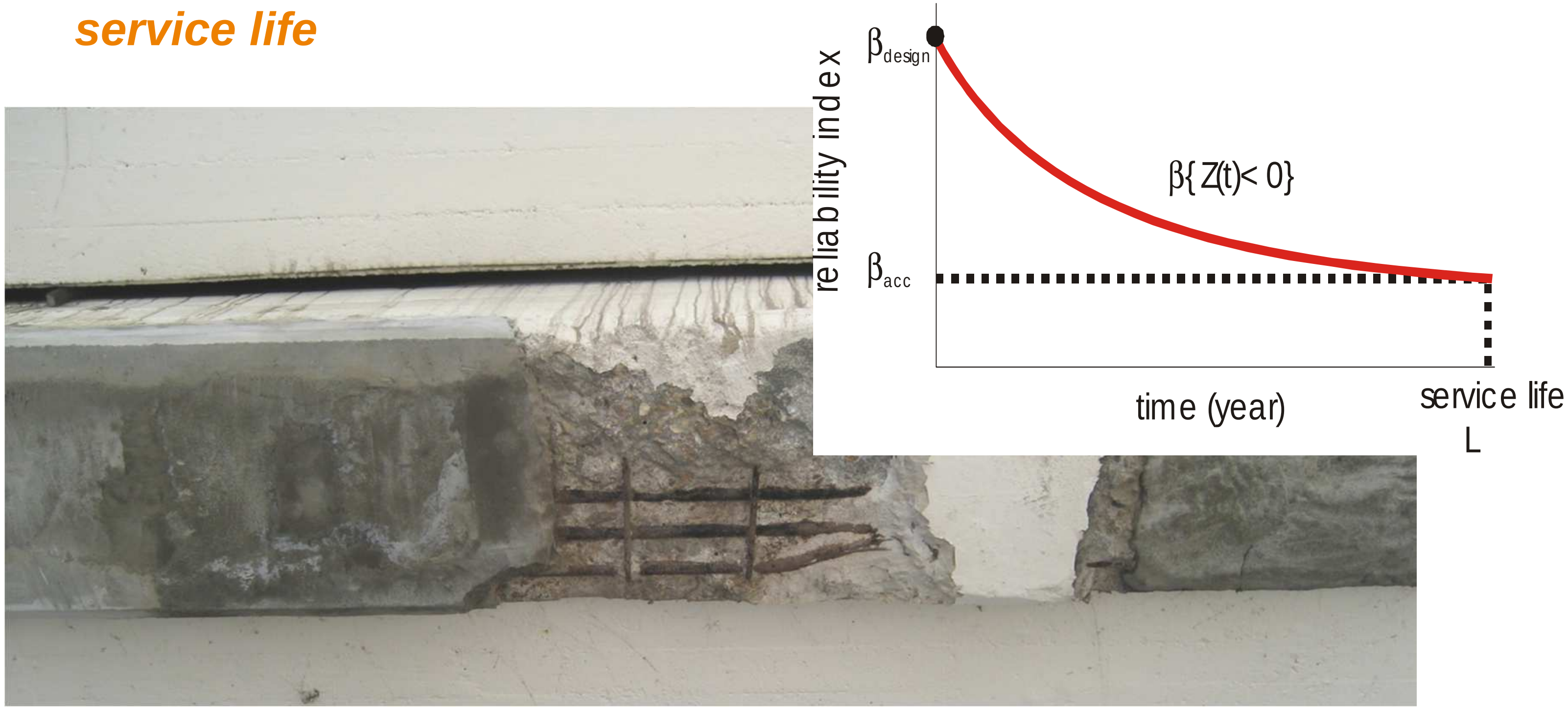
Contents:


1. Introduction: what is durability

- Durability is the resistance of concrete to degradation
- Degradation is the decrease in properties of concrete under influence of loads, mostly from the outside
- Loads include:
- - mechanical loads (e.g. self weight)
- - physical loads (e.g. T)
- - chemical loads (e.g. CO_2)

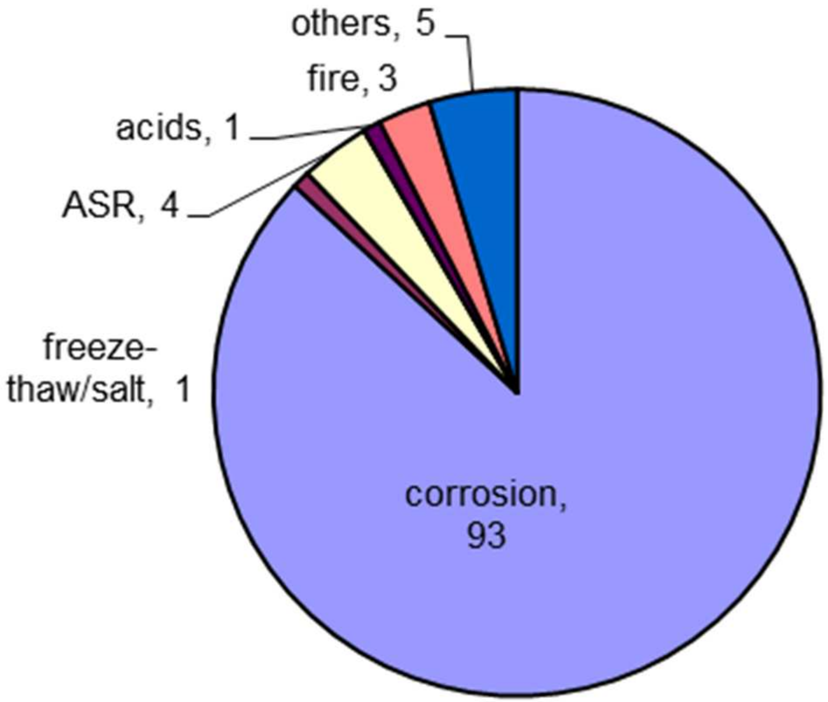
1. Introduction: why is durability important

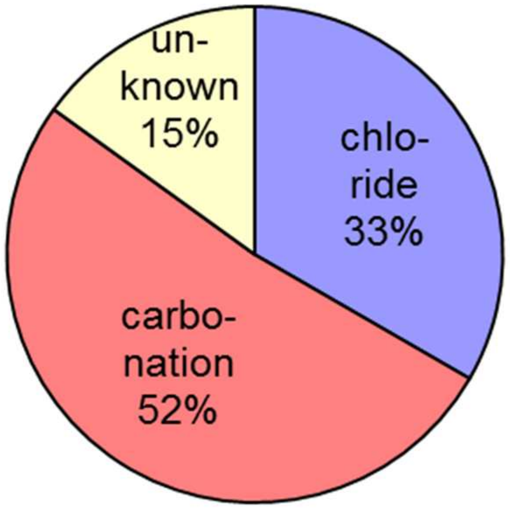
- ***Degradation** is most often due to attack of the cement stone but also the aggregates and / or rebars.*
- ***Damage** include spalling & cracking, loss of cover and loss of rebar diameter up to bending / shear and collapse*
- *This may lead to extensive repair & costs or even early **end of service life***



1. Introduction: why is it important?

- *The most often encountered durability issue is corrosion initiated by chloride or carbonation*



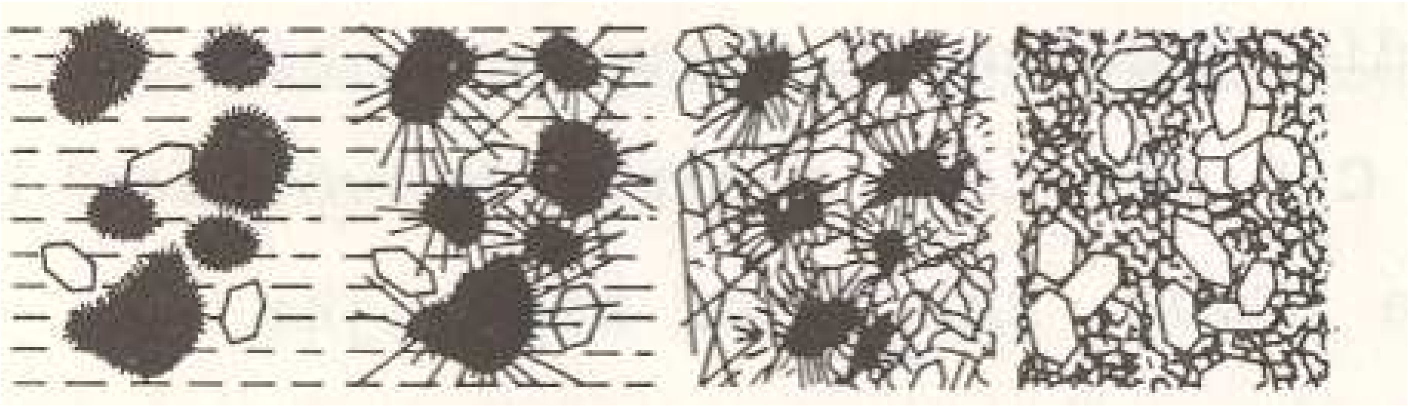


Performance based service life design: durability of concrete

Contents:

2. The structure of concrete

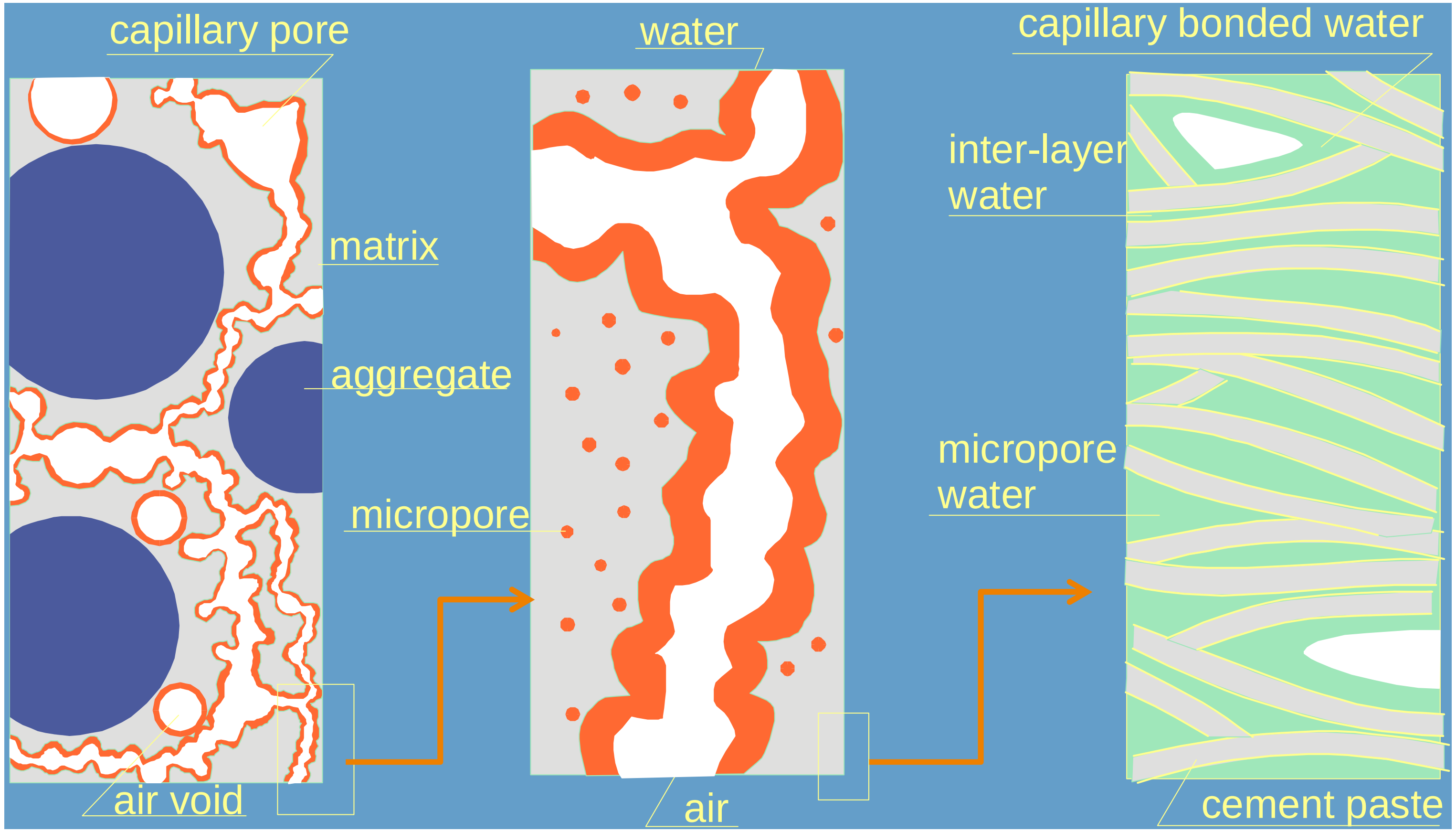
- Formation of hardened cement paste
  - Phase 1: plastics phase to semi-plastic phase
  - Phase 2: hardened phase



Phase 1
Growth of reaction products

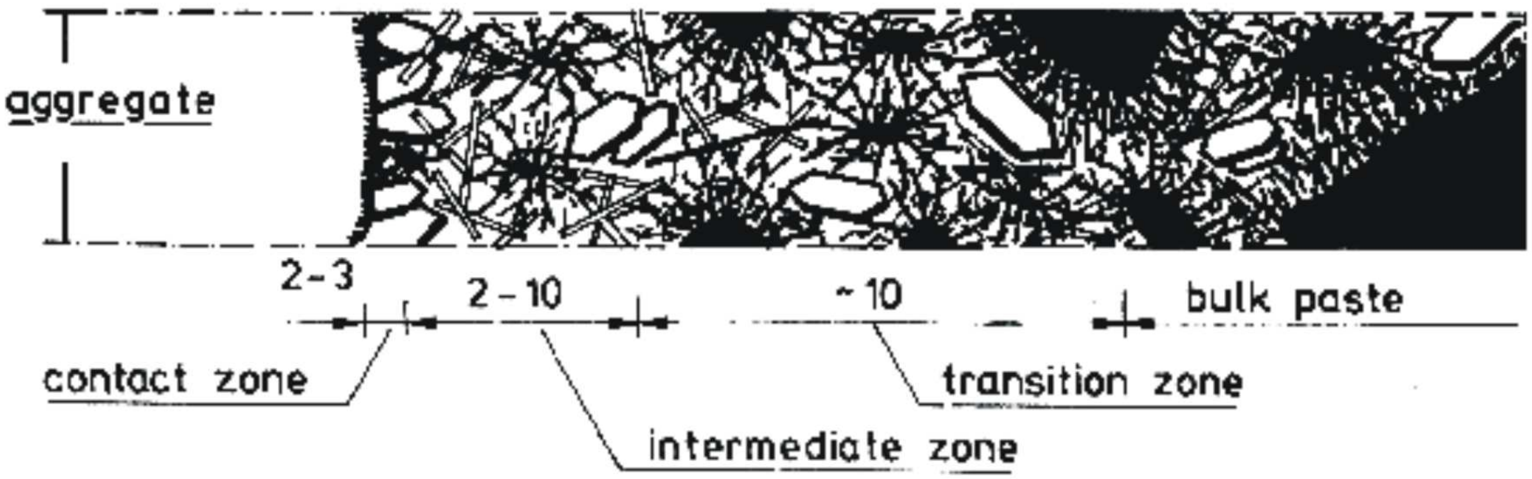
Phase 2
Connecting & Densification

2. The structure of concrete



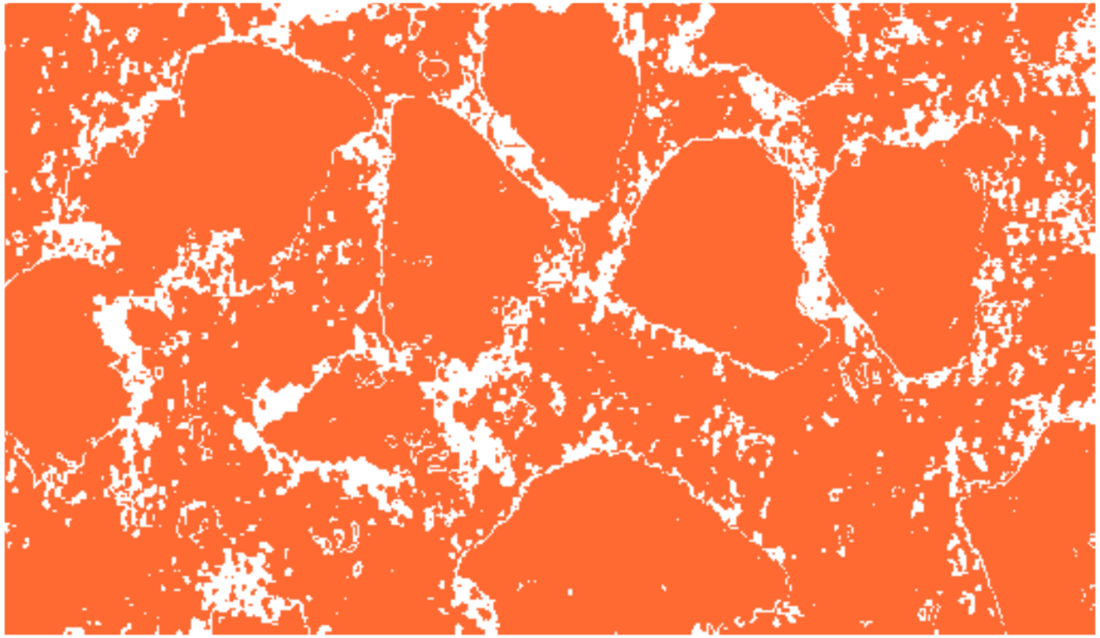
2. The structure of concrete

- Interface zone between aggregate and cement stone is often more porous than cement stone itself



2. The structure of concrete

- As a consequence it is not only the weakest link but also the most permeable part of the concrete



- Effect is smaller for fine grounded cements, e.g. CEM I 52.5 R versus CEM I 52.5 N or with fine additions (SF, FA)

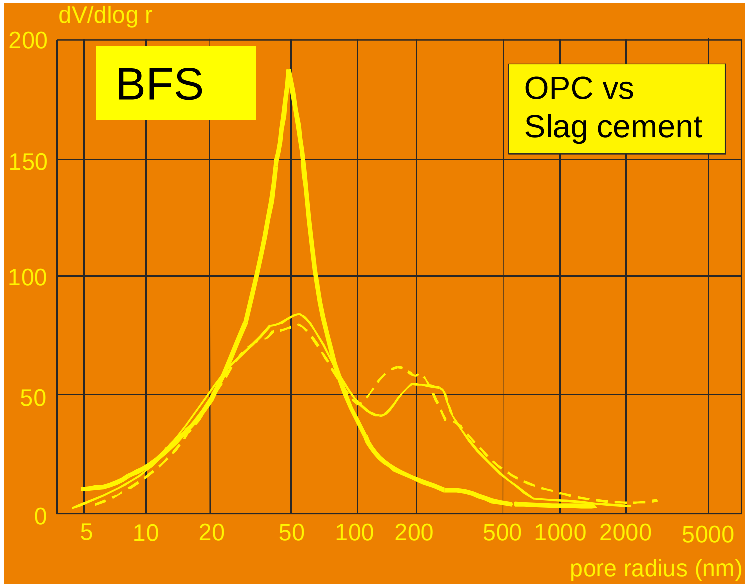
2. The structure of concrete

Some basics of the concrete’s structure that are important to understand degradation:

- porosity en pore size distribution
- degree of saturation and moisture distribution
- Relative humidity and absorption/desorption

2. The structure of concrete

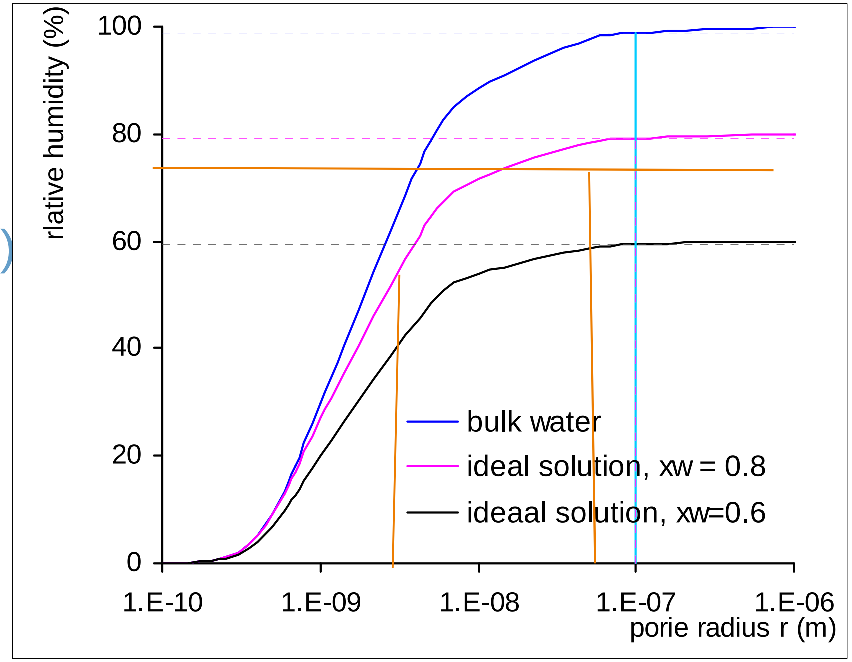
- Porosity = percentage (interconnected) hollow spaces (in vol%)
- Pore size distribution – depending on concrete composition, used cement and age (degree of hydration)



- Pore sizes are smaller for lower Ca-containing cement or with the use of additions (e.g. BFSC, FA)

2. The structure of concrete

- Degree of saturation = amount of water in the pores (% of total)
- Moisture distribution – depending on rh, concrete composition and presence of salts



BFS **OPC**

- Smaller pores (e.g. BFS cement) are saturated at lower RH

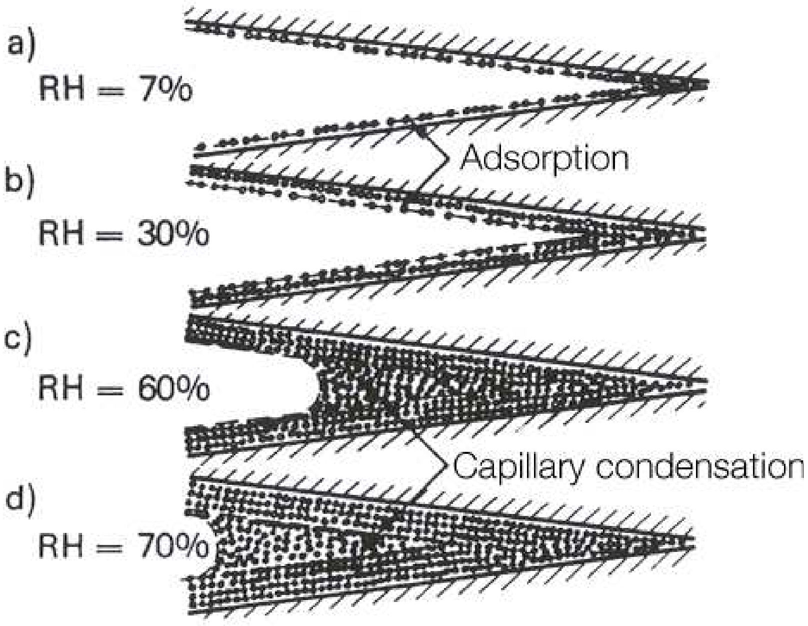
Examples full saturation at 75%:

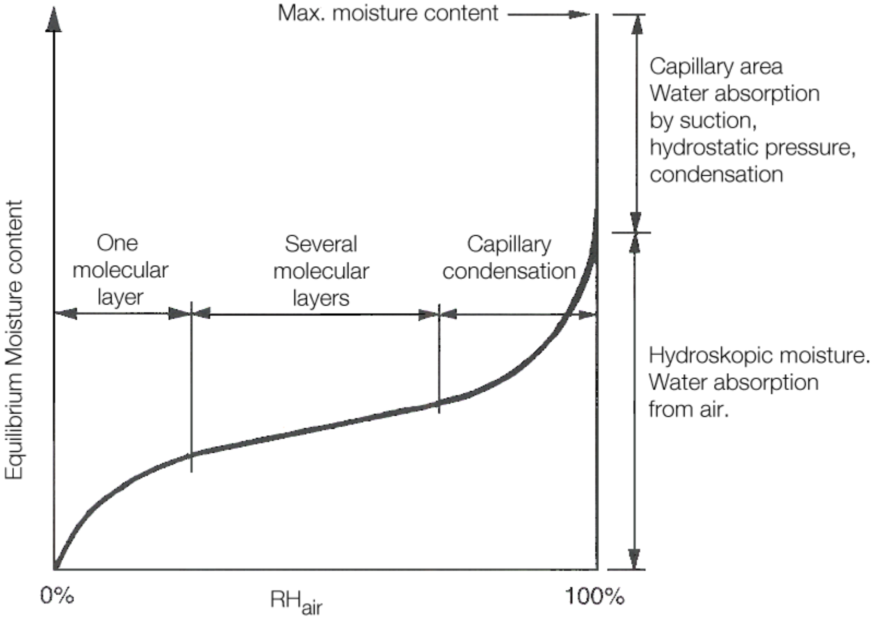
(1) no salt: r< 6 nm

(2) salt 0.2: r< 20 nm

(N.B. salt is hygroscopic!)

3. The structure of concrete – moisture distribution

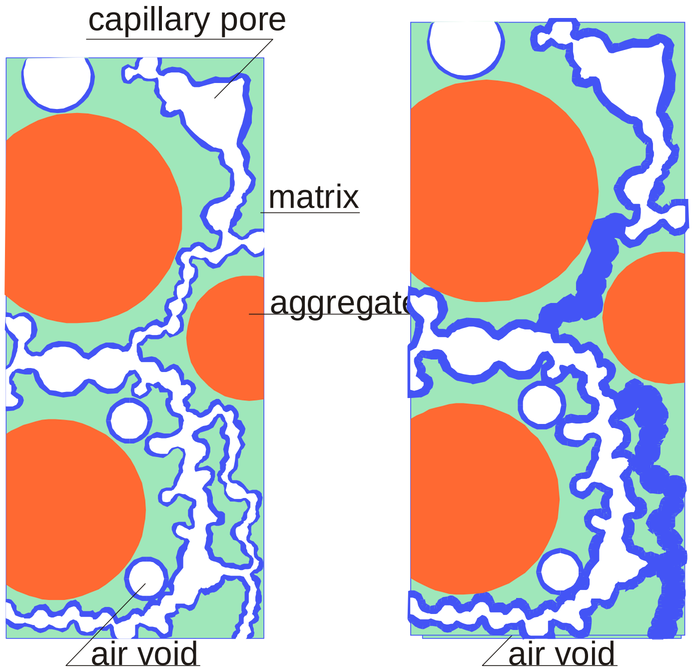




3. The structure of concrete

- Importance of the structure and the moisture distribution
  - Durability = transport + (chemical) reactions
  - Transport rate / type depend on structure and related moisture distribution

- Transport examples:
- Water/ions at S> S_{crit}
- water vapour/gas at S <S_{crit}



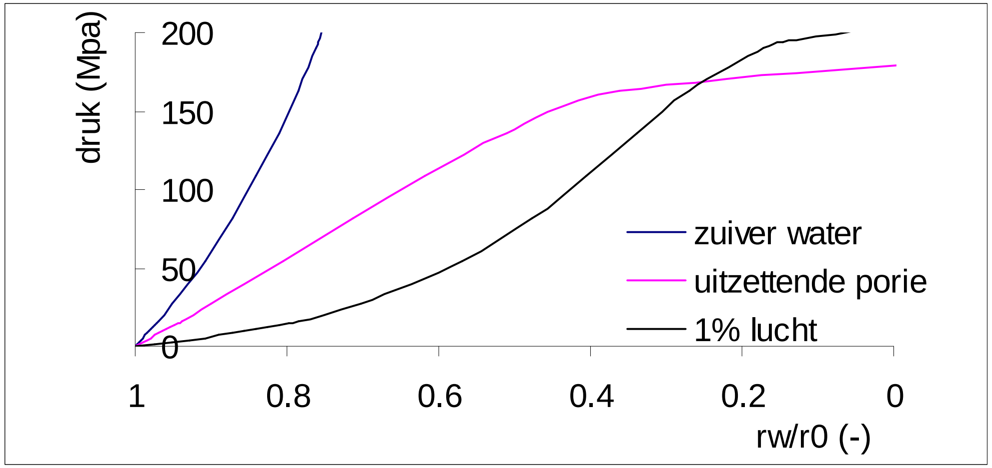
Performance based service life design: durability of concrete

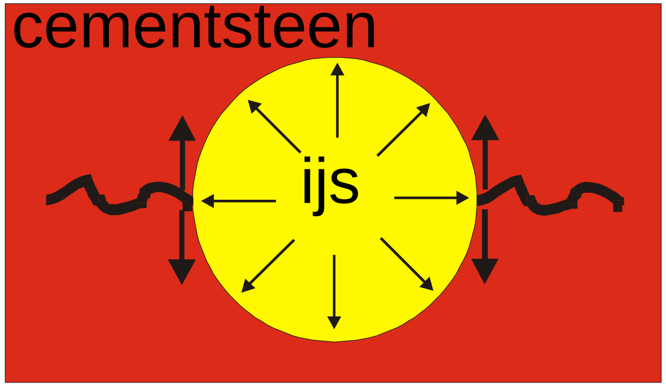
Contents:

1. Introduction: what is durability?
2. Getting a grip on probabilities: structure of concrete
3. Degradation mechanisms
   - Freeze-thawing
   - Alkali-silica reaction (ASR)
   - Carbonation an chloride penetration / corrosion
   - Sulfate and seawater resistance
4. Performance of different binders
5. Conclusions

3.1 Degradation mechanisms: Freeze-thawing

- Mechanism 1: expansion of ice (compared to water approx. 10%)

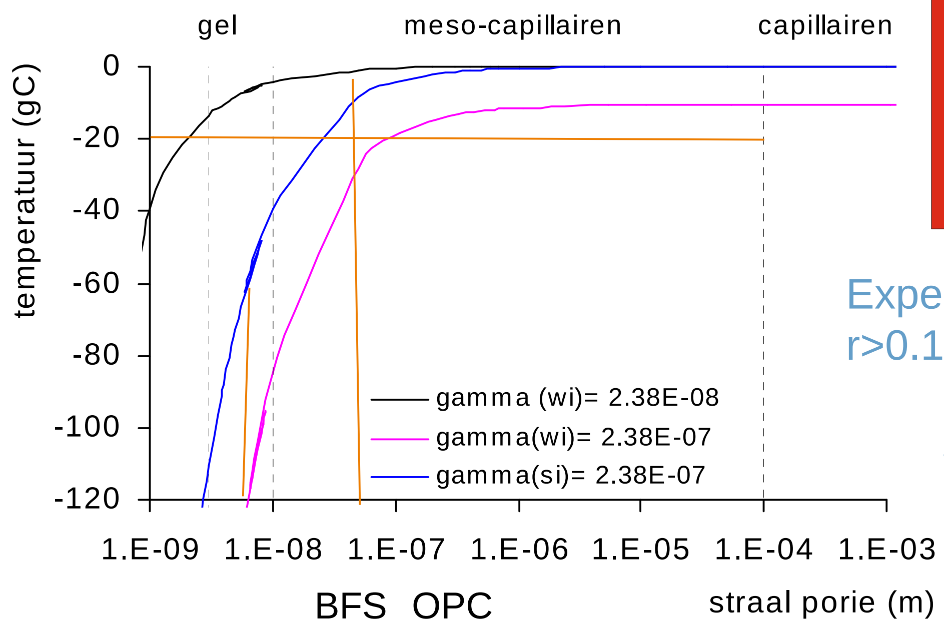


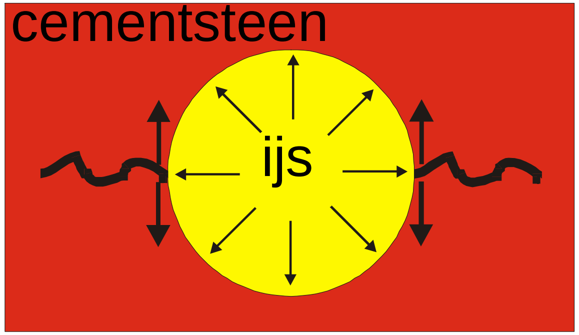


- Conditions:
- High enough Sr
- Low enough temperature
- Fast enough freezing

3.1 Degradation mechanisms: Freeze-thawing

- Mechanism 1: expansion of ice (compared to water approx. 10%)
- Mind: the freezing temperate increases with reduction in pore size and increase in salt concentration





Experiments

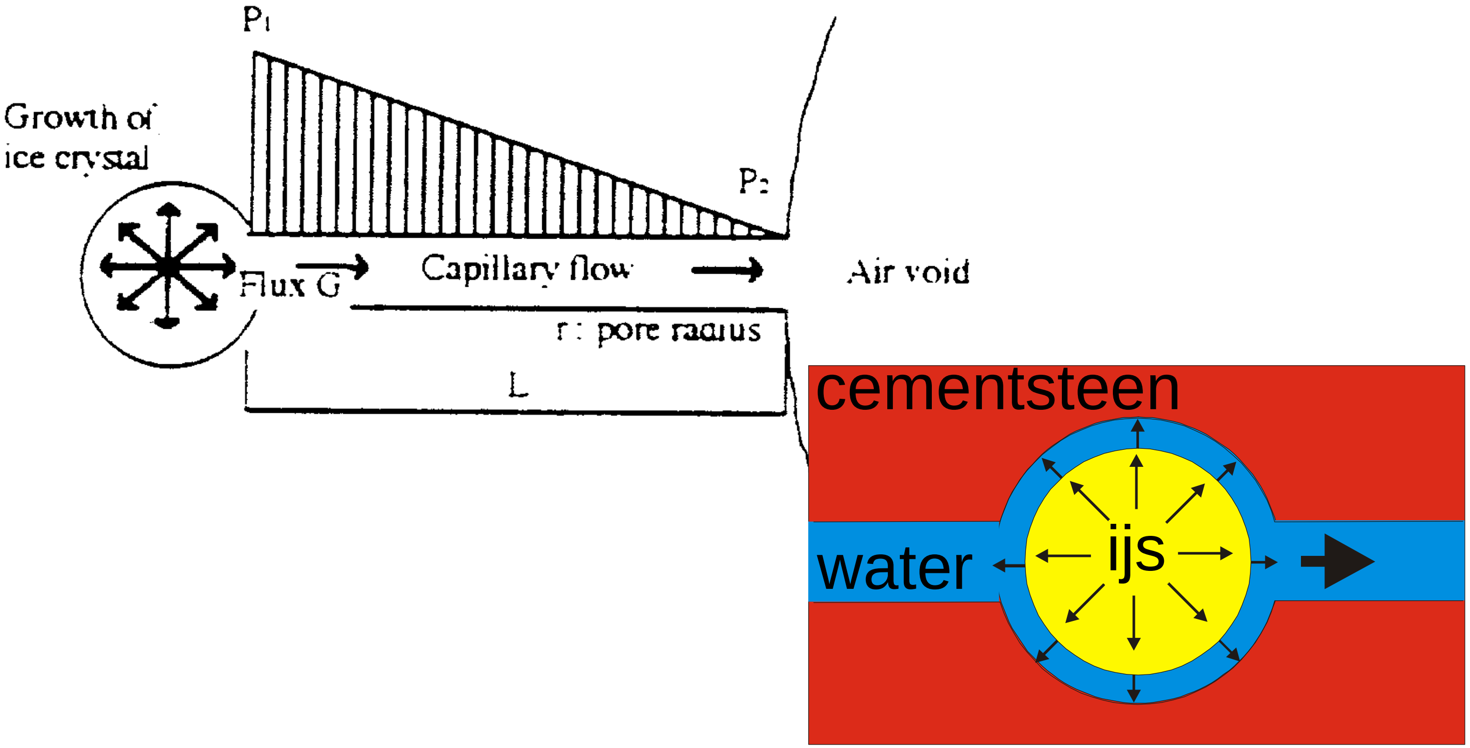
r>0.1 mm : 0 to -10 ^{o}C

r>10 nm : -20 to -30 ^{o}C

3 < r < 10 nm : -35 to -45 ^{o}C

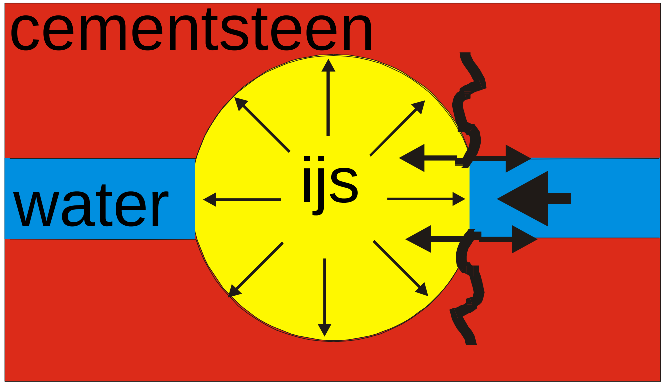
3.1 Degradation mechanisms: Freeze-thawing

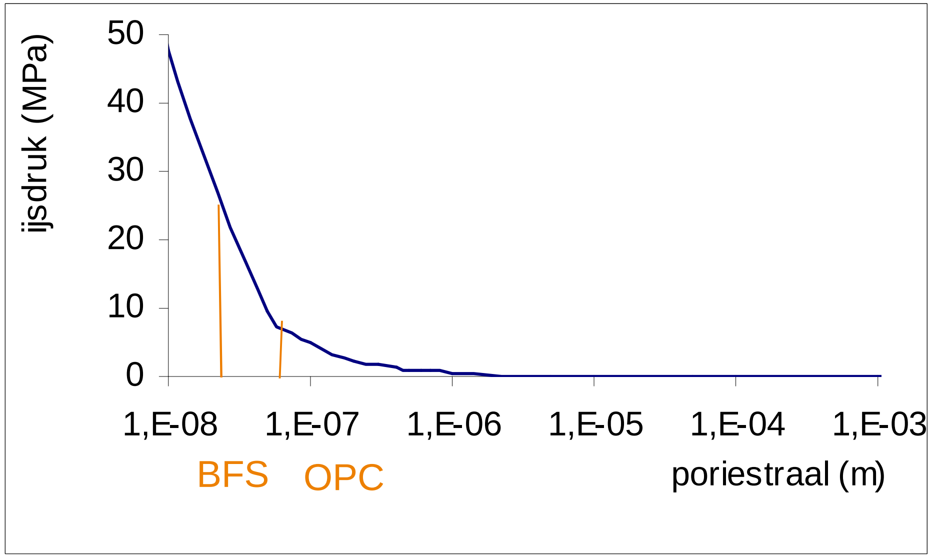
- Mechanisms 2: hydraulic pressure (is why air entrainment works!)



3.1 Degradation mechanisms: Freeze-thawing

- Mechanism 3. Ice over pressure due to transport of vapour pressure and growth

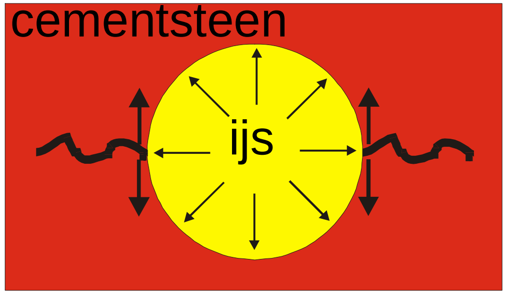




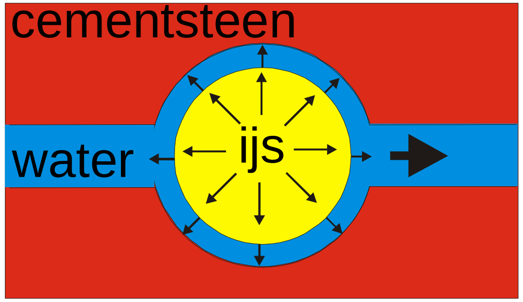
3.1 Degradation mechanisms: Freeze-thawing

- Summary mechanisms
- Fast freezing: low-permeable and fully saturated concrete

expansion of ice 10%

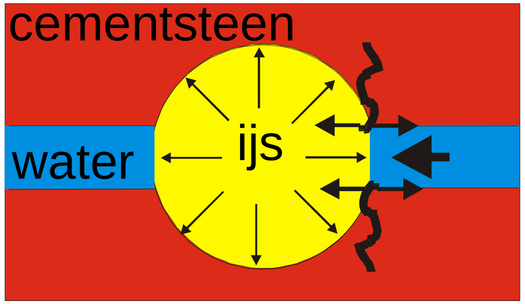


fast pressure build up



- Slow freezing (at modest T): any concrete, most damage for small pores

transport of vapour to ice – ice over pressure



3.1 Degradation mechanisms: Freeze-thawing

- Main differences types of cements (wcr < 0.45, no AE):
- OPC has larger pores and thus is more sensitive to freeze at moderate freezing temperatures (> -20 oC)

BUT

- Large pores are often not fully saturated

- Especially FA cement is sensitive at young age (not allowed to use after 1th October in NL)
- Especially carbonated top layer for FA concrete and BFS concrete is sensitive to freezing / thawing (due to increased porosity)

3.1 Degradation mechanisms: Freeze-thawing

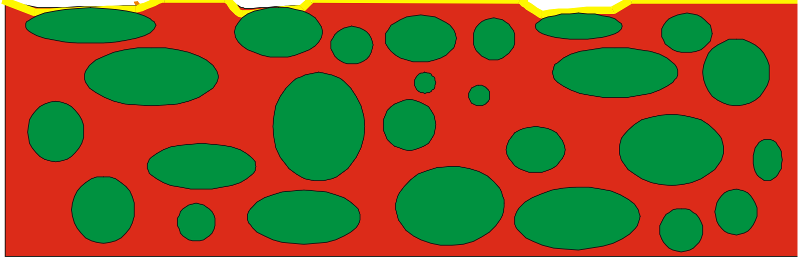
- BEST CHOICE OF CEMENT:
- Cement with very dense cement stone (no capillary pores – no freezing)
- Cement with large pores, enough to accommodate the 10 % expansion of the ice)

- Prescribed in NL:
- Wcr < 0.45 (all) OR wcr > 0.55 + AE

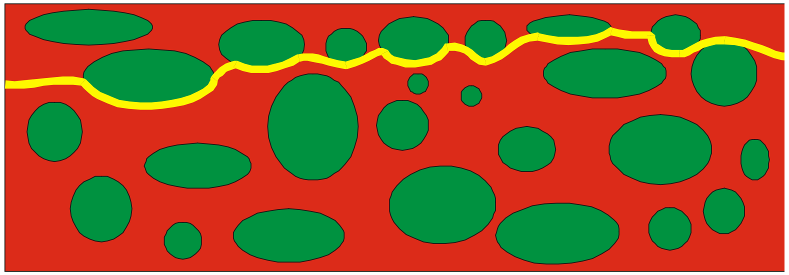
3.1 Degradation mechanisms: Freeze-thawing

Types of damage (depend on T, c & RH gradients):

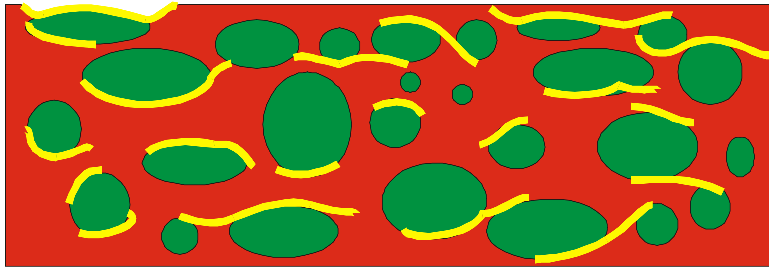
- Scaling



- Delamination



- Internal damage



3.1 Degradation mechanisms: Freeze-thawing in practice

- At moderate freezing temperatures: detection by either loss of surface cement (scaling) and progressively loosening of aggregates
- Consequences: loss of cover

3.1 Degradation mechanisms: Freeze-thawing in practice

Measures:

- Do nothing
- Stop using thawing salts
- Apply additional concrete layer for restoring cover thickness

- Best way:

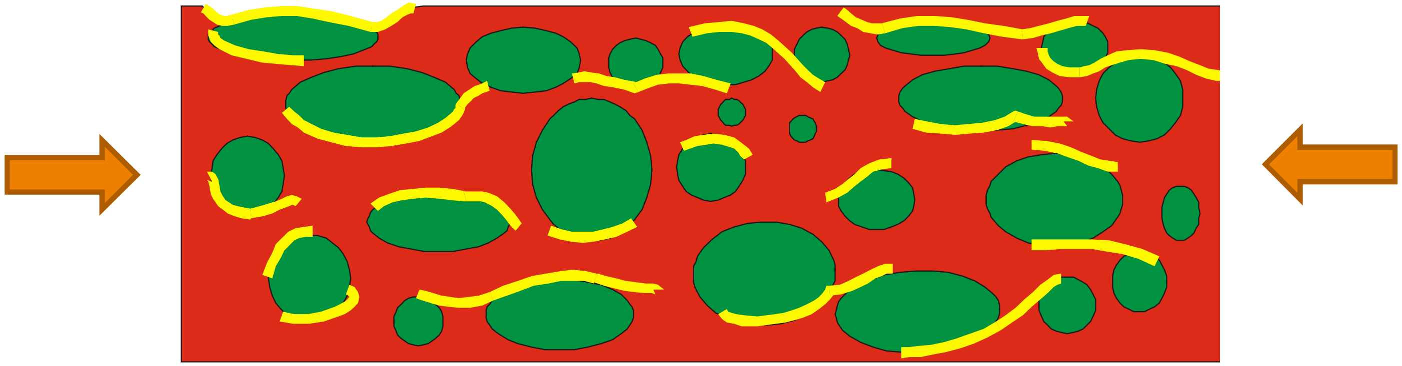
  PREVENT

3.1 Degradation mechanisms: Freeze-thawing in the lab to estimate sensitivity

- If scaling is larger than its threshold after freeze-thawing cycles, it is said to be sensitive

3.2 Degradation mechanisms: Alkali-Silicate Reaction

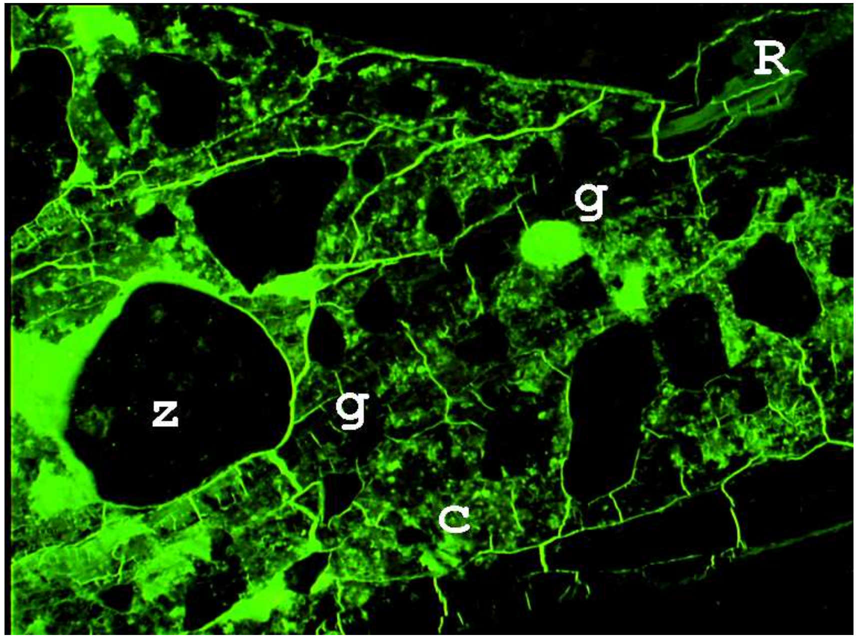
- Transport of alkali's (Na en K) from the cement paste OR from outside the concrete and silicas from reactive aggregates react to ASR-gel
- Can take up large amounts of water
- Consequence: internal pressure due to an expansive gel leading to extensive cracking (crackmapping in case of free expansion, plane parallel cracking in case of constrained cracking)



3.2 Degradation mechanisms:
Alkali-Silicate Reaction in practice

3.2 Degradation mechanisms: Alkali-Silicate Reaction

- Detection / confirmation mostly by PFM (Polarisation and Fluorescence Microscopy)



3.2 Degradation mechanisms: Alkali-Silicate Reaction

- Detection / confirmation also by gel around aggregates and cracks along and through aggregates

3.2 Degradation mechanisms: Alkali-Silicate Reaction in practice

Consequences for the structure

- crack-mapping with extruding gel
- Swelling and bending
- Loss of stress bearing capacity

3.2 Degradation mechanisms:
Alkali-Silicate Reaction in practice

Measures:

- Do nothing
- Hydrophobic treatment with coating (to dry out)
- Limit the loads on the structure
- Demolish

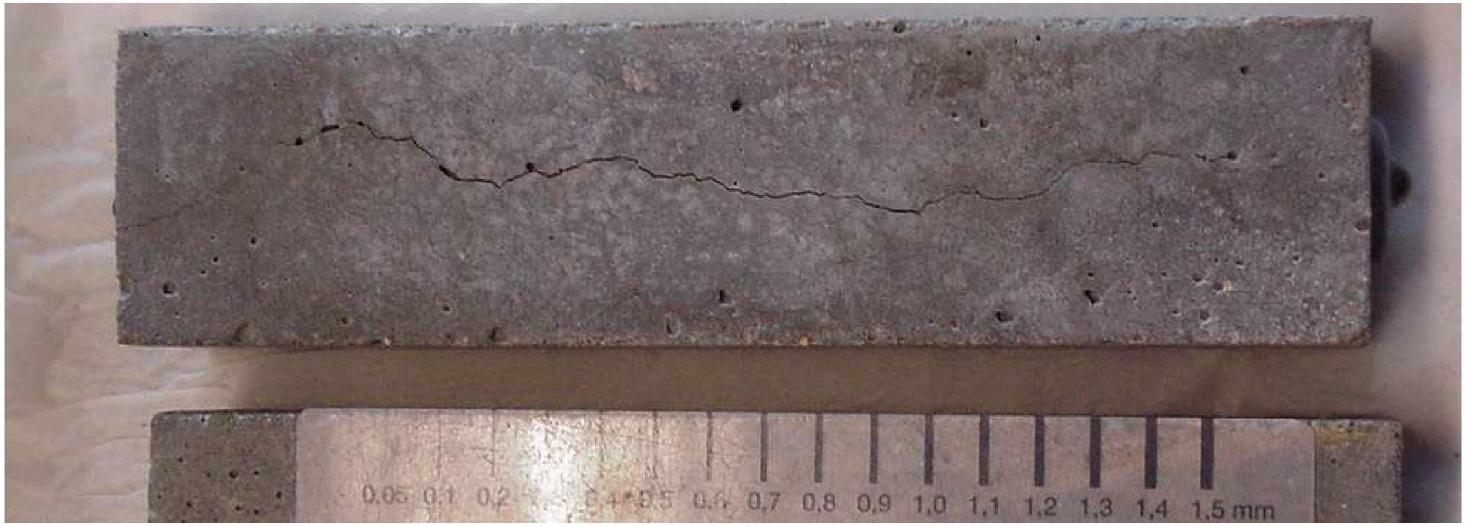
Best way:

- **AVOID**

3.2 Degradation mechanisms: Alkali-Silicate Reaction in the lab

Test methods:

- Concrete compositional limits: alkali content cement and petrographic analysis (amount of reactive aggregates)
- Swelling tests (in 1 M NaOH at 40 oC): should not exceed threshold

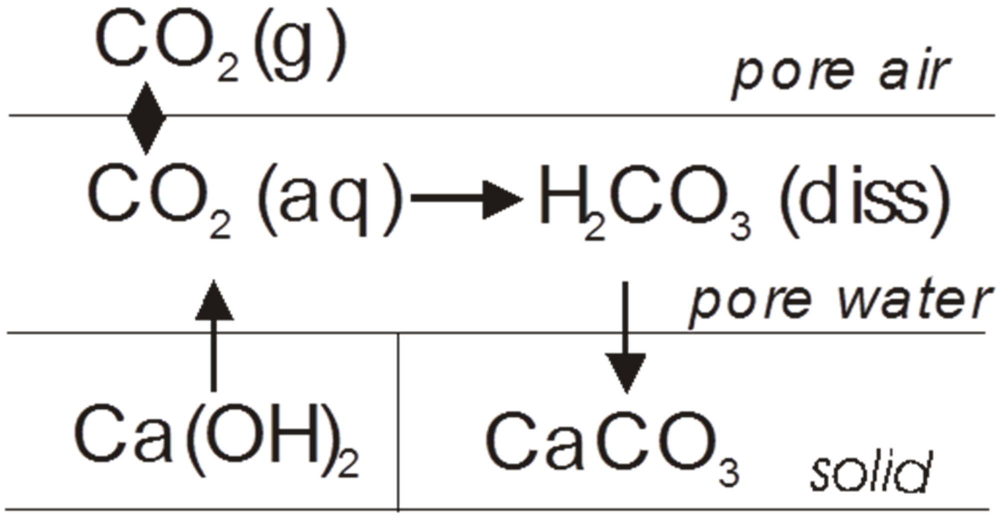


- Cement choice: alkali content low, cement matrix dense:

  BFSC > 50 % slag , OPCs, FA (usually high but discussion on binding)

3.3 Degradation mechanisms: carbonation

- *Chemical equilibrium:*
  - *Transport of CO2 due to concentration difference*
  - *Dissolution of CO2 in pore water and formation carbonic acid and dissociated (H_2CO_3, HCO_3^-, CO_3^{2-})*
  - *Precipitation $CaCO_3$ - dissolution $Ca(OH)_2$*

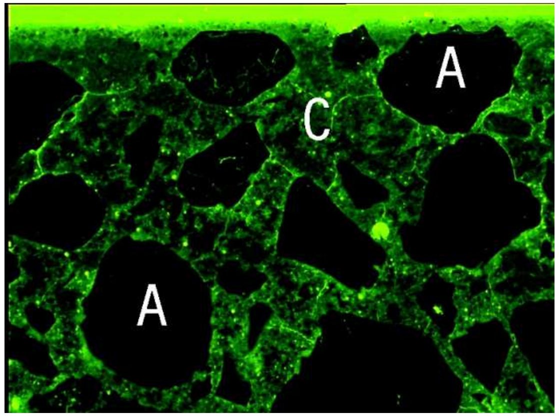


3.3 Degradation mechanisms: carbonation

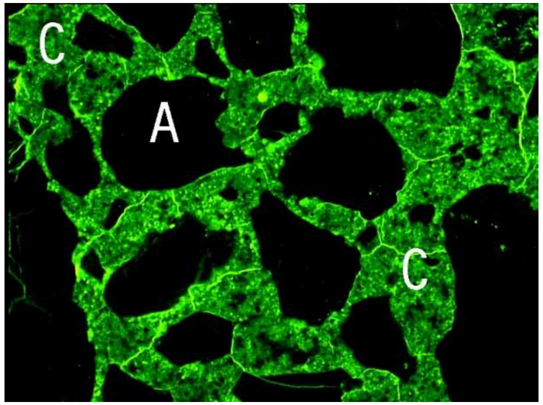
Type of damage / structural changes

- *Carbonation lead to* ***a change in the cement paste*** *(e.g. $Ca(OH)_2$ into $CaCO_3$)*
- *Carbonation leads to* ***a change in the pore structure*** *(e.g. more dense for OPC, more porous for BFSC)*
- *Carbonation leads to a* ***change in the pH*** *of the cement stone below pH< 9; this breaks the passivation of the reinforcement when the carbonation front reaches it, leading to* ***corrosion***

non-carbonated BFSC

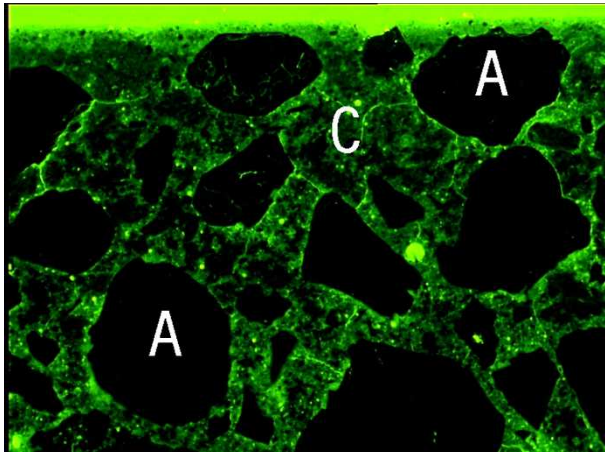


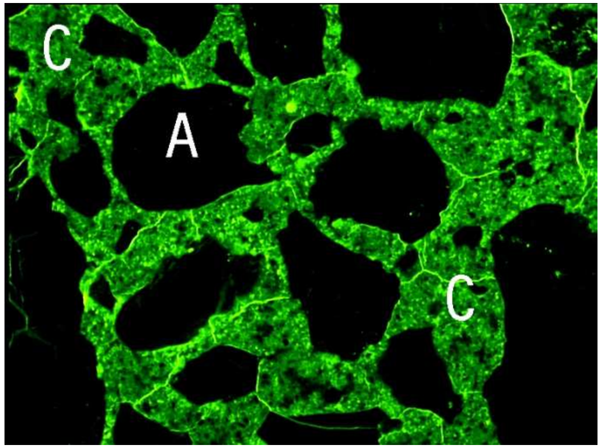
carbonated BFSC



3.3 Degradation mechanisms: carbonation

	degree of hydration	hollow space (% V/V)	carbonation depth (mm)	change from wcr = 0.45
Fine OPC	High	2 – 5	0.5 - 1	0.40
BFSC	Low	2 – 5	10 - 15	0.50
FAC	Medium	2 – 5	10 - 15	0.50





3.3 Degradation mechanisms: carbonation

- Carbonation of each cement phase occurs at phase stability pH
- No cement phase is stable below pH = 7 (c(CO_2) approx. 0)
- All cement phases react in a neutral way so can go to completion
- All calcium is consumed: buffer capacity = Ca content of cement

3.3 Degradation mechanisms: carbonation in practice

- In general has no external signs until corrosion starts
- Detection by creating fresh surface and spraying with phenolphthalein for colour reaction

- Consequences for the structure:
- For most SCM binders
 increase in porosity

3.3 Degradation mechanisms: carbonation followed by corrosion in practice

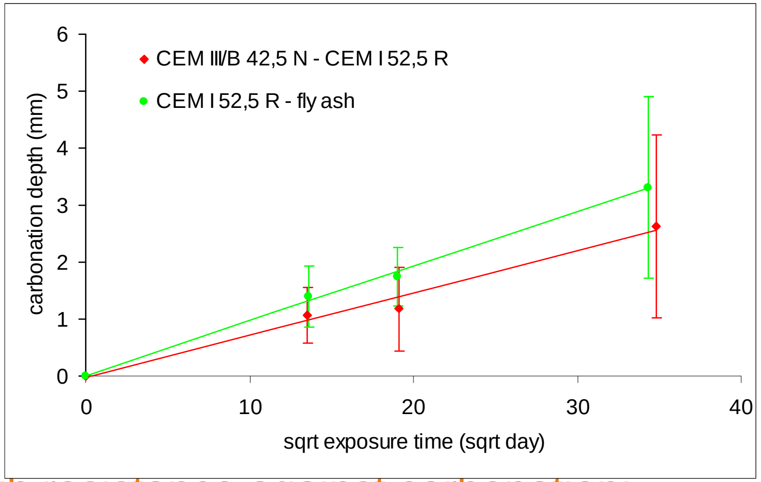
aa

3.3 Degradation mechanisms: carbonation

Measures:

- Cannot be prevented in general, carbonation rate is determined to ensure no corrosion during service life
- (Natural) carbonation test with colour reaction to measure x_c – t

(at favourable conditions for carbonation)



CHOICE OF CEMENTS - high resistance against carbonation:

> OPC: Ca(OH)2 -> CaCO3 = densification, high amount of carbonatable matter,

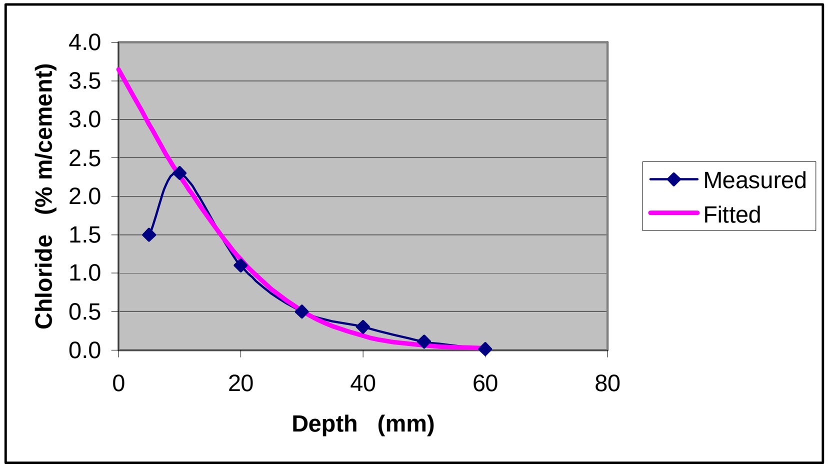
> FA/BFS: CSH -> CaCO3 = increase in porosity (depend on exact ratio)

3.3 Degradation mechanisms: chloride penetration followed by corrosion

- Chloride penetration is in general not harmful for the concrete, nor will it change its structures

- Its threat lies in breaking the passivation layer of the reinforcement

- Testing in LAB by measuring the resistance against chloride penetration

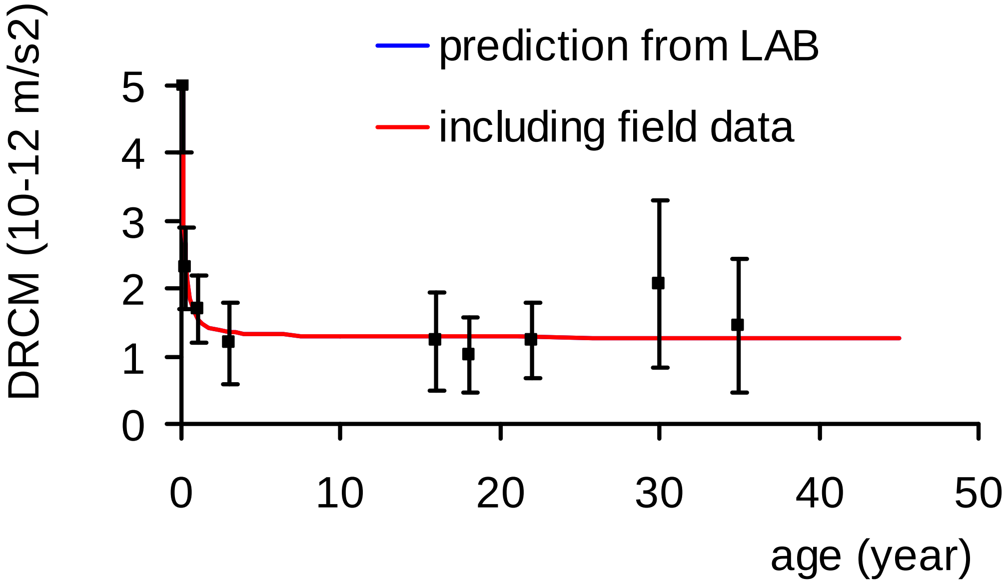


- Choice of cement: pore size
  - FA cement
  - BFSC
  - OPC

3.3 Degradation mechanisms: chloride penetration - prediction

Measures:

- Ensure a dense & thick enough cover that have sufficient resistance during service life



	Dinf	D0	n	χ^2
model + field	1.2 (0.1)	5.0 (0.2)	1.00 (0.08)	1.000

3.3 Degradation mechanisms: corrosion

Recap:

- Corrosion – rusting of the reinforcement
- Rust has a higher volume than the original steel
- It exerts a pressure on the concrete, leading to the largest cracks in the free expansion direction: delamination of the concrete cover

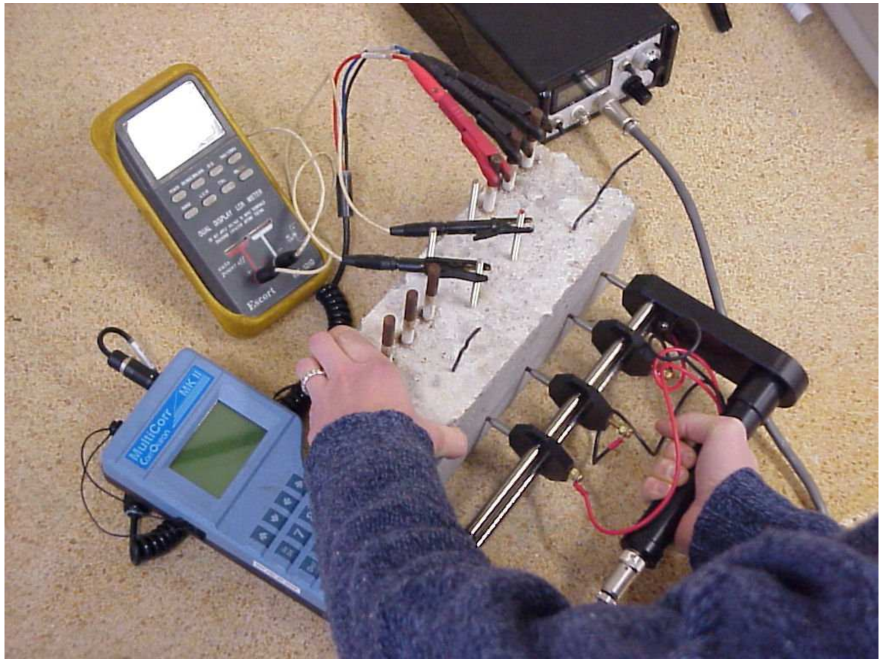
3.3 Degradation mechanisms: corrosion

Measures:

- PREVENT
- Cathodic Protection
- Removal of the cover and replacing it

Testing in LAB for corrosion :

- Resistivity
- Potential Measurements



3.4 Degradation mechanisms: sulfate attack

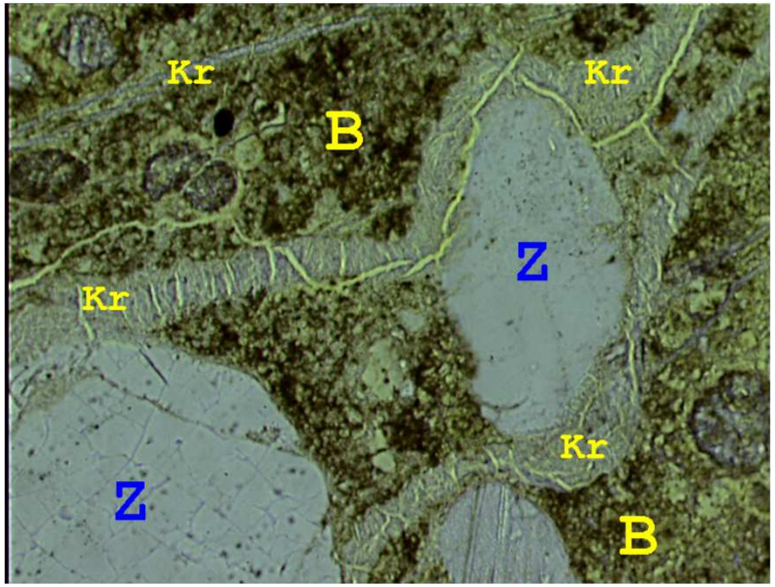
- Recap, main reactions:

  $Ca(OH)_2 + SO_4^{2} \rightarrow$ gypsum

  gypsum + $C_3A/C_4AF \rightarrow$ ettringite

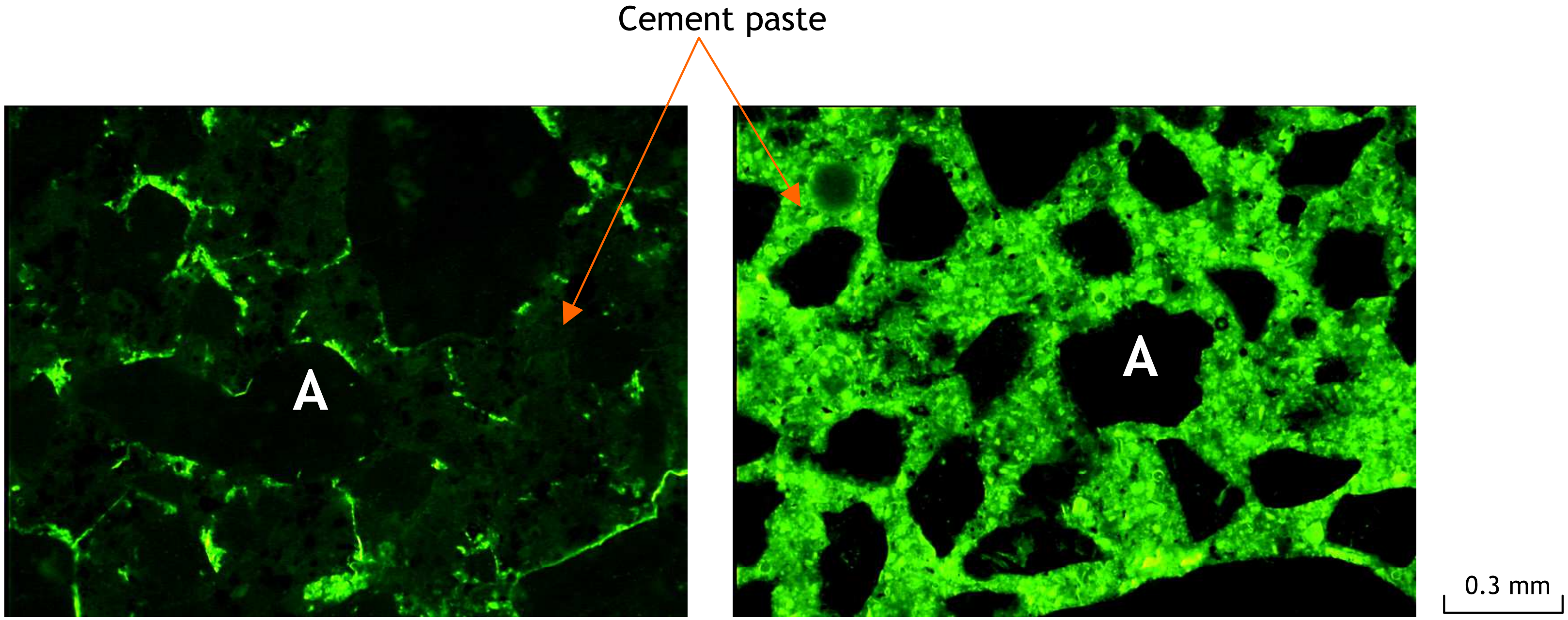
- main difference OPC / blended cements
  - Portland clinker fraction
    - contents of C_3A/C_4AF
    - concentration $Ca(OH)_2$
  - Microstructure (permeability)

- Consequences for concrete:
- Swelling,
- Cracking
- Spalling top layer



3.4 Degradation mechanisms: sulfate attack

- Change in structure in sodium sulfate



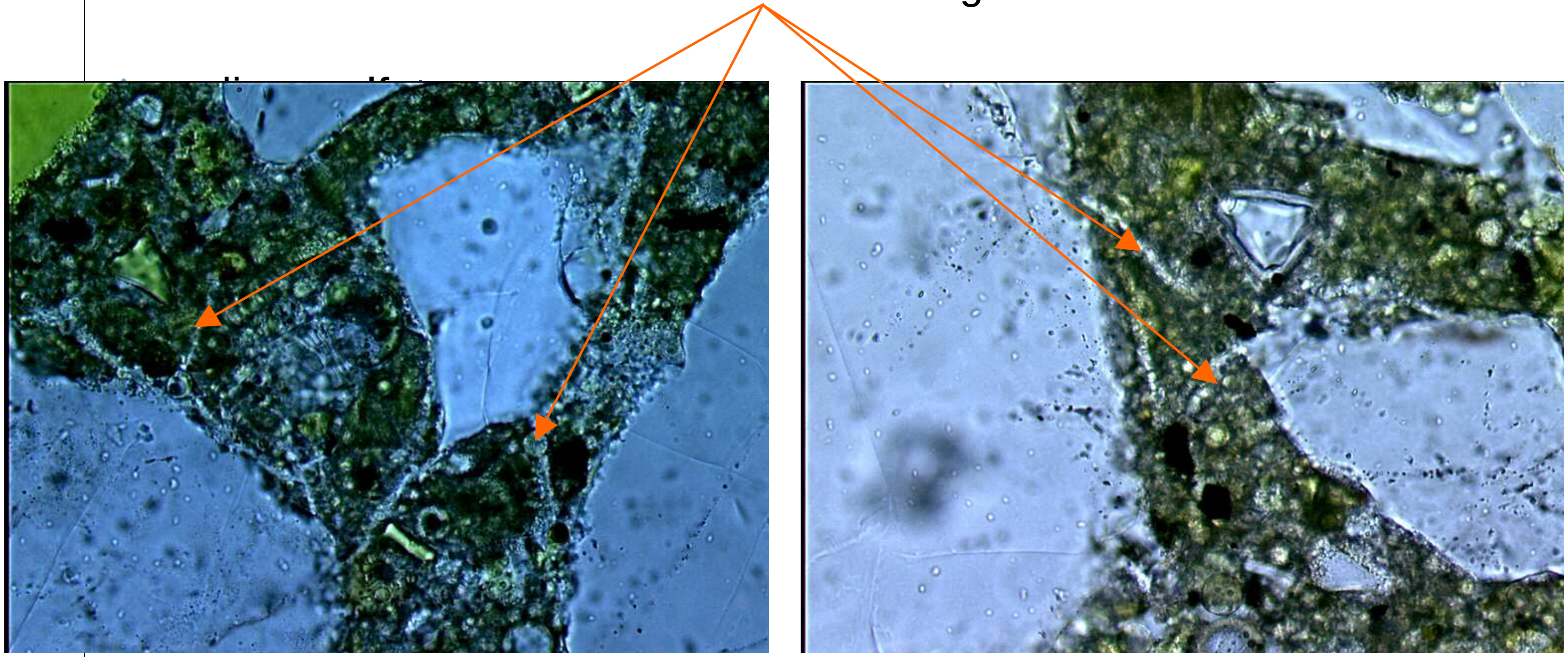
a.

b.

CEM V/A: demi-water

sodium sulfate

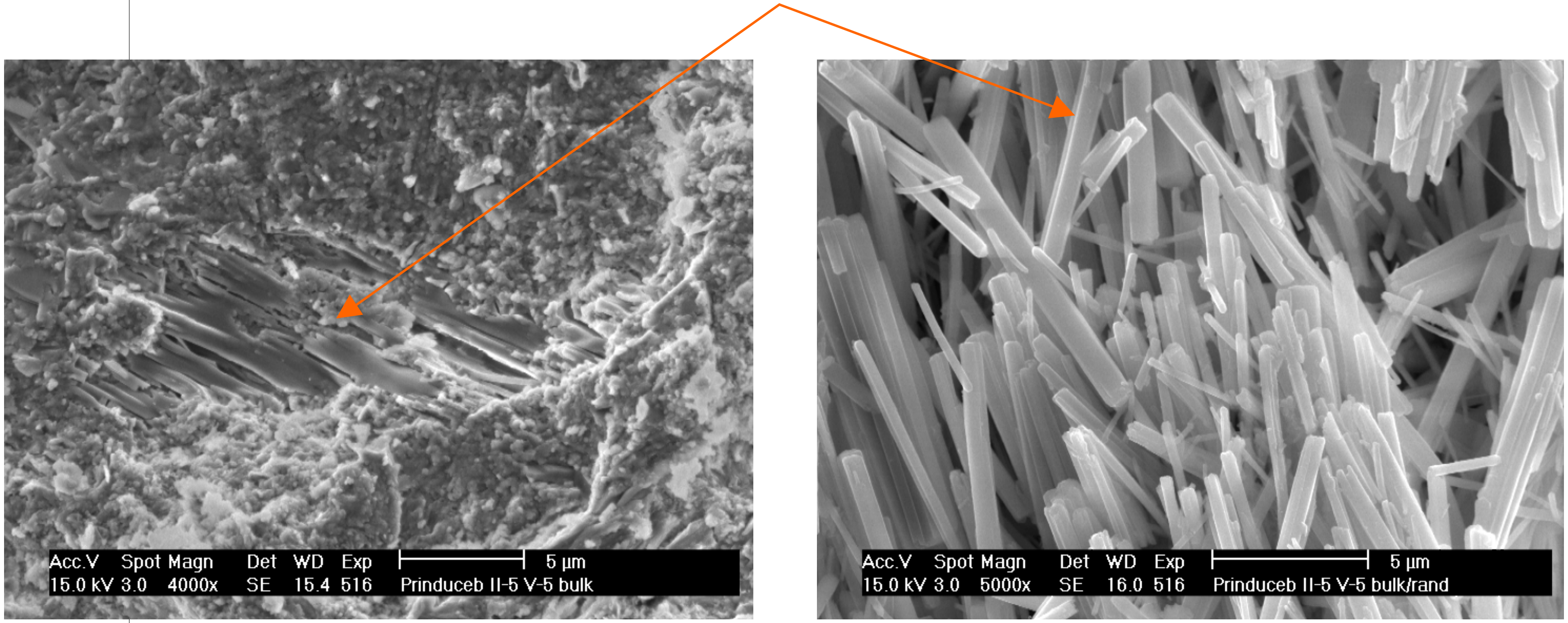
3.4 Degradation mechanisms: sulfate attack



sec. ‘massive ettringite

3.4 Degradation mechanisms: sulfate attack

sec. ‘massive ettringite



3.4 Degradation mechanisms: sulfate attack

- Prevention by using special HS resistance cement = any cement with low C3A content
- Some swelling is allowed – testing in LAB for senstivity

3.4 Degradation mechanisms: sea water attack

- Main reactions:

  $Ca(OH)_2$+$MgSO_4$ → gypsum (CaSO4)+ brucite (Mg(OH)2)

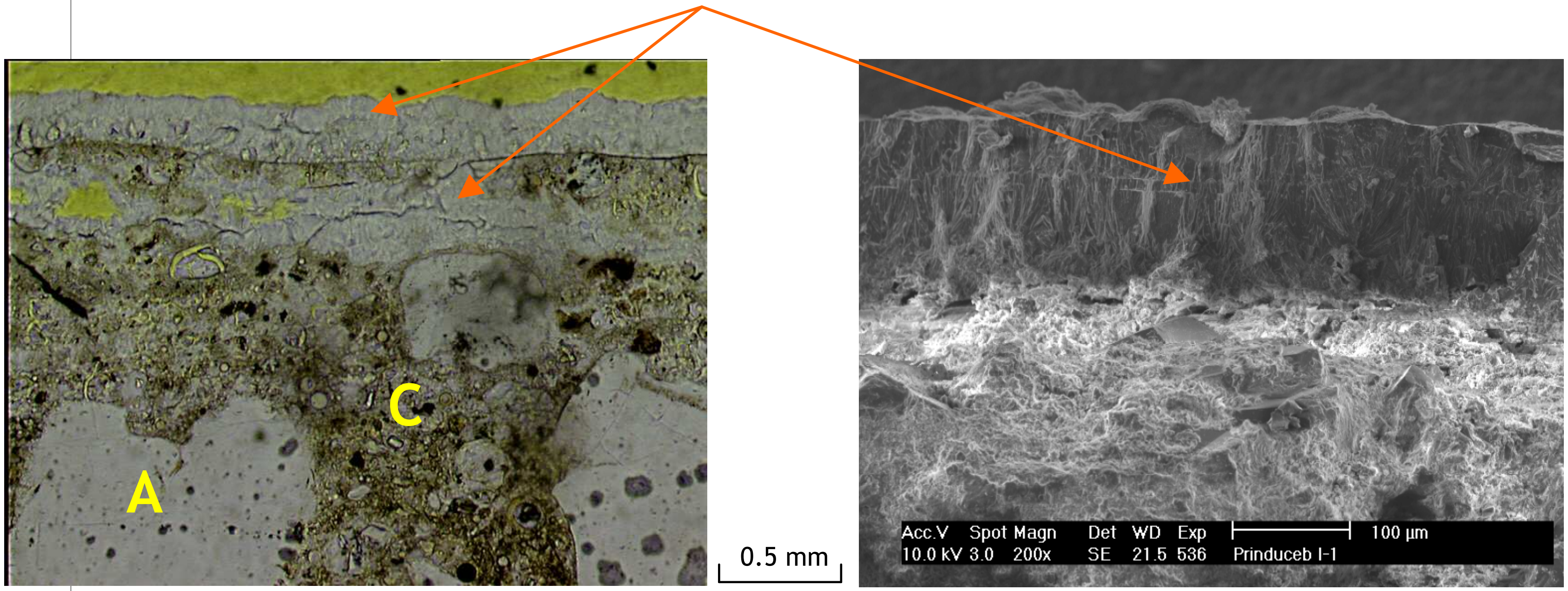
  $MgSO_4$ + CSH→ MSH + gypsum

- main difference OPC / blended cements
  - Portland clinker fraction
    - contents of C_3A/C_4AF
    - concentration $Ca(OH)_2$
  - Microstructure (permeability)

- Change in structure
  - increase in capillary porosity (0.5-0.55), no/low $Ca(OH)_2$
  - high amount of cracks

3.4 Degradation mechanisms: sea water attack

- artificial seawater: CEM V/A



Thick layers of brucite and gypsum

a.

b.

- Prevention by using slag at high content (formation of stable CASH and dense structure)
- Some swelling is allowed – testing in LAB for sensitivity

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4. Performance of different binders for durability
5. Conclusions

4. Performance of different binders for durability

- In case of cements already accepted by the standards for mechanical properties (27) but not for durability

- Tested against the performance of any, already accepted cement (5)

4. Performance of different binders for durability

cements	Slag content	Fly ash content
CEM I 32.5 R	0	0
CEM I 52.5 R	0	0
CEM II/B-F 32.5 N	0	30
CEM III/A 52.5 N	57	0
CEM III/B 42.5 N	76	0
CEM V/A (S-F) 42.5 N	25	25

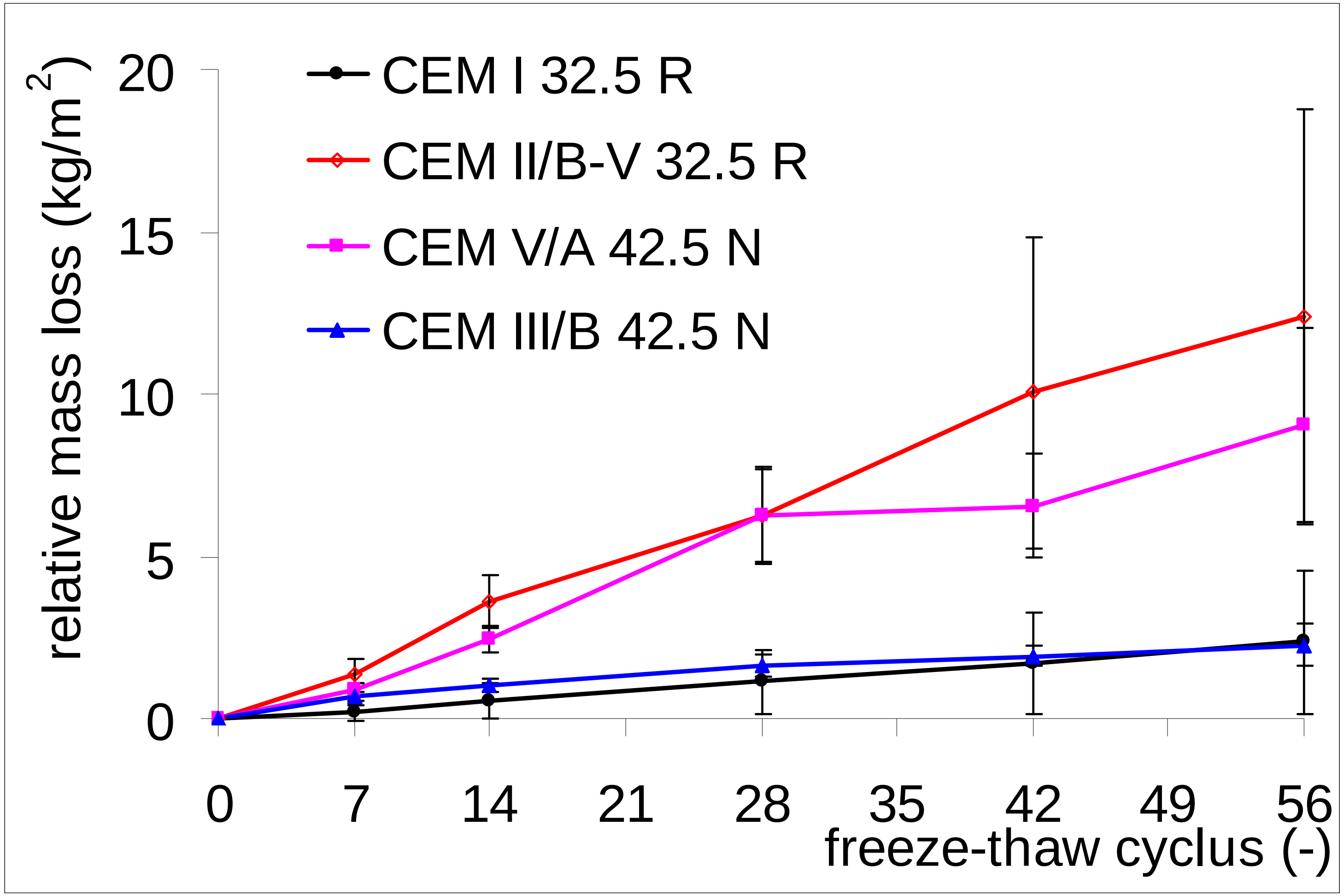
Concrete composition =
wbr = 0.45, total binder = 340 kg/m^3, river aggregate, D_{max} = 31.5 mm

Mortar composition =
wbr = 0.5, a/b-ratio = 2.25, standard sand, D_{max} = 4 mm

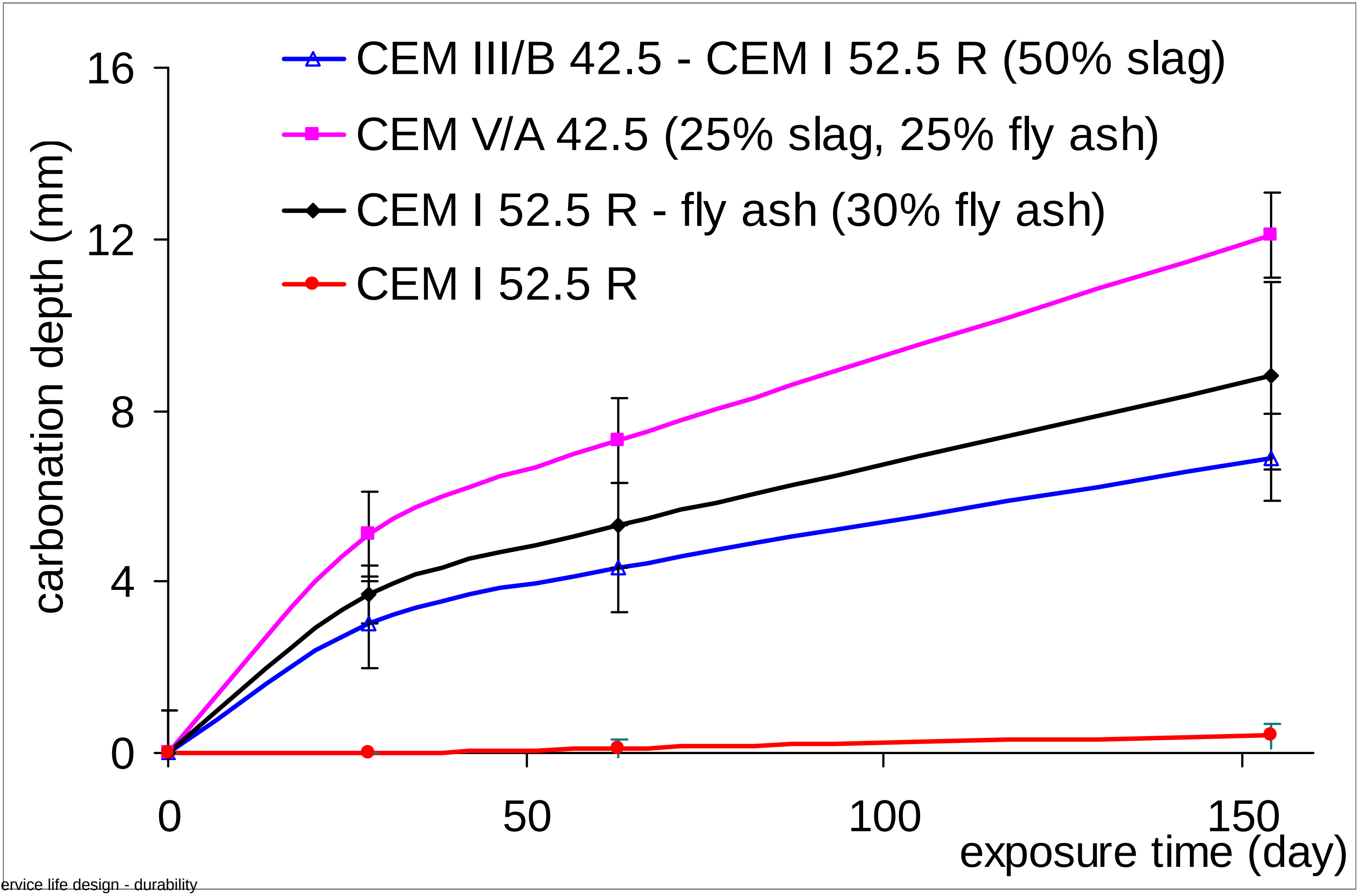
4. Performance of different binders for durability

resistance against:	freeze-thaw with deicing salt	carbonation	chloride penetration	Sulfate and seawater
Name test	Scandinavian Slab Test (SST)	Accelerated Carbonation (AC)	Rapid Chloride Migration (RCM)	Sulfate/seawater Resistance Test
Spec. (mm^3)	concrete half cubes 75x150x150 mm^3	concrete prisms 300x100x100	concrete disks D 100 x h 50	Mortar bars 40 x 40 x 160
curing	7 days wrapped 21 days 20/65 3 days 3% NaCl	7 days fog room; 21 day 20/65 and atm. CO_2	under water	Under demi-water
start test	31 days	28 days	different ages	28 days
execution	Weigth loss after 56 cycles of 24 h -20/+20 °C	Carbonation front after 6 months 20/65 /2% CO_2,	Chloride penetraton depth after forced penetration under current	Expansion compared to demi-water after 1 year of exposure

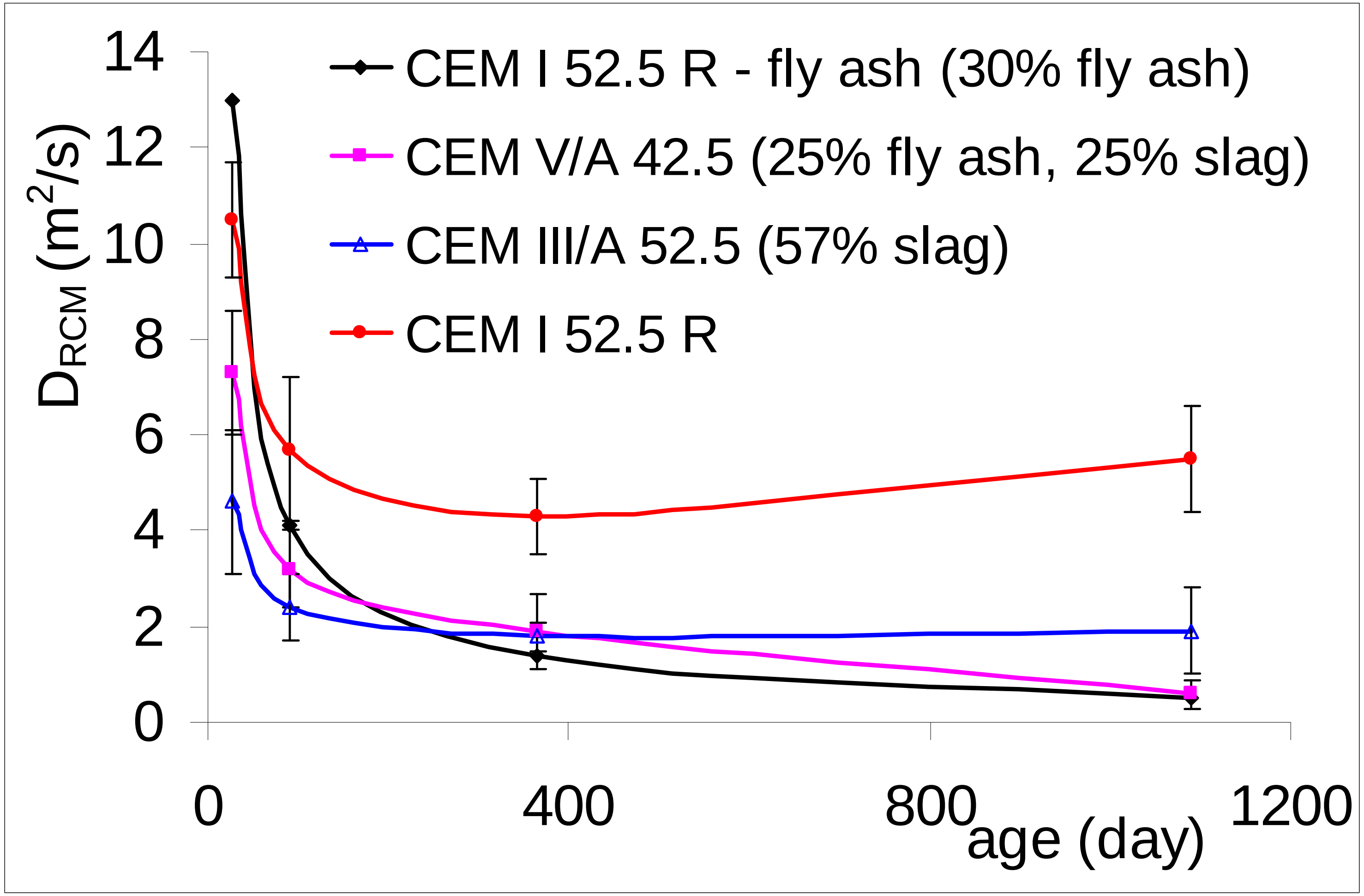
4. Performance of different binders for durability Scandinavian Slab Test



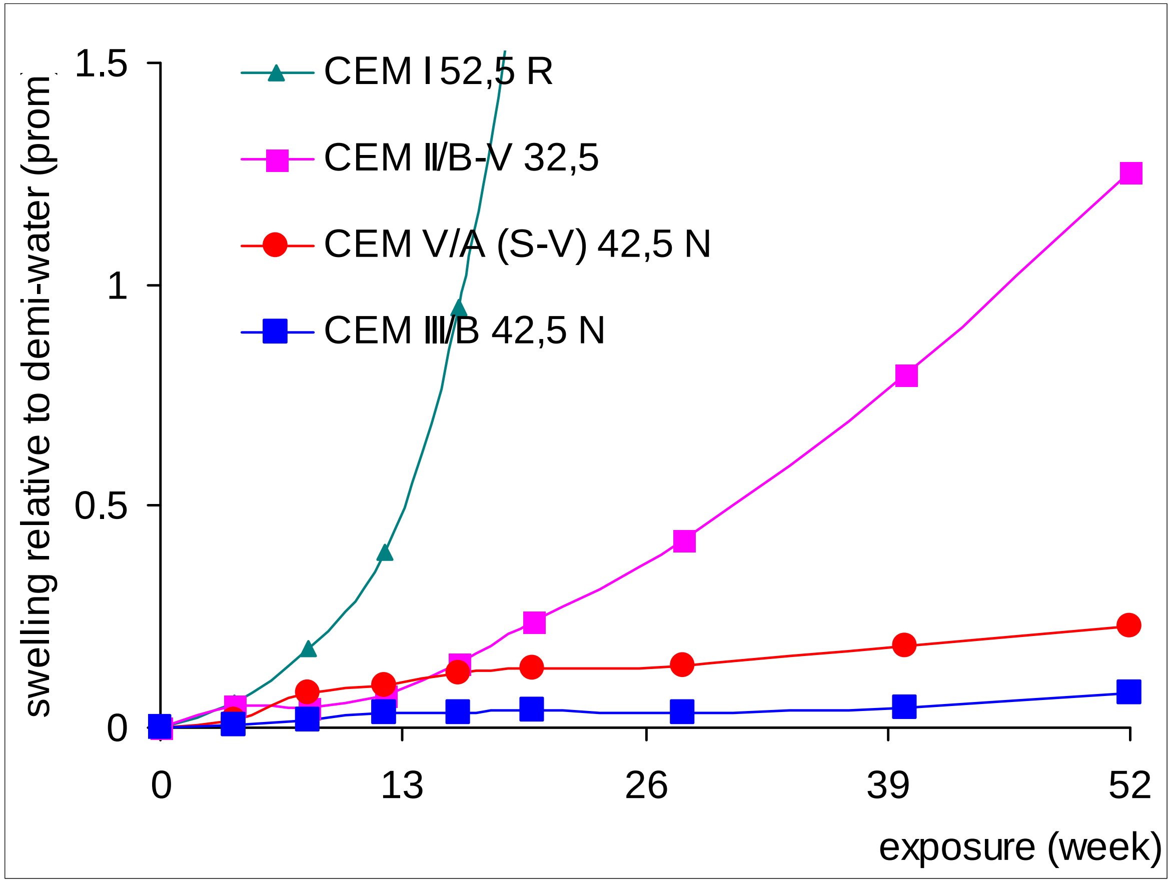
4. Performance of different binders for durability
Accelerated Carbonation



4. Performance of different binders for durability Rapid Chloride Migration



4. Performance of different binders for durability
Sulphate and Seawater Resistance



4. Performance of different binders for durability overview performance

cement	carbonation	Chloride penetration	Freeze-thawing	Sulfate attack
CEM I	+++	**0**	+++	- - -
CEM II/B-F	**0/-**	+++	**[-]** (> 28 cycles better)	**0**
CEM V/A (S-F)	**-**	+++	**[-]** (> 28 cycles better)	+++
CEM III	**0**	++	+++ (not carbonated)	+++

5. Conclusions

- Durability is a container term: many different mechanisms may threat the durability of concrete.

- The mechanisms may be contradictive in concrete or binder demand

- For each situation therefore the best performance cement may be different.