Durability based design of concrete

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Workshop Durability of Concrete, FIB conference on ‘Improving Performance of Concrete Structure, Mumbai 10-15 February 2014.

Performance based service life design: durability of concrete

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2. Getting a grip on service life
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   1. Mechanical: freeze-thawing
   2. Chemical: carbonation
5. Conclusions

1. Introduction: what is durability

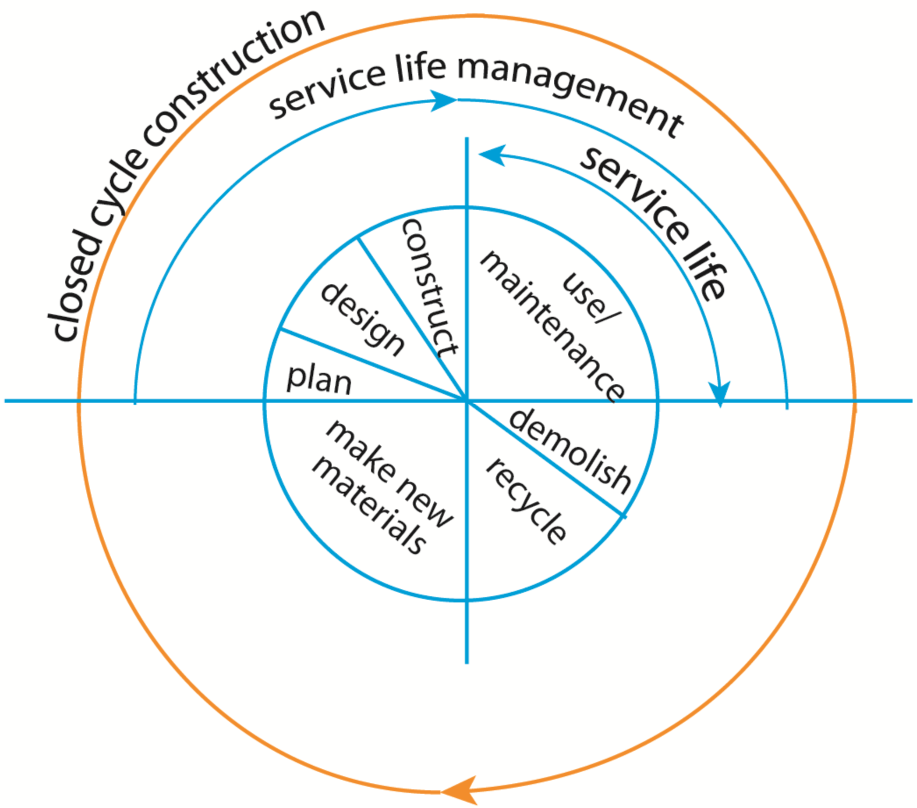
- Durability is the resistance of concrete to degradation
- Degradation is the decrease in properties of concrete under influence of loads, mostly from the outside
- Loads include:
- - mechanical loads (e.g. self weight)
- - physical loads (e.g. T)
- - chemical loads (e.g. CO_2)

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 upto bending / shear and collapse*
- ***This may lead to extensive repair & costs or even early end of service life***

1. Introduction

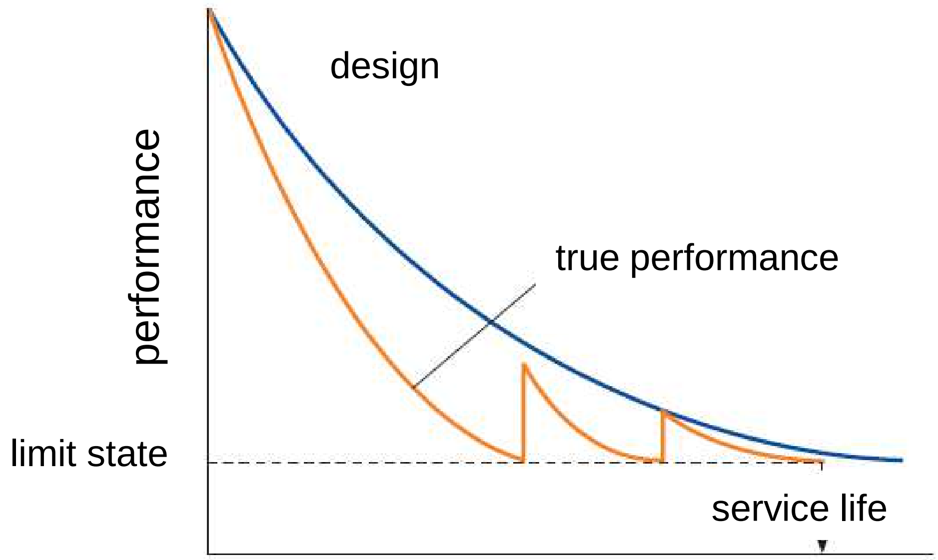
Service life is that stage of a life of a structure when it is in use



end of service life

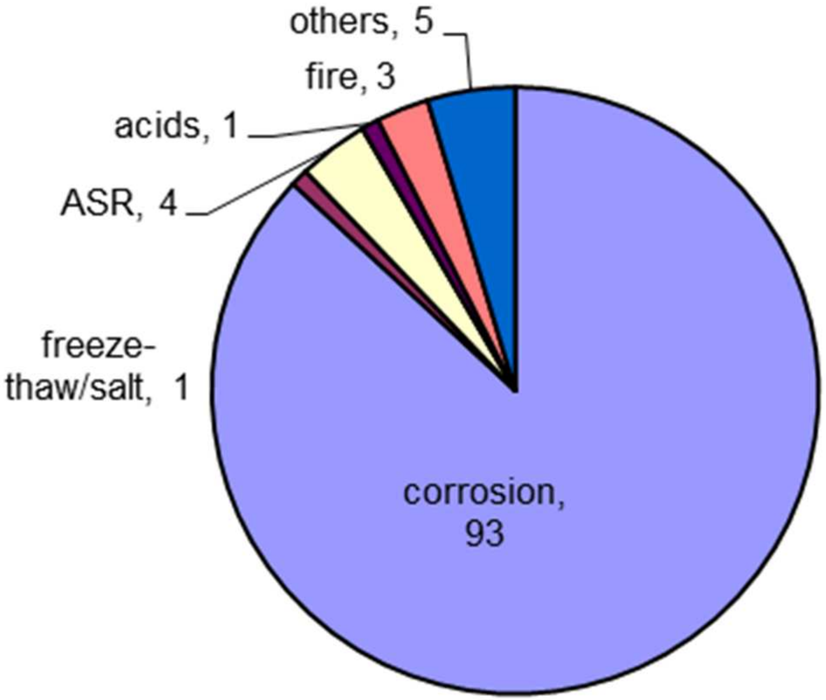
1. Introduction

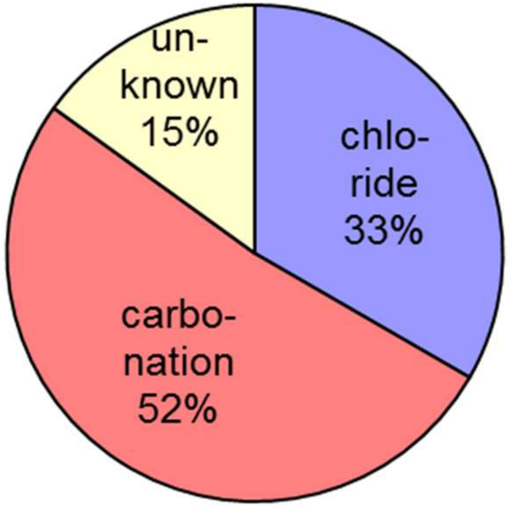
A **performance** is a **task** that is executed with a certain **quantified** result (limit state)



1. Introduction

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



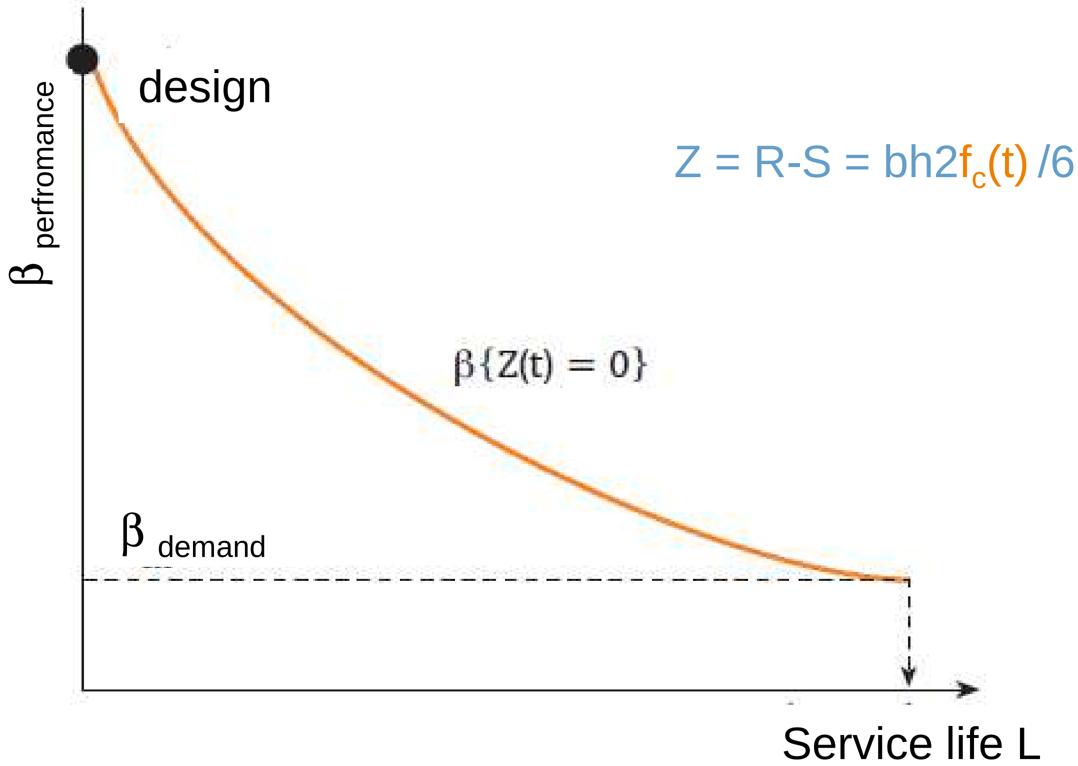


1. Introduction

Why should you care
about the performance?

2. Performance in a service life design

- A performance consists of:
  1. A behaviour model Z(t) of which Z(t) = 0 the limit state describes
  2. A pre-defined, agreed upon, reliability index β
  3. A pre-defined, agreed upon service life L

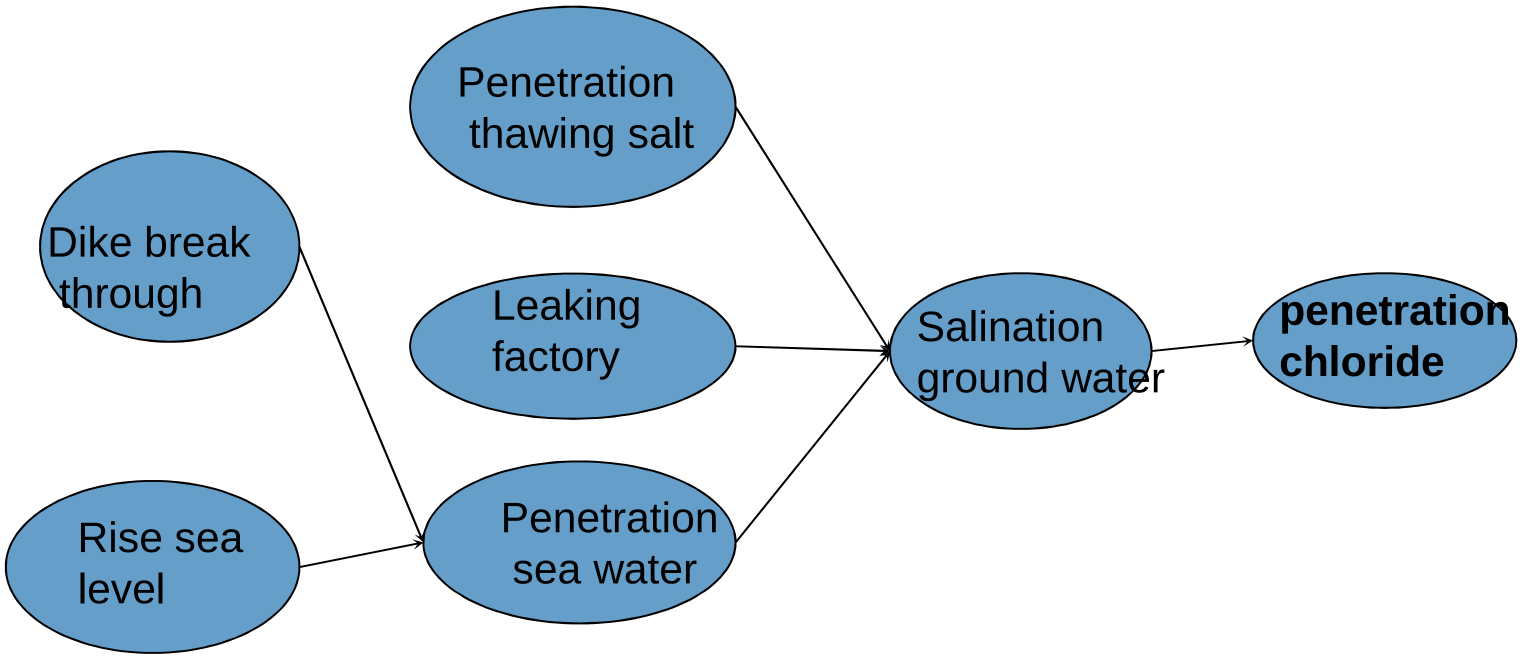


$Z = R\text{-}S = bh2f_c(t)/6 - lF(t)/4$

2. Performance in service life design

(1) Question 1: **which loads**?

- First: try to assess which of the loads are of importance, now, or **DURING SERVICE LIFE** (e.g. make an event tree)

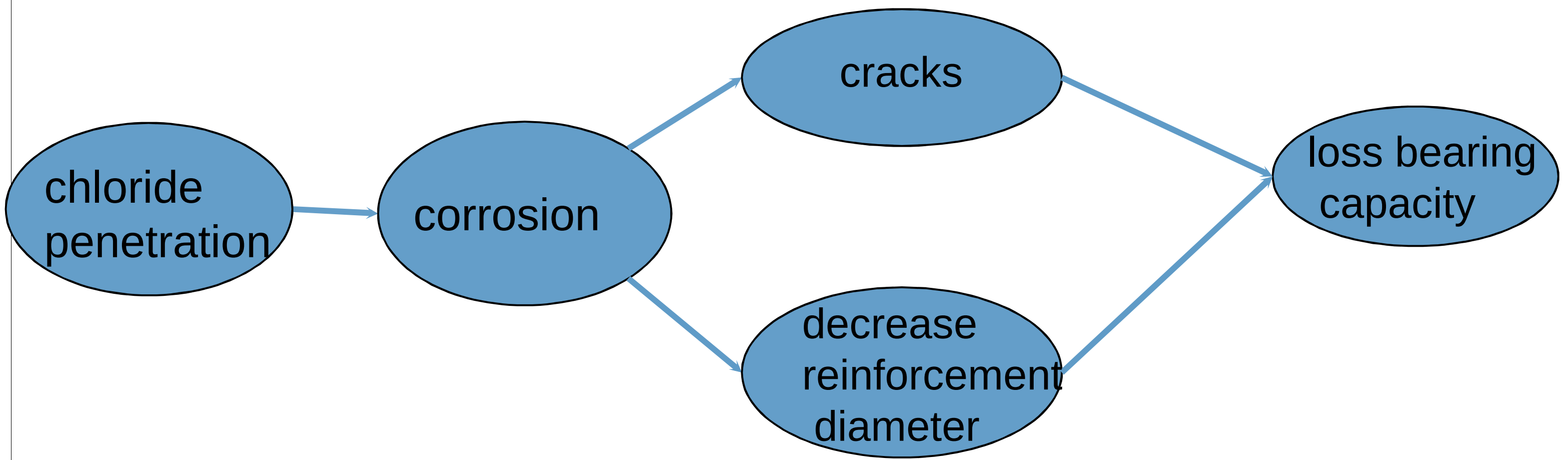


Reminder: structures fail more often due to forgotten treats rather than identified treats!

3. Performance in service life design

(1) Question 2: **does it matter**?

- Second: check the effect of the load (e.g. use a failure mode and effect analysis (FMEA)



3. Determining the performances to take into account

(1) Question 2: **does it matter**?

- Third, and last step (much later on in the process) will be to consider the consequence of the effects of failure (e.g. make a risk analysis):
  - loss of lives / health issues
  - Economical loss
  - Ecological loss etc.

- **Risk = probability of an event x the consequences**

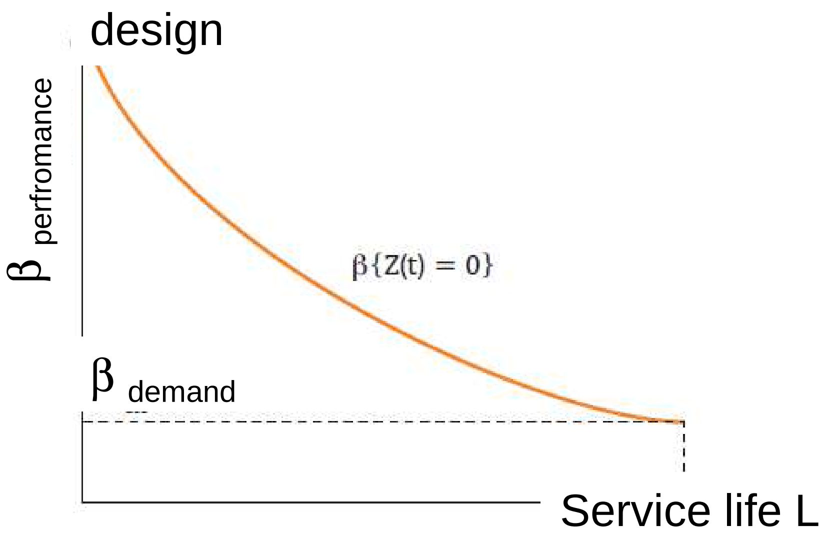
- Most often, the risks are expressed as costs.

2. Performance in service life design

- Recap:
- Performance consists of:
  1. A behaviour model Z(t) of which Z(t) = a the limit state describes
  2. A pre-defined, agreed upon, reliability index β
  3. A pre-defined, agreed upon service life L

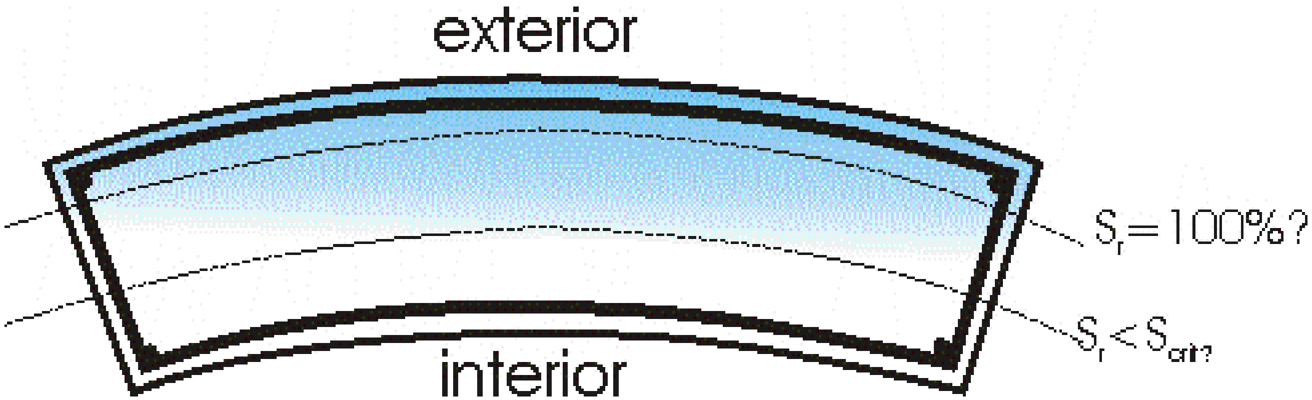
- Its importance is determined from:
  1. Failure Mode
  2. And Effect

  Analysis (BOWTIE MODEL)



3. Example of the importance of the environment: moisture distribution in a tunnel

- Problem statement: where is the moisture front?
-



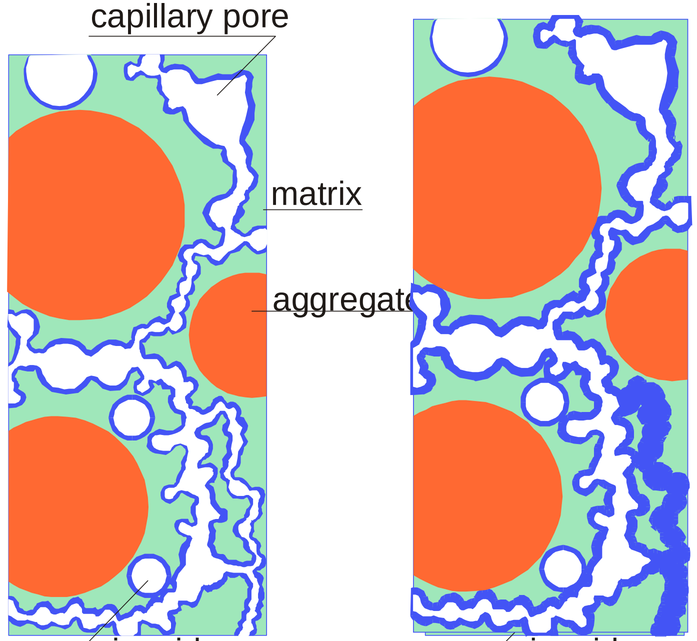
- E.g:
  - Reinforcement in saturated concrete: no corrosion
  - Reinforcement in dry concrete: no water, no corrosion

3. Example of the importance of the environment: moisture distribution in a tunnel

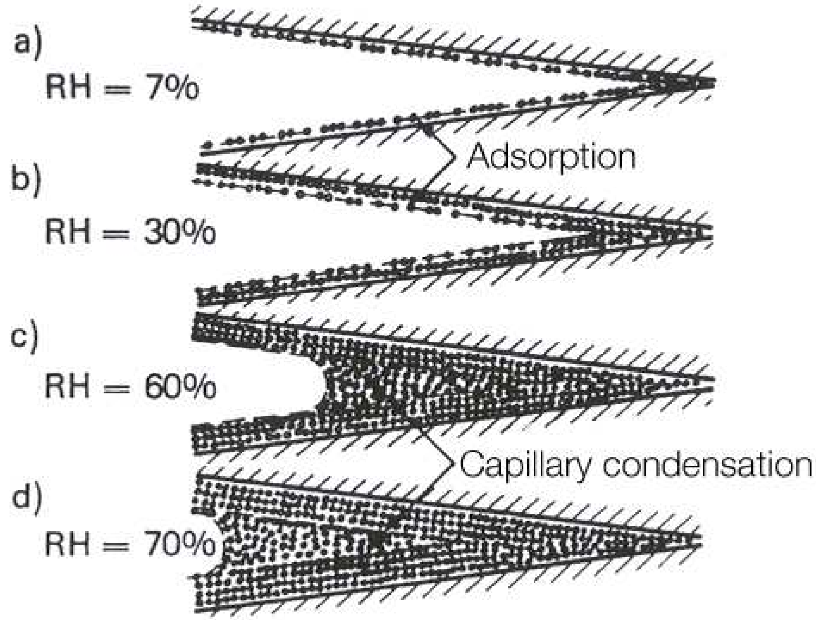
- Importance of the structure and the moisture distribution
  - Durability = transport + (chemical) reactions
  - Transport rate / type depend on structure and related moisture distribution

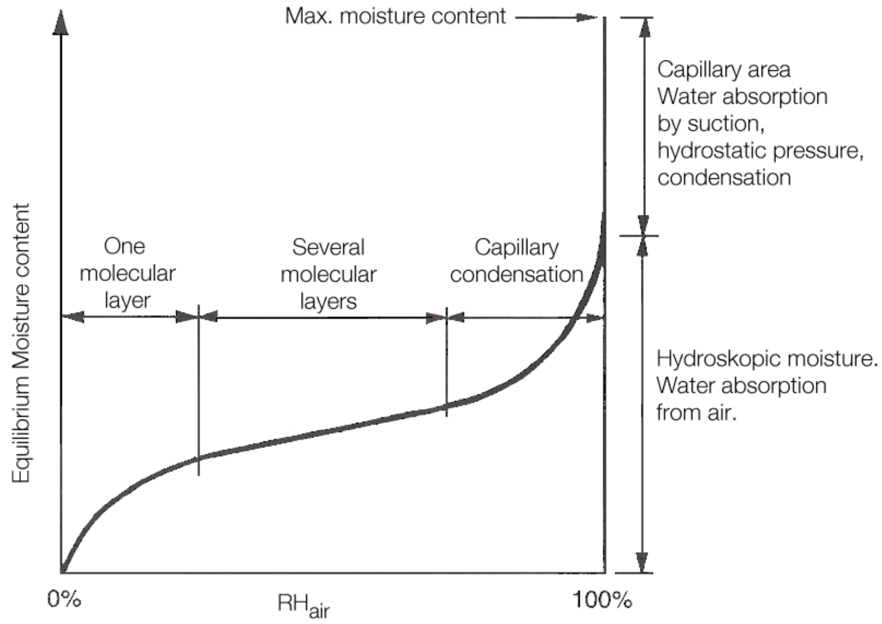
- Transport examples:
- Water / ions at S> S_{crit}

- gasses at S < S_{crit}



3. Example of the importance of the environment: moisture distribution in a tunnel

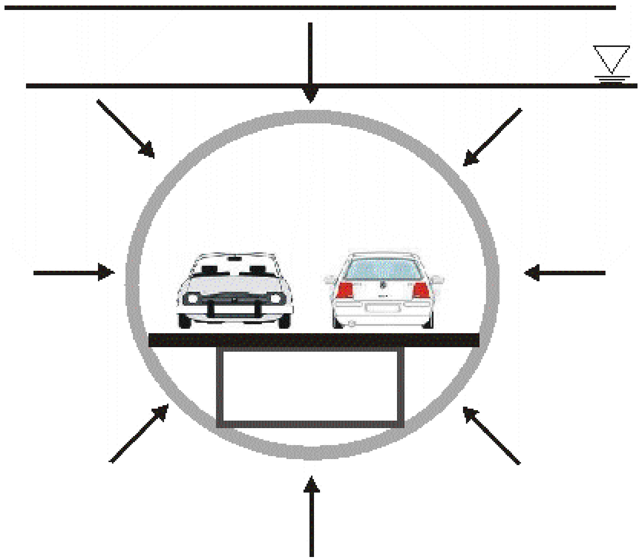


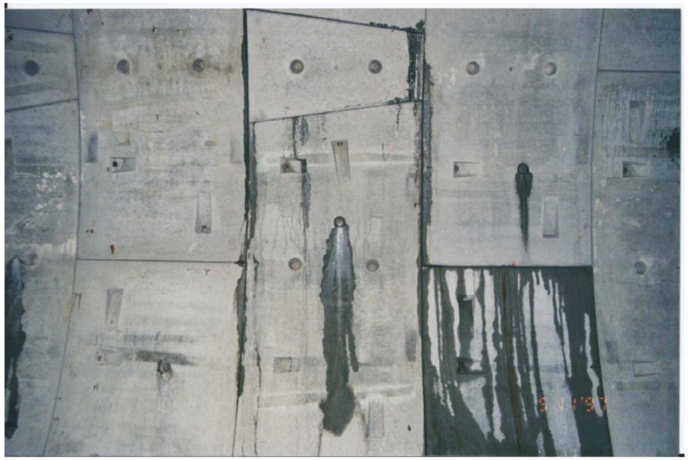


3. Example of the importance of the environment: moisture distribution in a tunnel

Exterior = below ground water table:

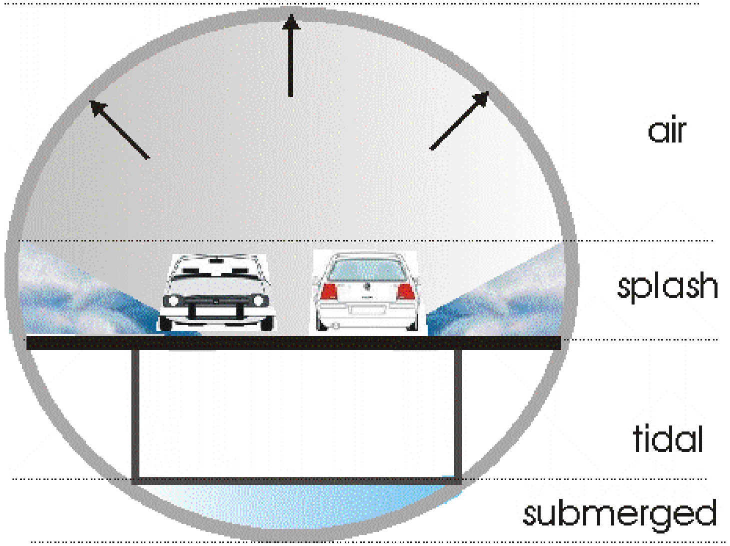
- pressure: 0.1 – 0.5 bar
- temperature: 12 °C (from -20 m)
- composition : sweet (< XA1), pH 6.0 – 7.1





3. Example of the importance of the environment: moisture distribution in a tunnel

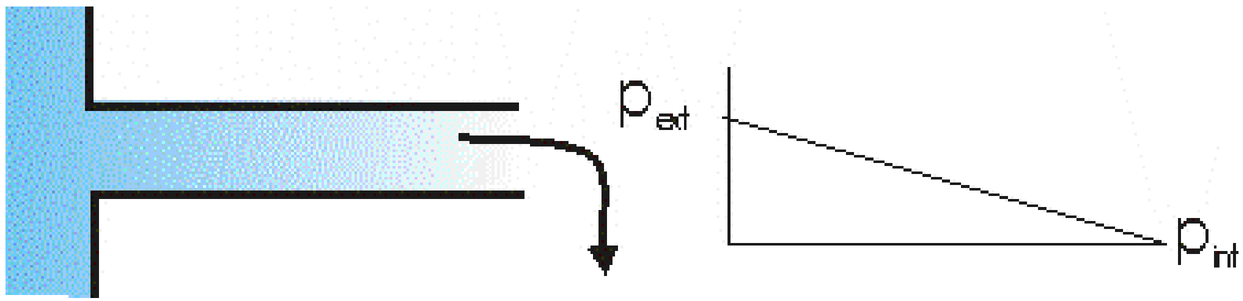
Interior – different environments



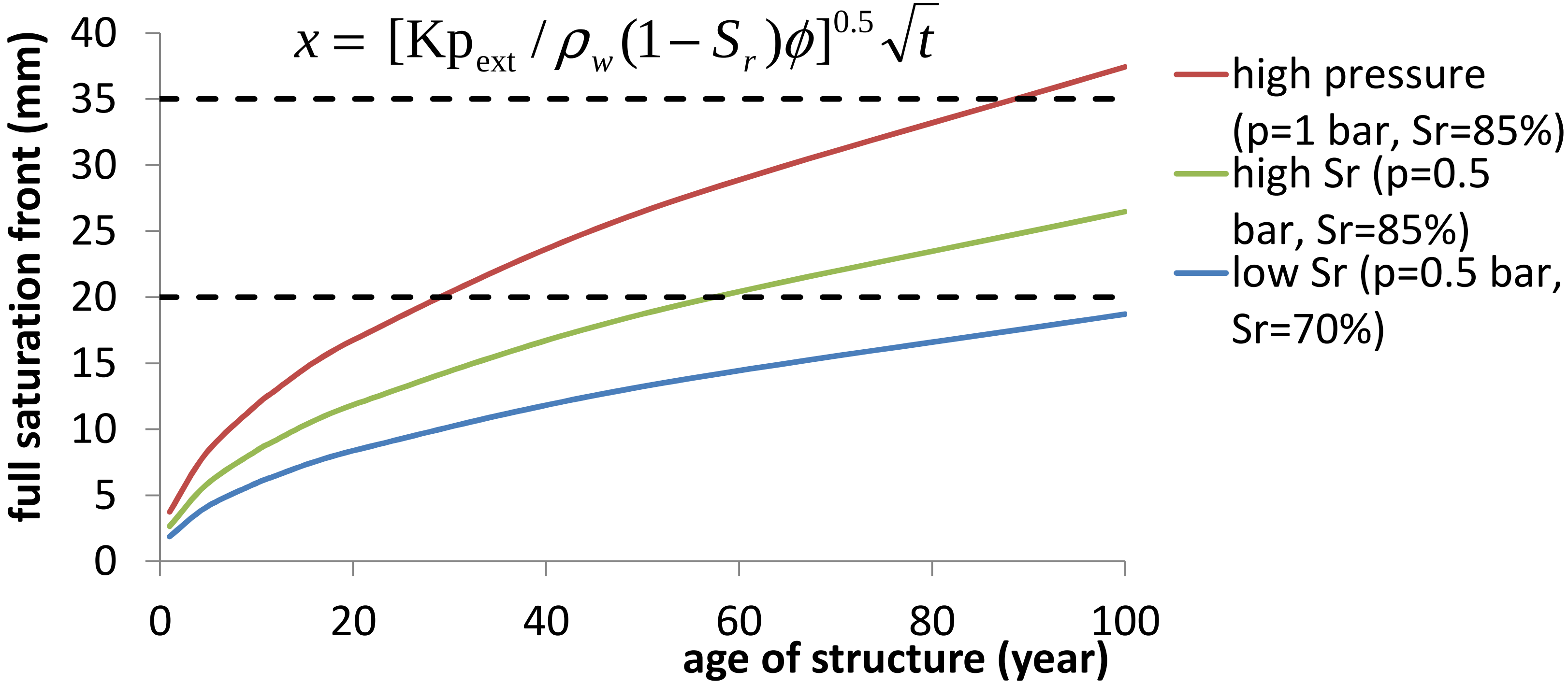
air zone	average	st.dev	minimum	maximum
RH_{int} (%)	70-65	10	20	92
RH_{out} (%)	80	10	24	100
T_{int} (°C)	12-14	6	-7 - -5	34-32
T_{out} (°C)	12	6	-8	32
CO_2 (ppm)	400-580	20-50	400	650-1250

3. Example of the importance of the environment: moisture distribution in a tunnel

Further assessment by modelling: Darcy flow



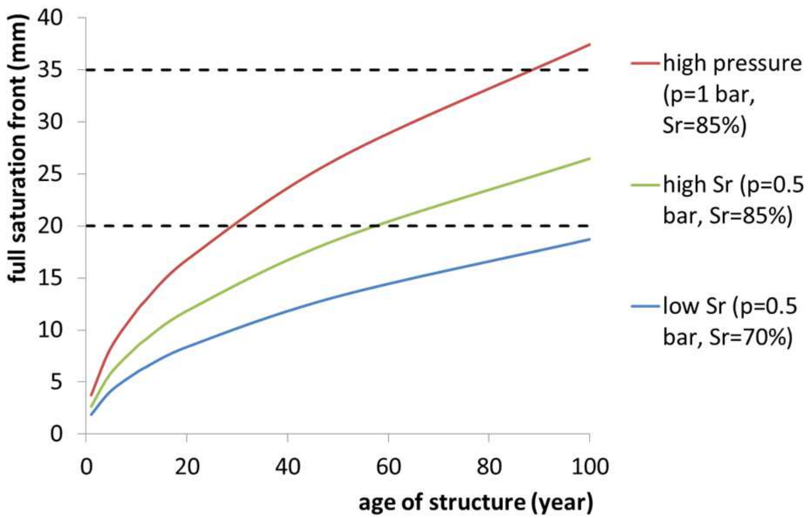
$$x = [Kp_{\text{ext}} / \rho_w (1 - S_r)\phi]^{0.5} \sqrt{t}$$

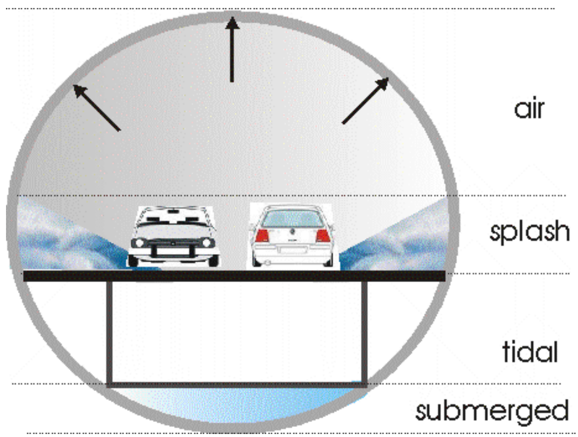


3. Example of the importance of the environment: moisture distribution in a tunnel

Conclusions:

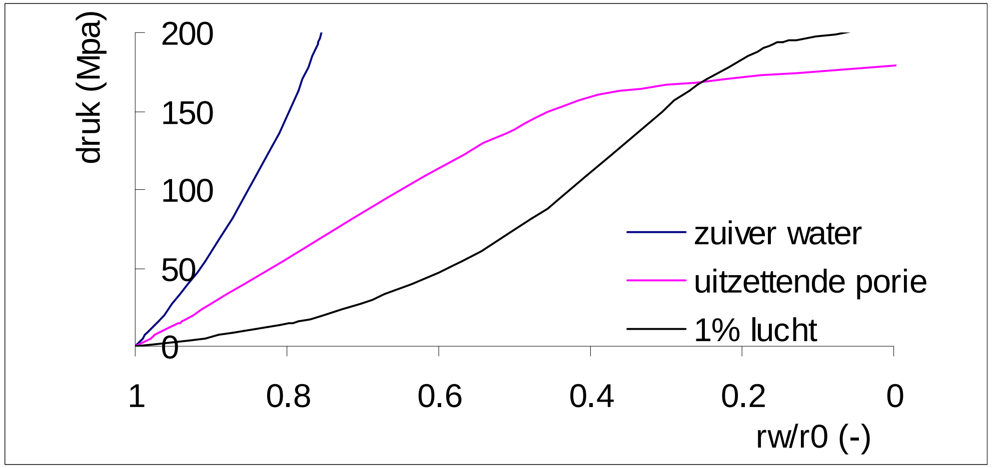
- Moisture conditions are in equilibrium with the internal RH
  - Water on the exterior functions as impervious
  - Moisture conditions further constant throughout, about 85%
- Corrosion of the reinforcement at the interior due to carbonation is a risk;
- Corrosion of the reinforcement at the exterior due to chloride penetration is much less likely



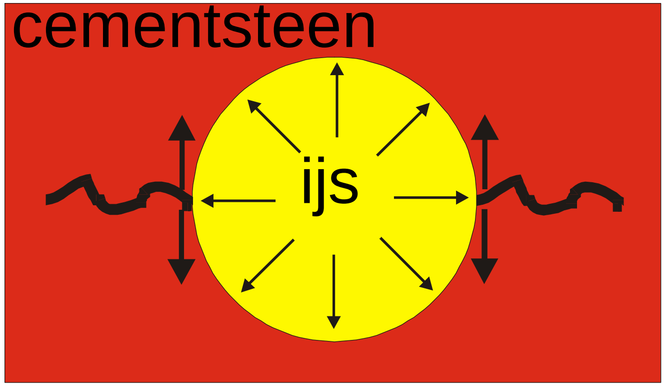


4.1 Degradation mechanisms: Example freeze-thawing

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

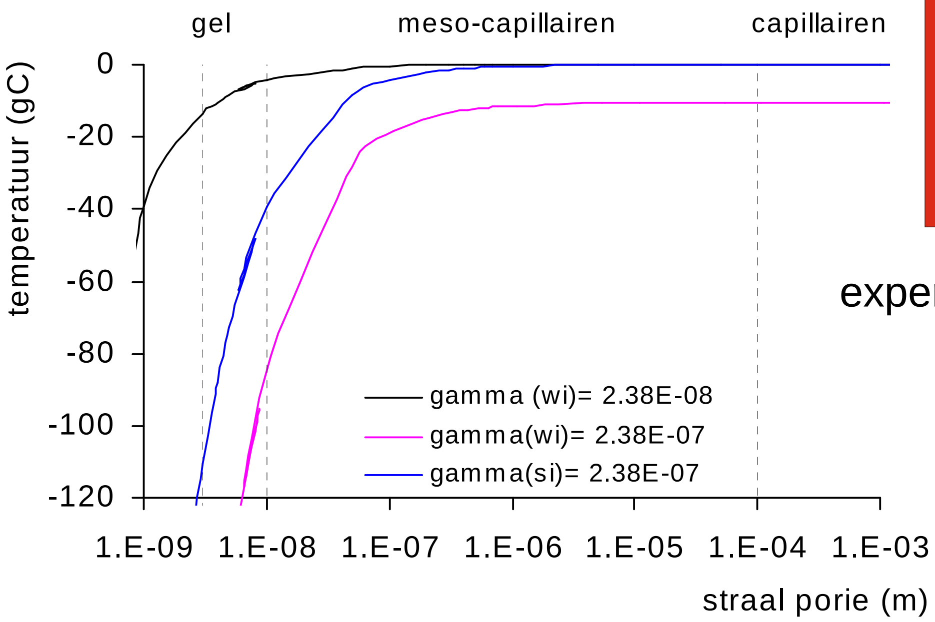


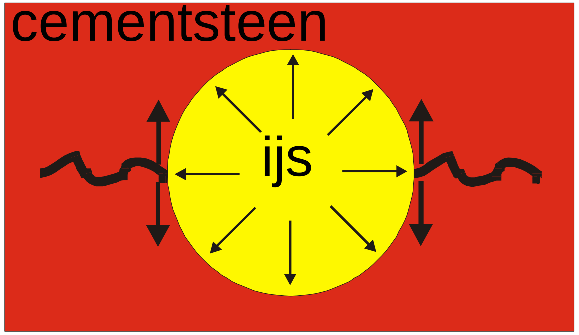
- Conditions:
- High enough Sr
- Low enough temperature
- Fast enough freezing



4.1 Degradation mechanisms: Freeze-thawing

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



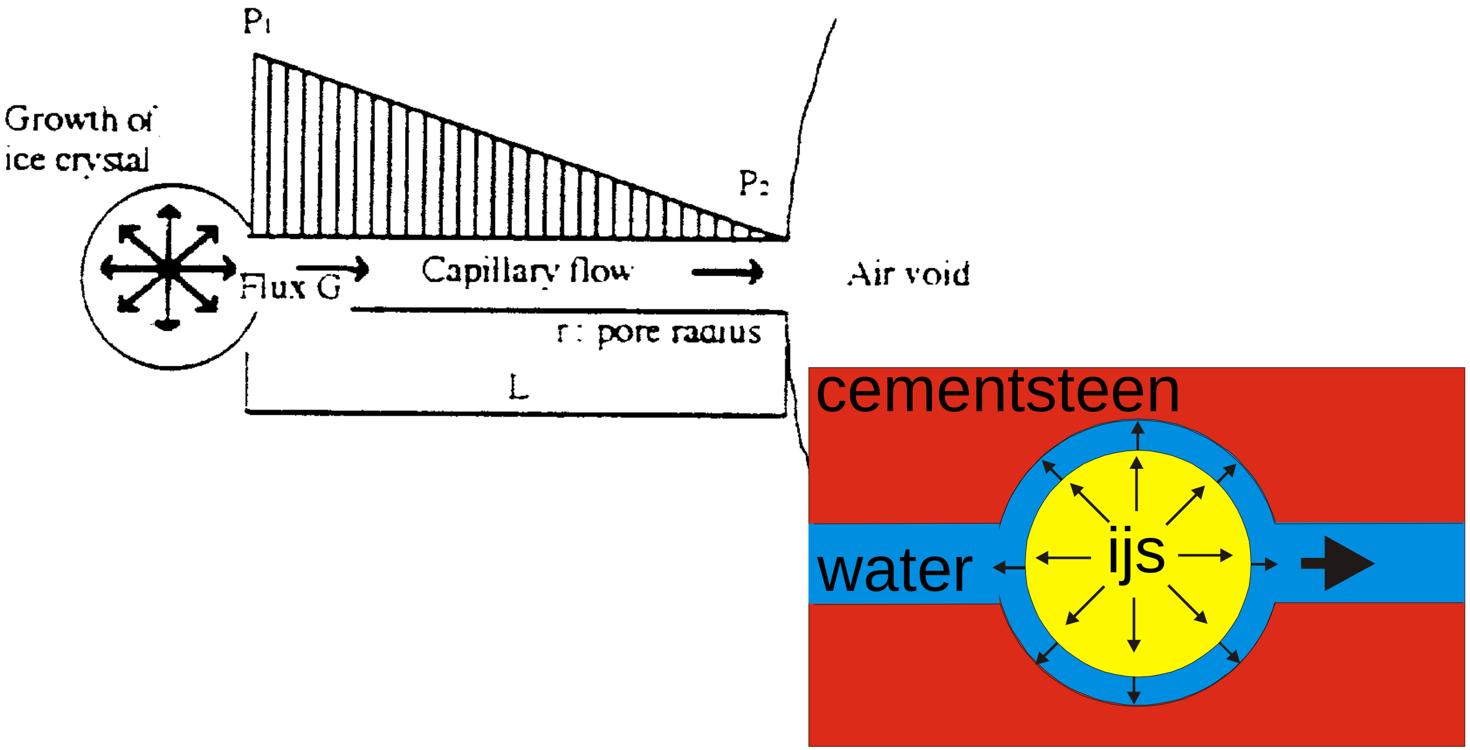


experiments

r>0.1 mm	:	0 tot -10 °C
r>10 nm	:	-20 tot -30 °C
3 < r < 10 nm	:	-35 tot -45 °C

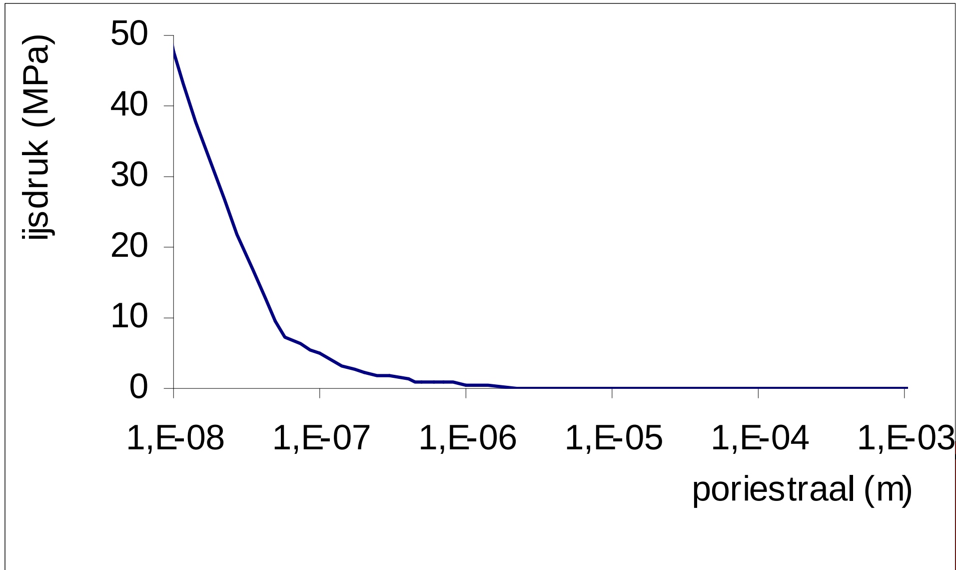
4.1 Degradation mechanisms: Freeze-thawing

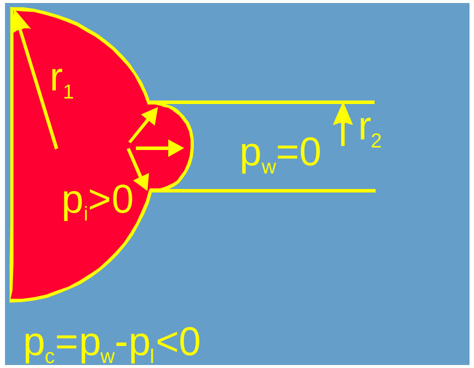
- Mechanisms 2: hydraulic pressure (is why air entrainment works!)

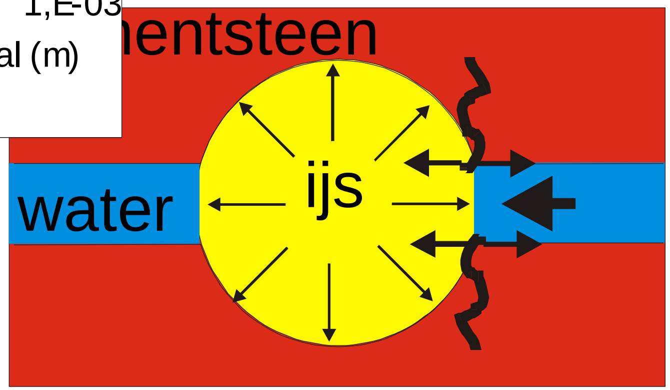


4.1 Degradation mechanisms: Freeze-thawing

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





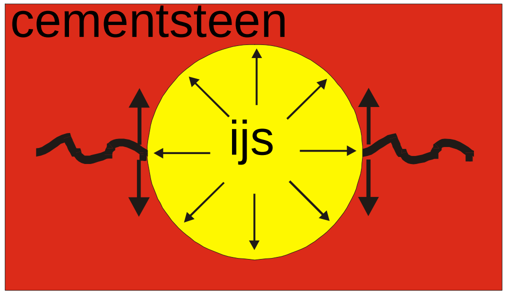


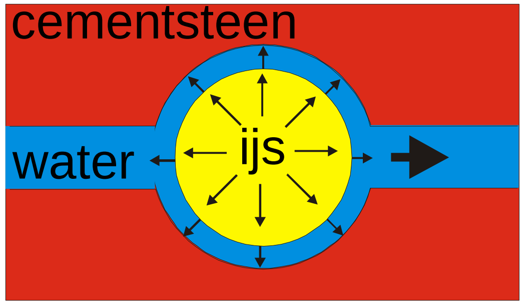
4.1 Degradation mechanisms: Freeze-thawing

Summary mechanisms

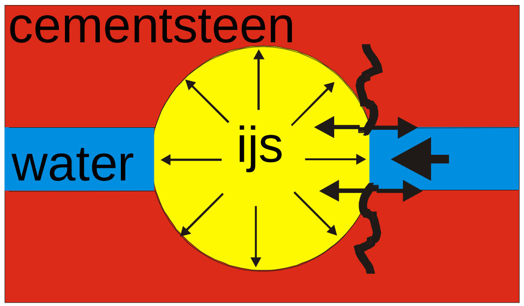
- Fast freezing:

expansion of ice 10%; fast pressure build up





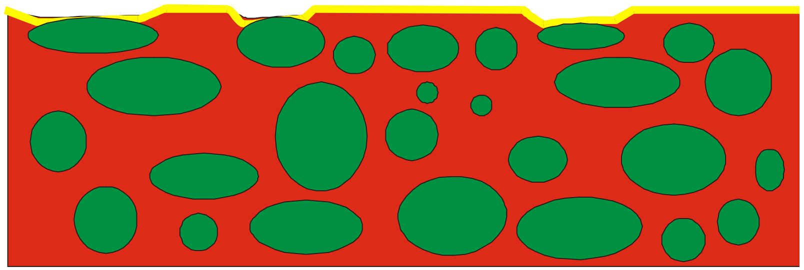
- Slow freezing (at modest T): transport of vapour to ice in larger pores – ice over pressure



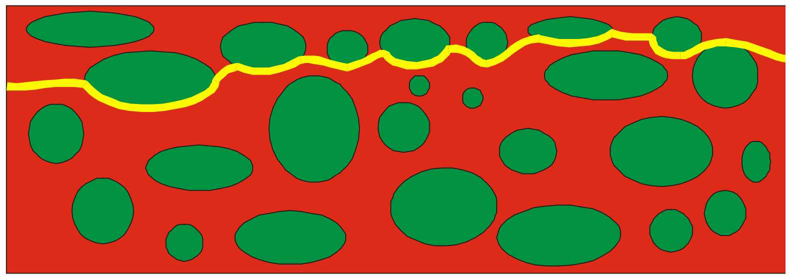
4.1 Degradation mechanisms: Freeze-thawing

Damage types:

- Scaling

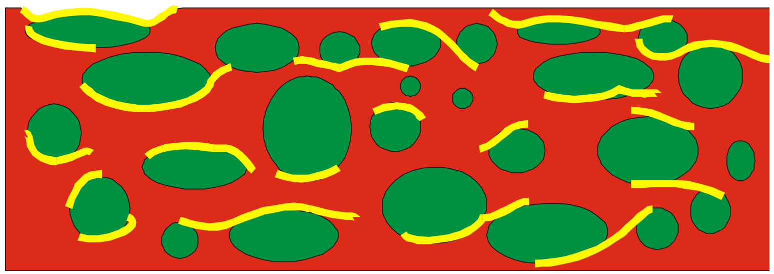


- Top layer delamination



- Total desintergration

(due to internal cracking)

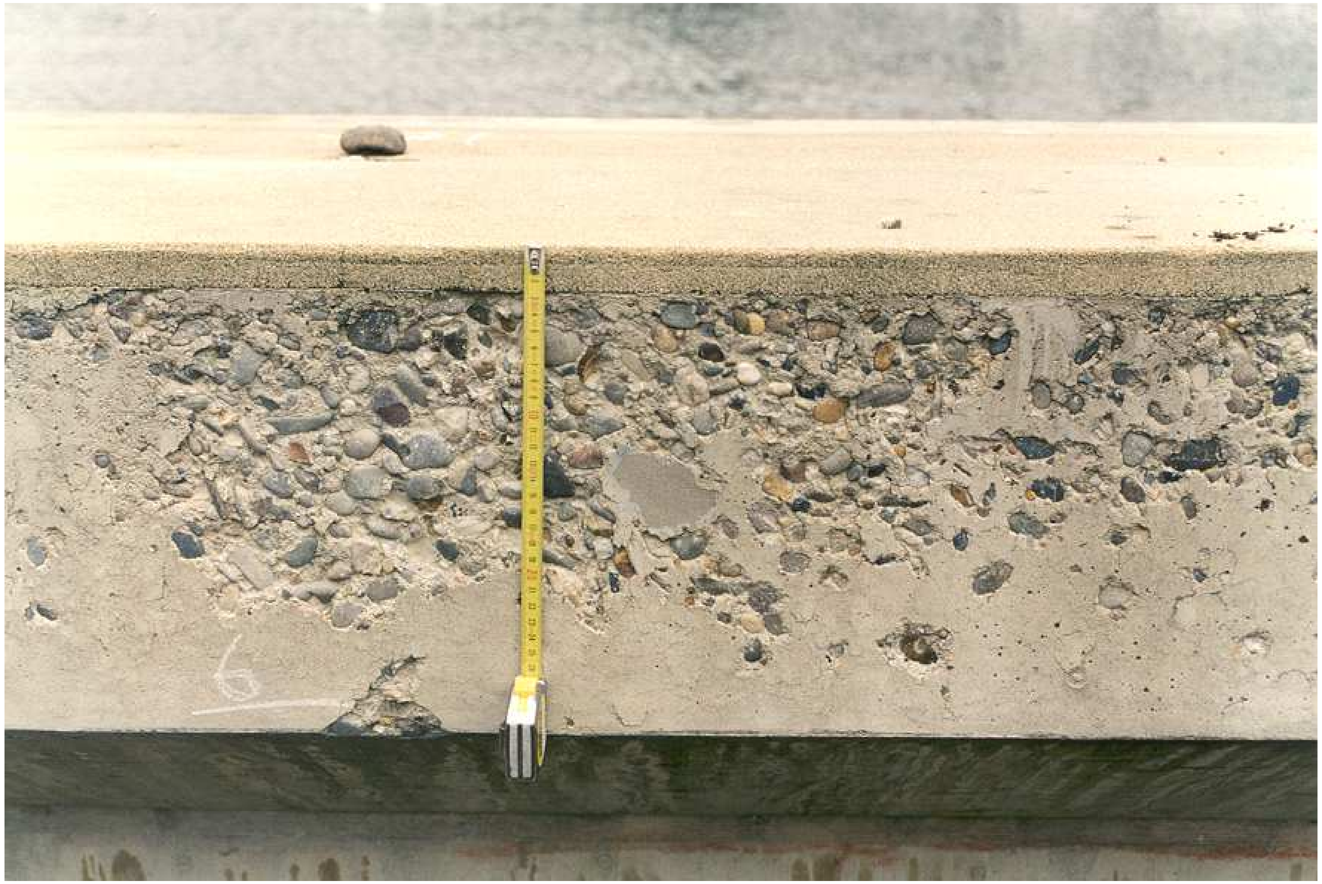


4.1 Degradation mechanisms: Freeze-thawing

Conditions:

- Sufficient low T
- Sufficient fast (or slow) freezing
- High enough degree of saturation
- (depends of rh, r and c(salt))

4.1 Degradation mechanisms: Freeze-thawing



4.1 Degradation mechanisms: Freeze-thawing

4.1 Degradation mechanisms: Freeze-thawing

4.2 Degradation mechanisms: chemical attack

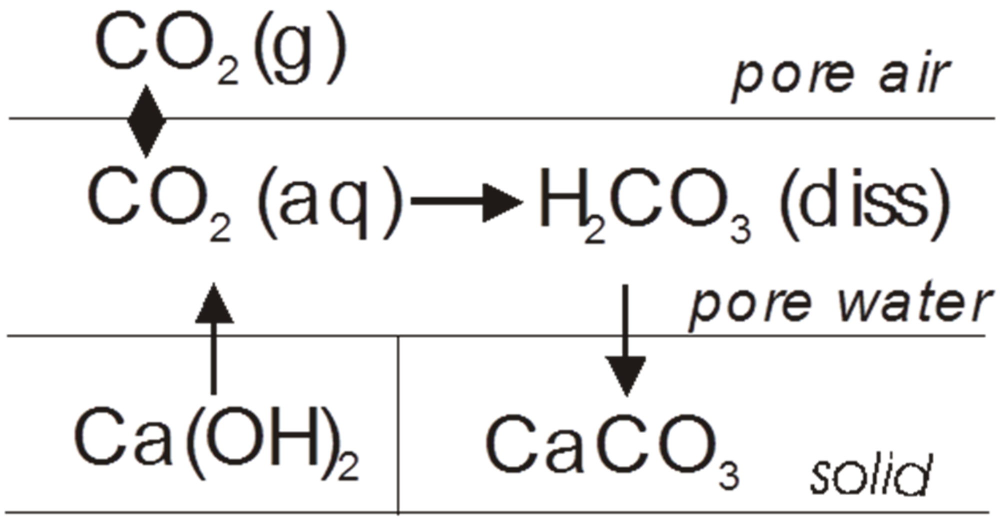
- formation of new chemical products:
  - volume increase / swelling
  - lower binding capacity
  - higher solubility

- consequences
  - cracking, scaling and spalling, debonding
  - loss of stress bearing capacity
  - reduction of service life


innovation for life

4.2 Degradation mechanisms: chemical attack

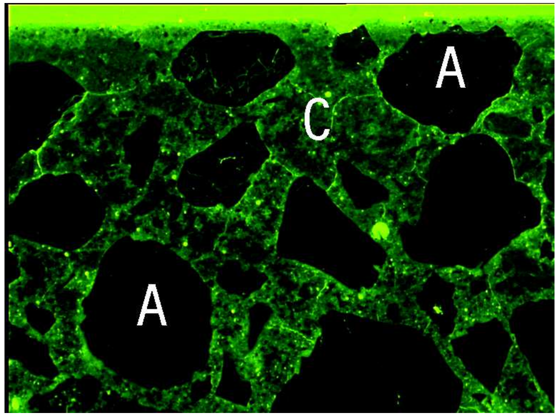
- *Chemical equilibrium (carbonation example):*
  - ***Transport** of CO2 due to concentration difference*
  - ***Dissolution** of CO2 in pore water and formation carbonic acid and dissociated (H_2CO_3, HCO_3^-, CO_3^{2-})*
  - ***Precipitation** $CaCO_3$ - dissolution $Ca(OH)_2$*



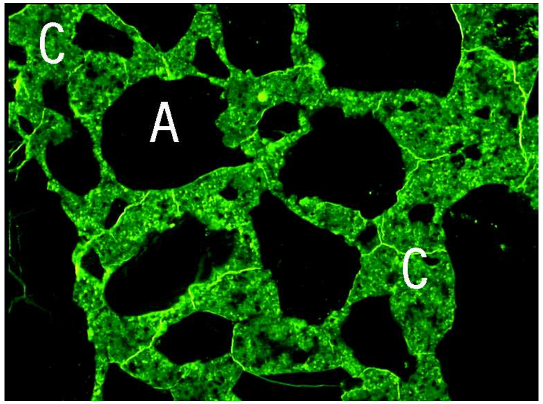
4.2 Carbonation

- *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



4.2 Carbonation

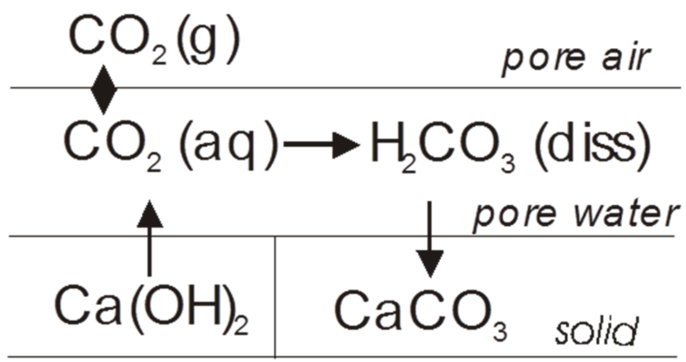
- *Chemical equilibrium – in detail:*
  - *Dissociation is acidification process*

$$H_2CO_3 + H_2O \Leftrightarrow H_3O^+ + HCO_3^-$$

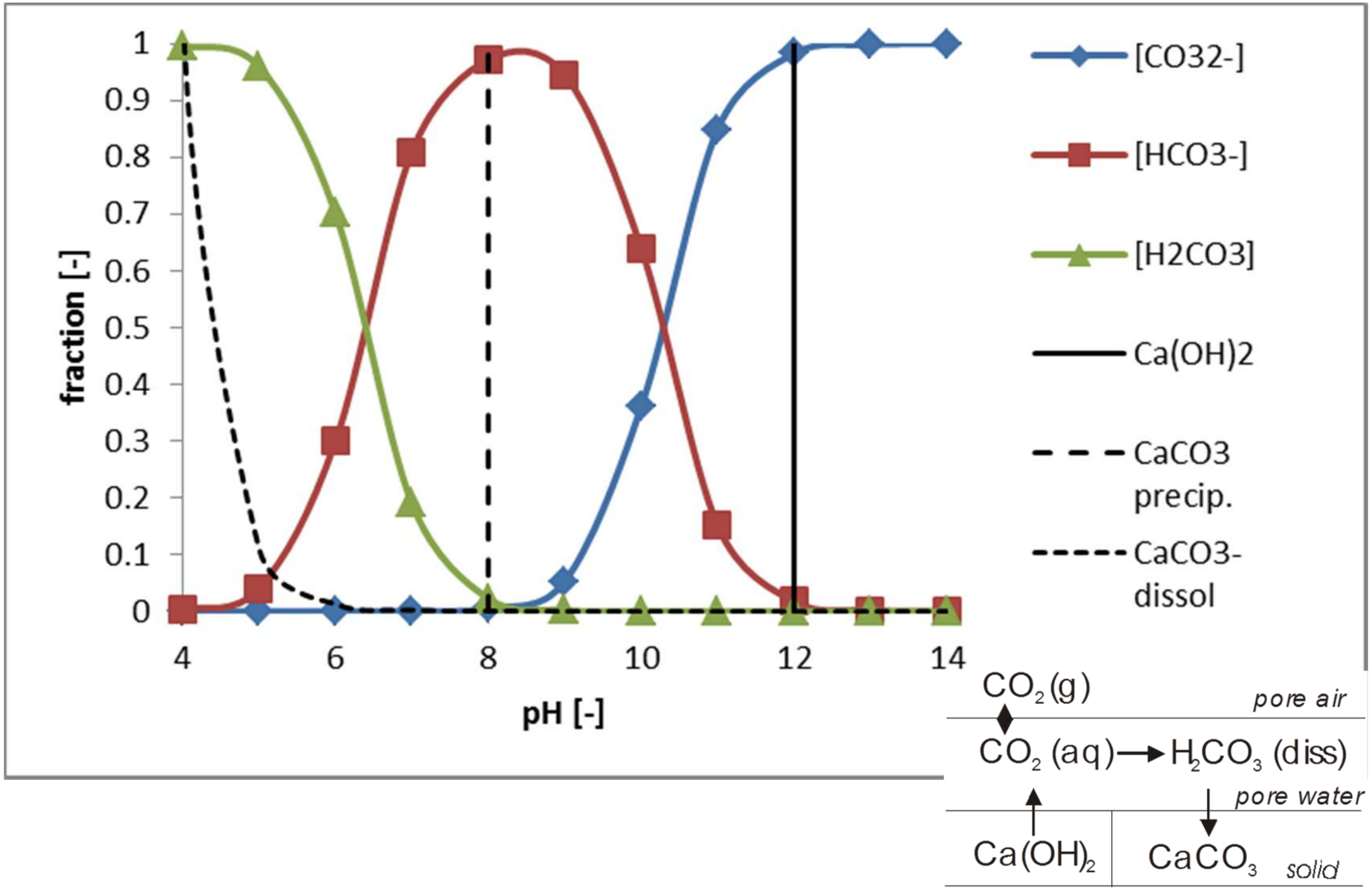
$$HCO_3^- + H_2O \Leftrightarrow H_3O^+ + CO_3^{2-}$$

  - *Precipitation of Ca^{2+} goes to completion:*

$$CO_3^{2-} + Ca^{2+} \Leftrightarrow CaCO_3\ (s)$$

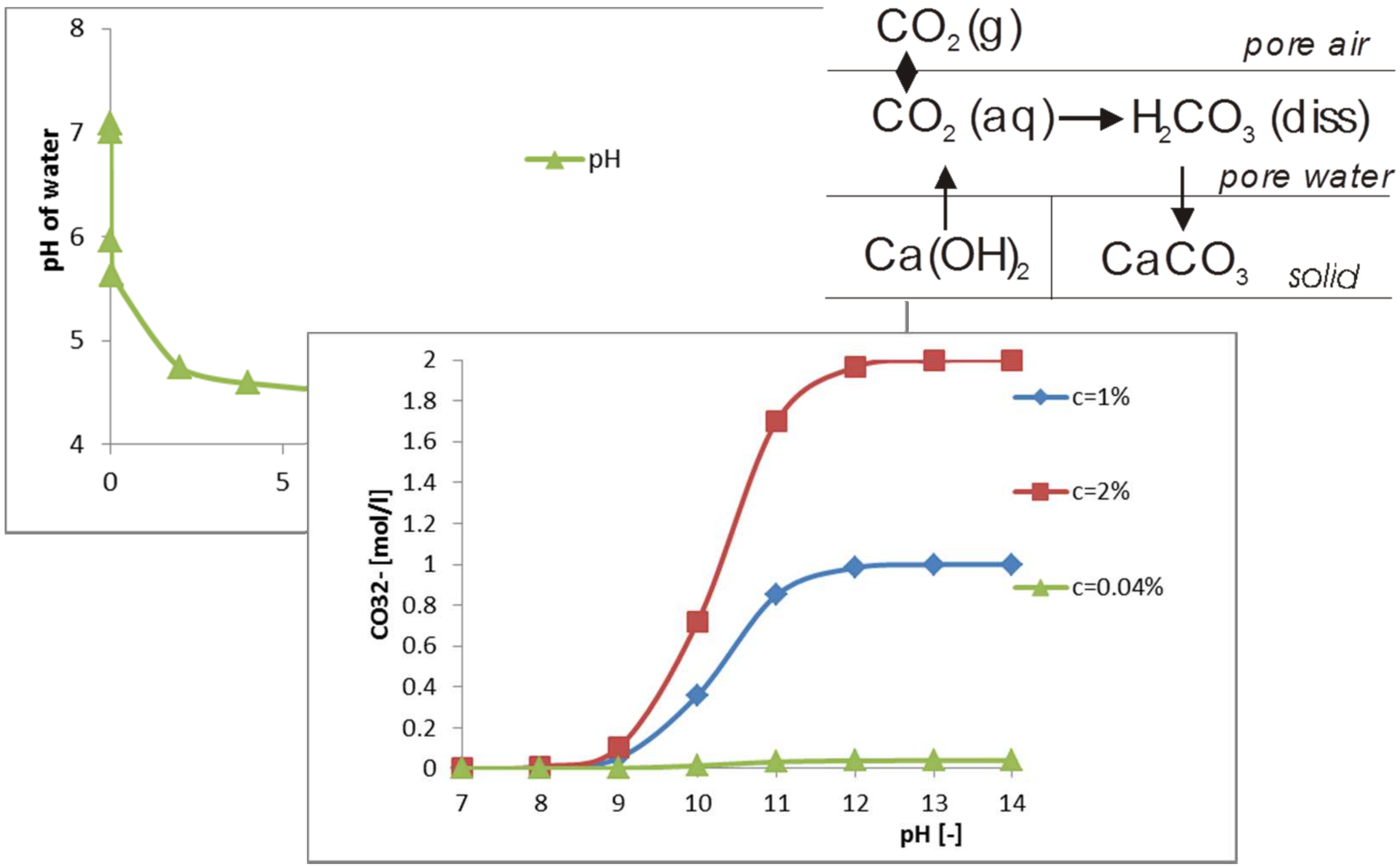



4.2 Carbonation



4.2 Carbonation

- *Equilibrium pH depending on CO2 concentration*

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4.2 Carbonation

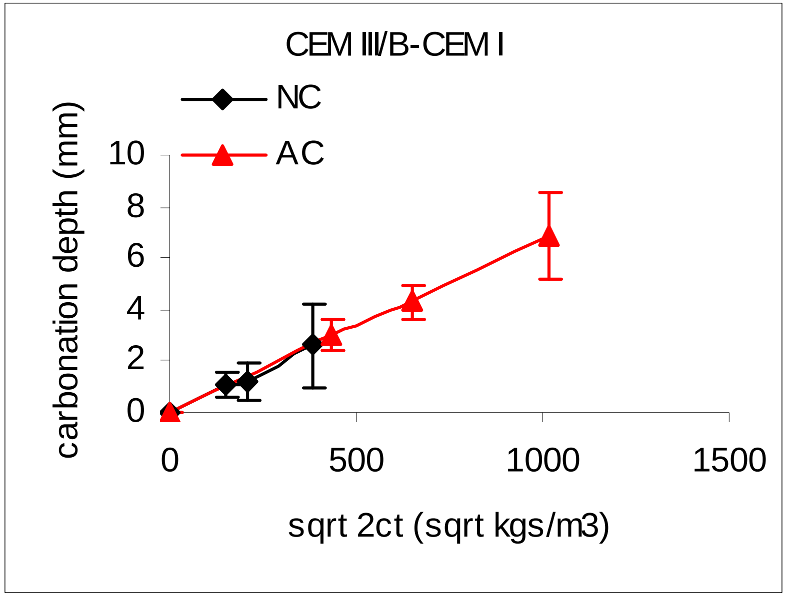
- ***Stability & pH***

Stage	pH	stable phases
1 (non-carbonated)	>12.6	$Ca(OH)_2$, CSH (Ca/Si > 1.8 or at high common ion effect), AFt, AFm
2	11.6 – 12.6	CSH (Ca/Si< 1.8), AFt, AFm
3	10.5 – 11.6	CSH (Ca/Si< 1.05), AFt, $Al(OH)_3$
4	10.0 – 10.5	CSH (Ca/Si< 0.85), $Fe(OH)_3$, $Al(OH)_3$
5 (fully carbonated)	< 10	SiO_2 with some CaO, $Fe(OH)_3$, $Al(OH)_3$

Data from literature, mostly from Lagerblad, 2005

4.2 Carbonation

- *Carbonation is a very slow process*
- *Testing taking often a year to obtain reliable results*
- *In a design-by-testing a year is too long*
- *Acceleration of the test is required*

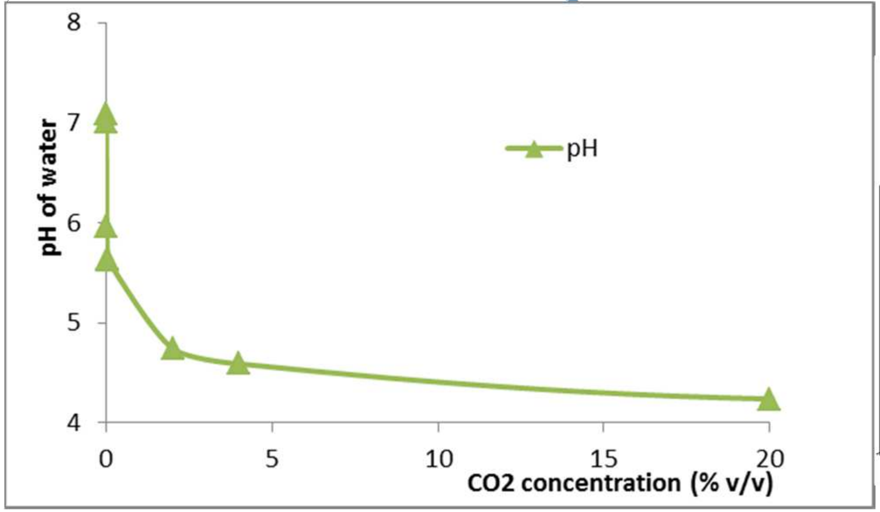


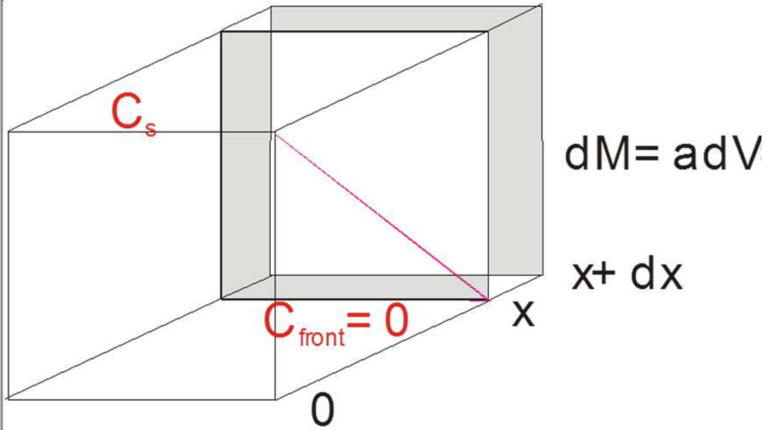
$$x_c = \sqrt{\frac{D}{a}}\sqrt{2ct} = \sqrt{1/R_{carb}}\sqrt{2ct}$$

E.g.
Acceleration concentr.: c= 2 %
Natural concentration: c = 0.04 %
Acceleration = 2/0.04 = 50 x

4.2 Carbonation

- *Carbonation starts with **diffusion of CO2-molecules***
- *At the carbonation front, it **dissolves** in the pore water*
- *It is instantly **consumed by Ca2+** in the pore fluid*
- *Buffer capacity of cement phases **releases new Ca2+***
  - *First Ca(OH)2 & high Ca CSH, next the other phases at succ. Lower pHs*
- *Concentration CO_2 at the front remains 0 until no more buffer*
- *CO2 concentration only effect = **faster delivery CO2 molecules***





4.2 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

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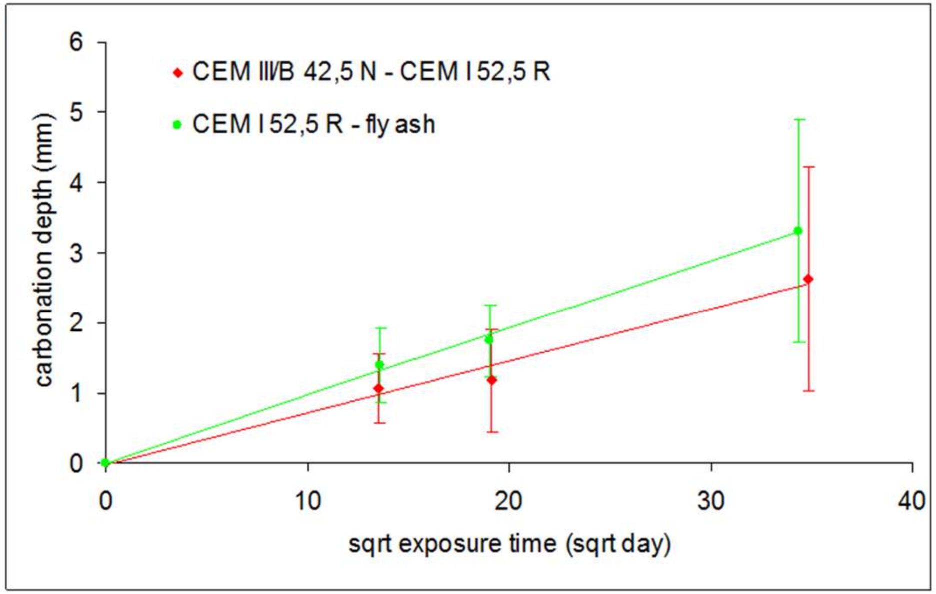

4.2 Carbonation: FMEA

- 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

4.2 Degradation mechanisms: carbonation

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Performance based service life design: durability of concrete

Conclusions:

1. Understanding all successive steps in the degradation mechanism is of importance; also from the viewpoint of prevention
2. Manipulating the structure of the concrete / cement paste is also a good way to either prevent or slow down degradation
3. There is however not one type of degradation: freeze-thawing, corrosion due to carbonation or chloride, ASR, sulfate resistance and so on may be of importance – a good assessment of the environment thus is important