Karlsruhe Institute of Technology

Freeze-thaw resistance of concrete

New findings on the mechanisms and prognosis of the degradation

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IMB
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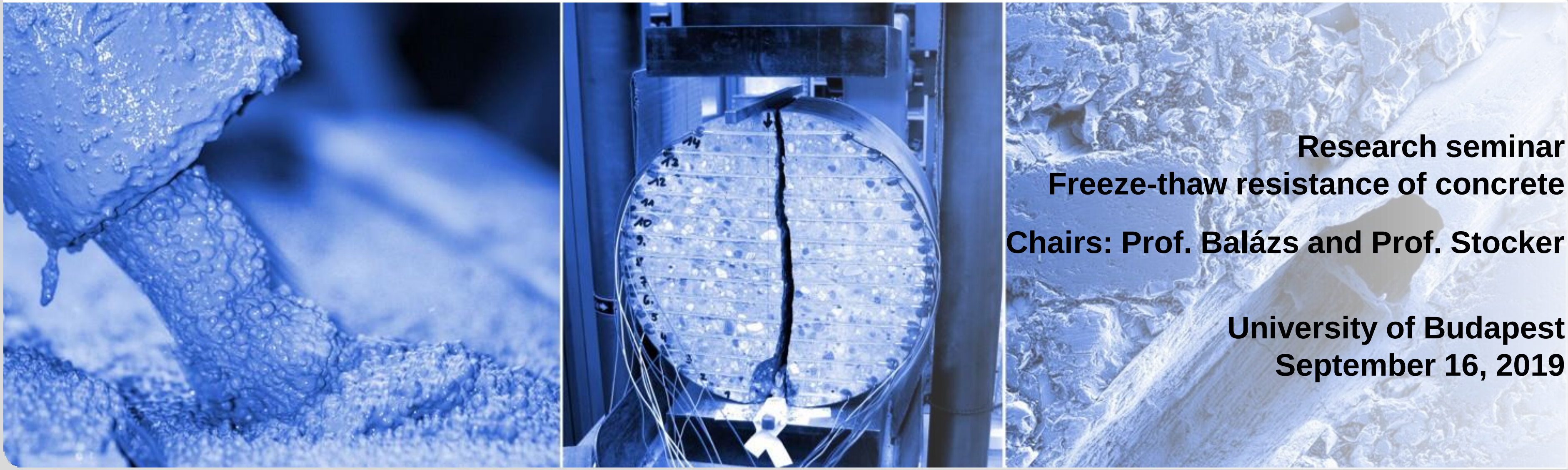


Research seminar
Freeze-thaw resistance of concrete

Chairs: Prof. Balázs and Prof. Stocker

University of Budapest
September 16, 2019

Contents

- Freeze-thaw attack – problem statement
- Service life design for frost attack
- Mechanisms of deterioration
- Experimental investigations and model development
- Conclusions and outlook

Frost damage of concrete

Basic conditions for a frost damage

low temperatures and numerous freeze-thaw cycles

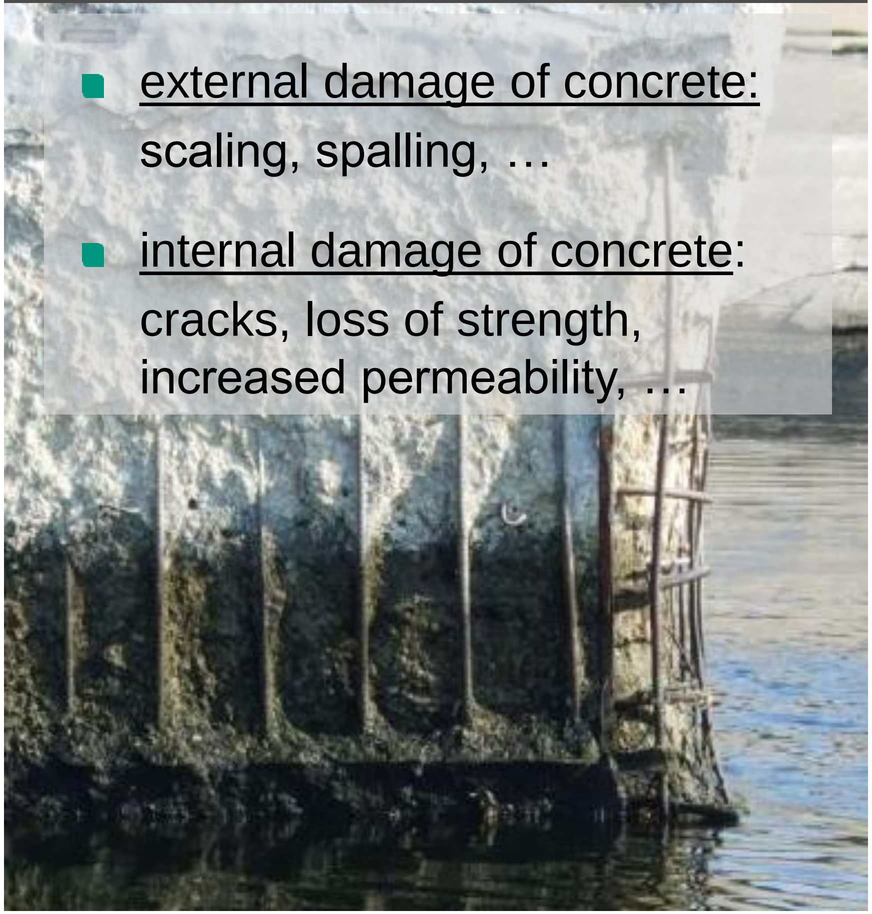
+

high water saturation

+

insufficient concrete properties

Example: Frost damage on a hydroelectric power plant



- <u>external damage of concrete:</u>
  scaling, spalling, …
- <u>internal damage of concrete</u>:
  cracks, loss of strength, increased permeability, …

Frost damage – problem statement

- The **degradation mechanism** (interactions of action/resistance) are not sufficiently understood
  - ⇨ reliable, physically based models are lacking

- The **descriptive concept** given in standards (limiting values for material properties) is based just on experience
  - ⇨ proved to be a rather uncertain approach

- Accelerated **performance tests**
  - ⇨ only partially and with considerable uncertainities transferable to the conditions in practice

Heft 577

DEUTSCHER AUSSCHUSS FÜR STAHLBETON

Zusammenfassender Bericht
zum Verbundforschungsvorhaben
„Übertragbarkeit von Frost-Laborprüfungen
auf Praxisverhältnisse“

von

Harald S. Müller
Ulf Guse

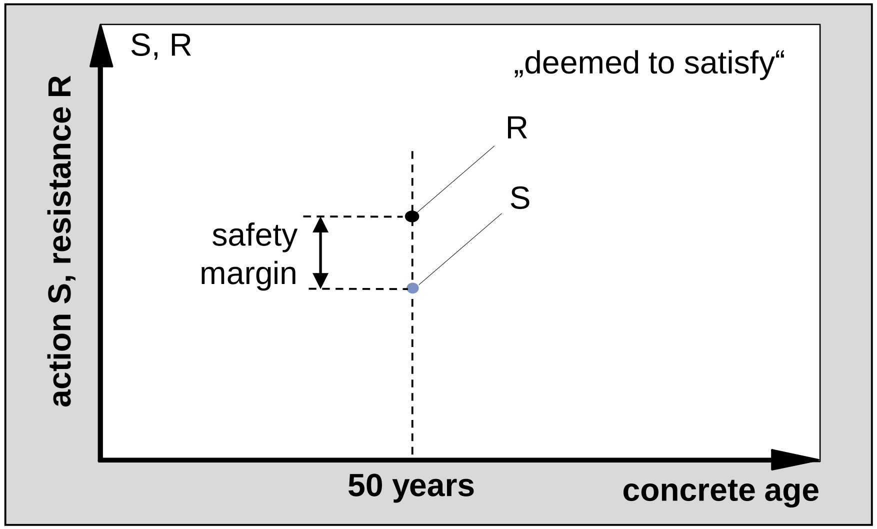
Berlin 2010

Beuth

Service life design for frost attack – approaches applied in practice today

Descriptive concept

approach: R – S > 0

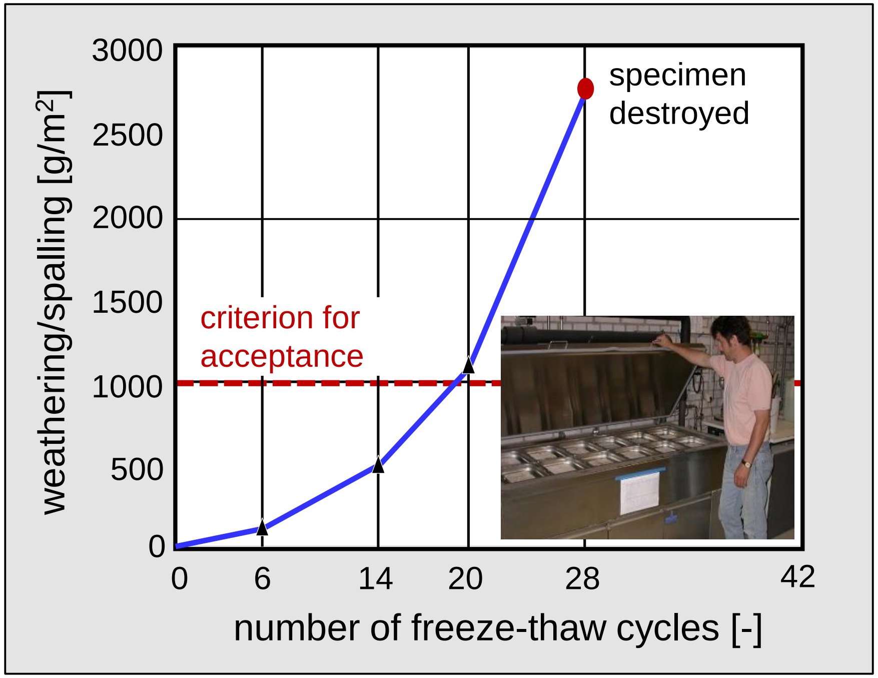


Guideline, e.g. EN 206 / DIN 1045-2

action S	resistance R				
exposure condition	max w/c [-]	min f_{ck} [N/mm^2]	min c [kg/m^3]	min. air content [%]	concrete cover [mm]
XF3: frost, high water saturation, no de-icing agent	0,55 0,50	C25/30 C35/45	300 320	4,5 -	- -

Performance concept (tests)

approach: CIF test acc. to Setzer (RILEM)

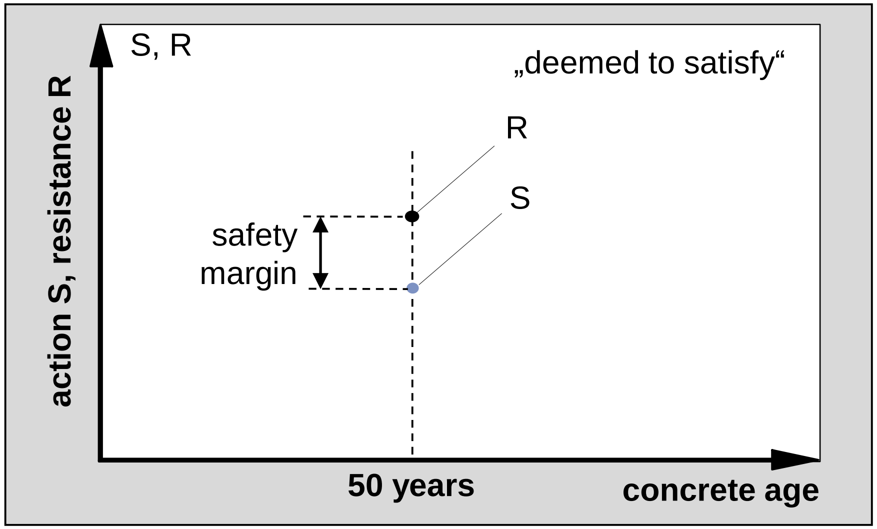


The criterion for acceptance is based on experience („deemed to satisfy“) and represents not an explicit design value

Service life design for frost attack – approaches of today and tomorrow

Descriptive concept

approach: $R - S > 0$



Guideline, e.g. EN 206 / DIN 1045-2

action S	resistance R				
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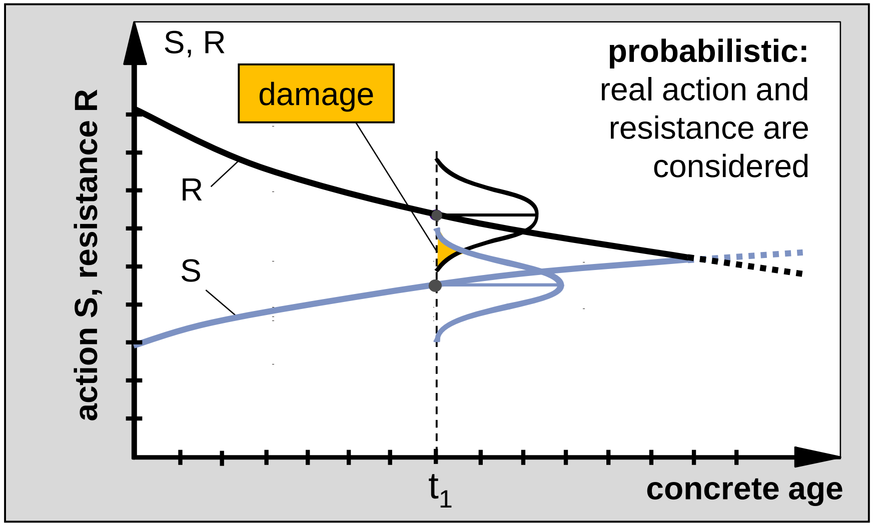
Performance concept (models)

approach: $p_f(t) = p_f\,[R(t) - S(t) \le 0] \le p_{target}$



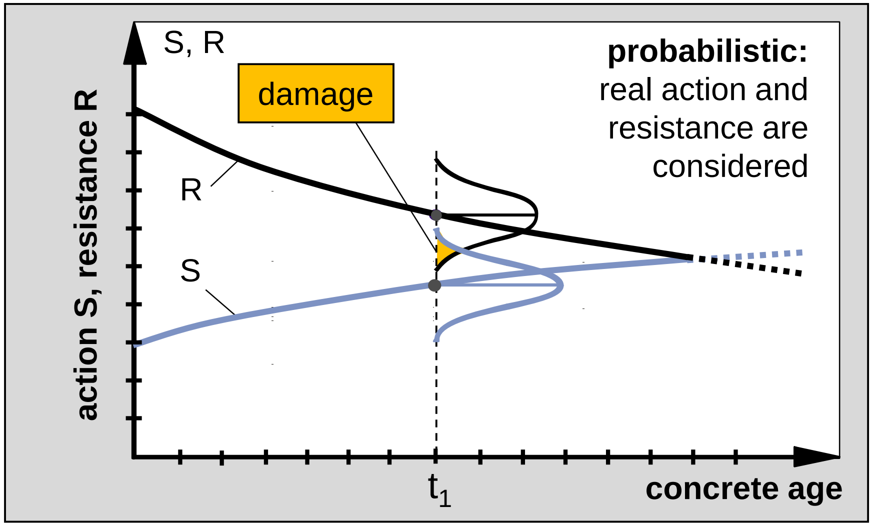
To be developed (research)

physical model for frost damage	**S** = function (concept) to consider the local climatical actions
	R = material model based on physical mechanisms to describe the resistance

Service life design for frost attack

Performance concept (models)

approach: $p_f(t) = p_f\,[R(t) - S(t) \leq 0] \leq p_{target}$



probabilistic: real action and resistance are considered

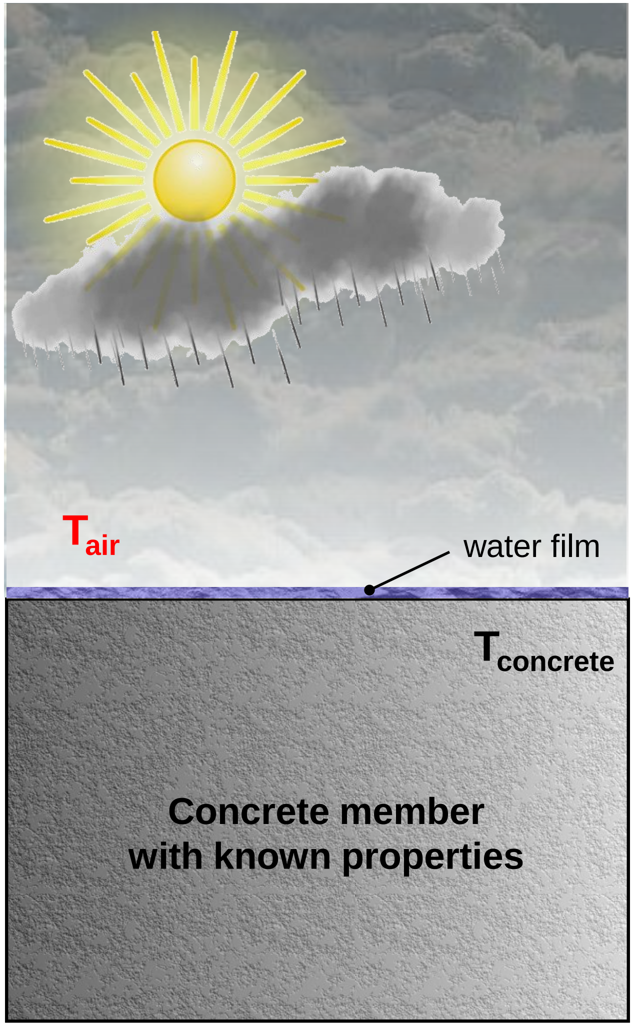
To be developed (research)

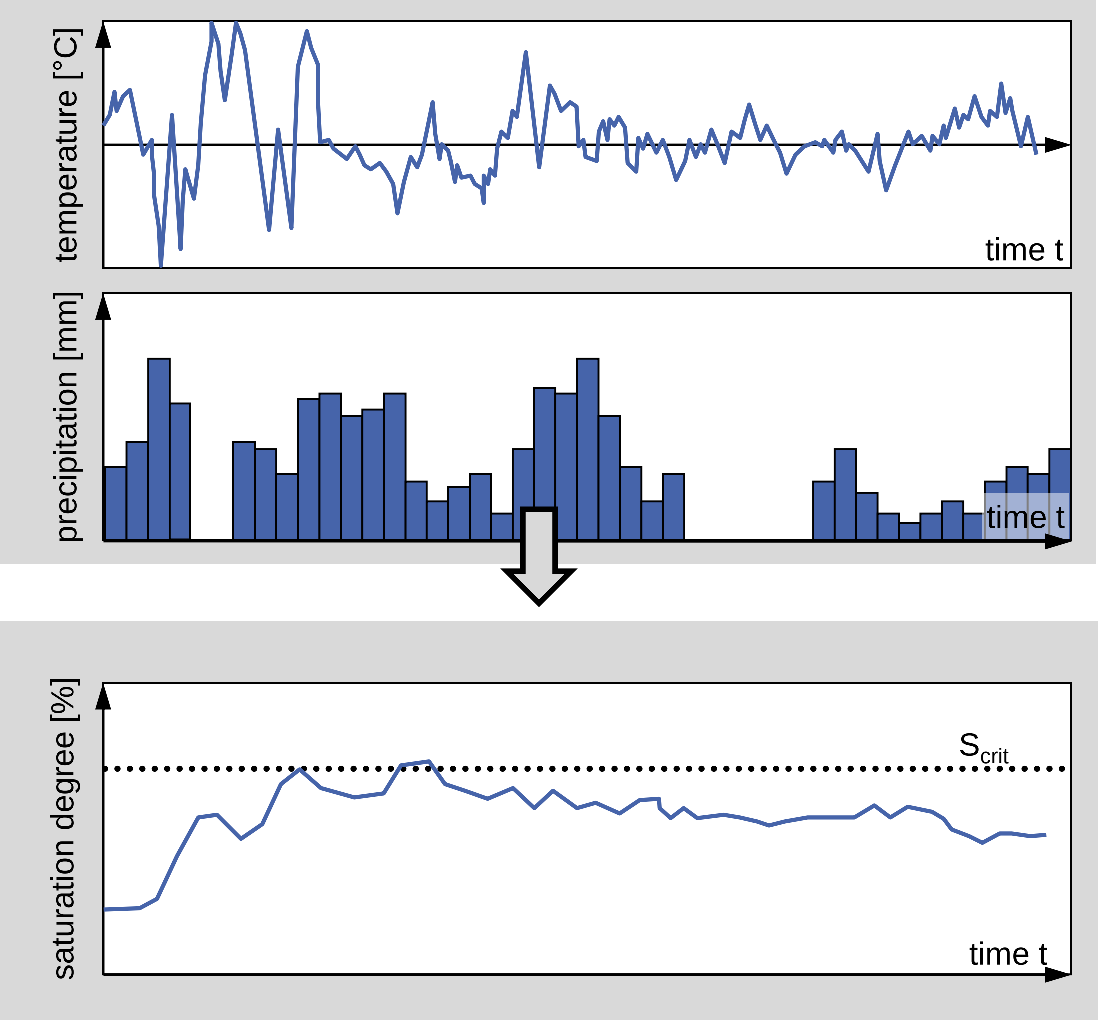
physical model for frost damage	**S** = function (concept) to consider the local climatical actions
	R = material model based on physical mechanisms to describe the resistance

Remarks:

- Full probabilistic design means that all mechanisms are understood and correspondingly modelled, and that the statistical characteristics of the governing parameters are known.
- Based on such an approach simplyfied code-type models may be derived, such as concepts with partial safety factors etc.
- Suitable code-type design tools, such as simple formulas, diagrams or tables can be developed while maintaining the probabilistic concept, which is characteristic for engineering design!
- **Research is mendatory!**

Actions causing damages due to real weather events

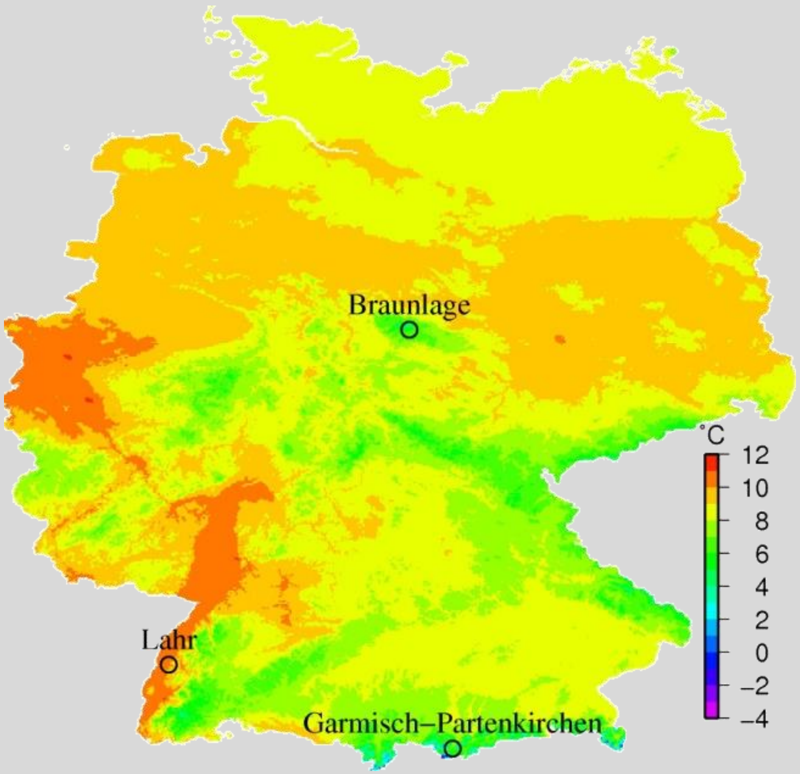




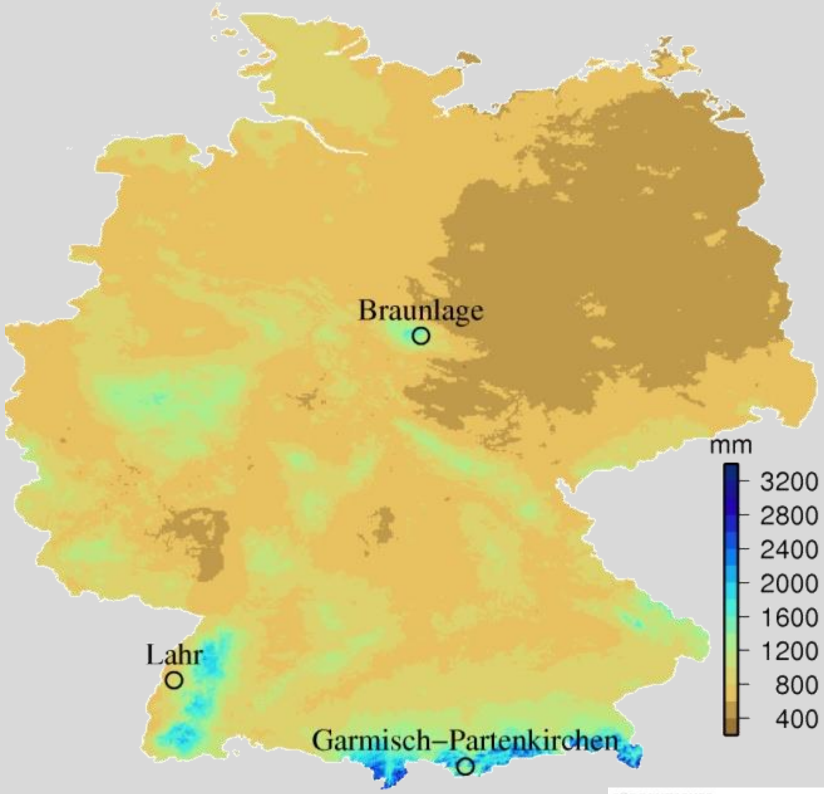
Determination of the frequency and intensity of frost attacks

Karlsruhe Institute of Technology

Mean annual temperature



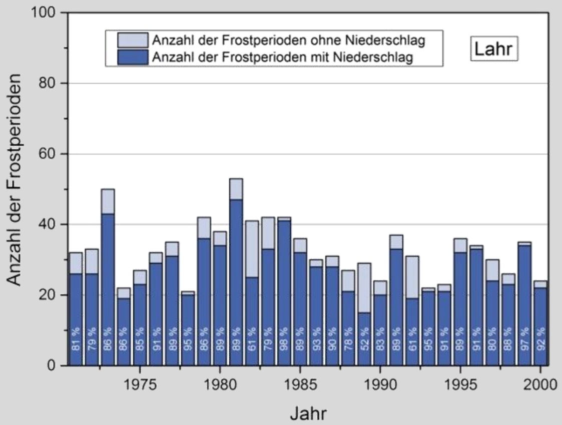
Annual precipitation



in collaboration with: SÜDDEUTSCHES Klima büro

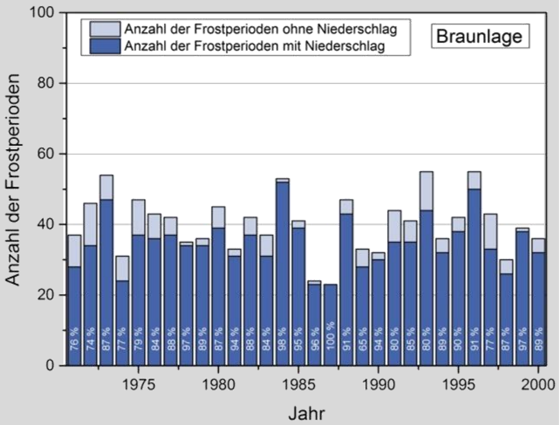
Number of frost periods in 1970 – 2000

Lahr



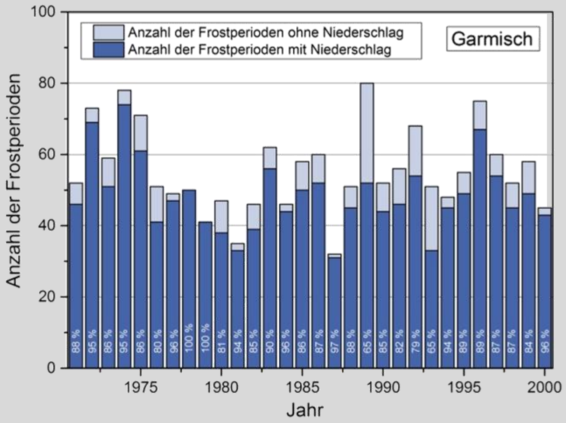
total number: 985
with precipitation: 839

Braunlage



total number: 1214
with precipitation: 1050

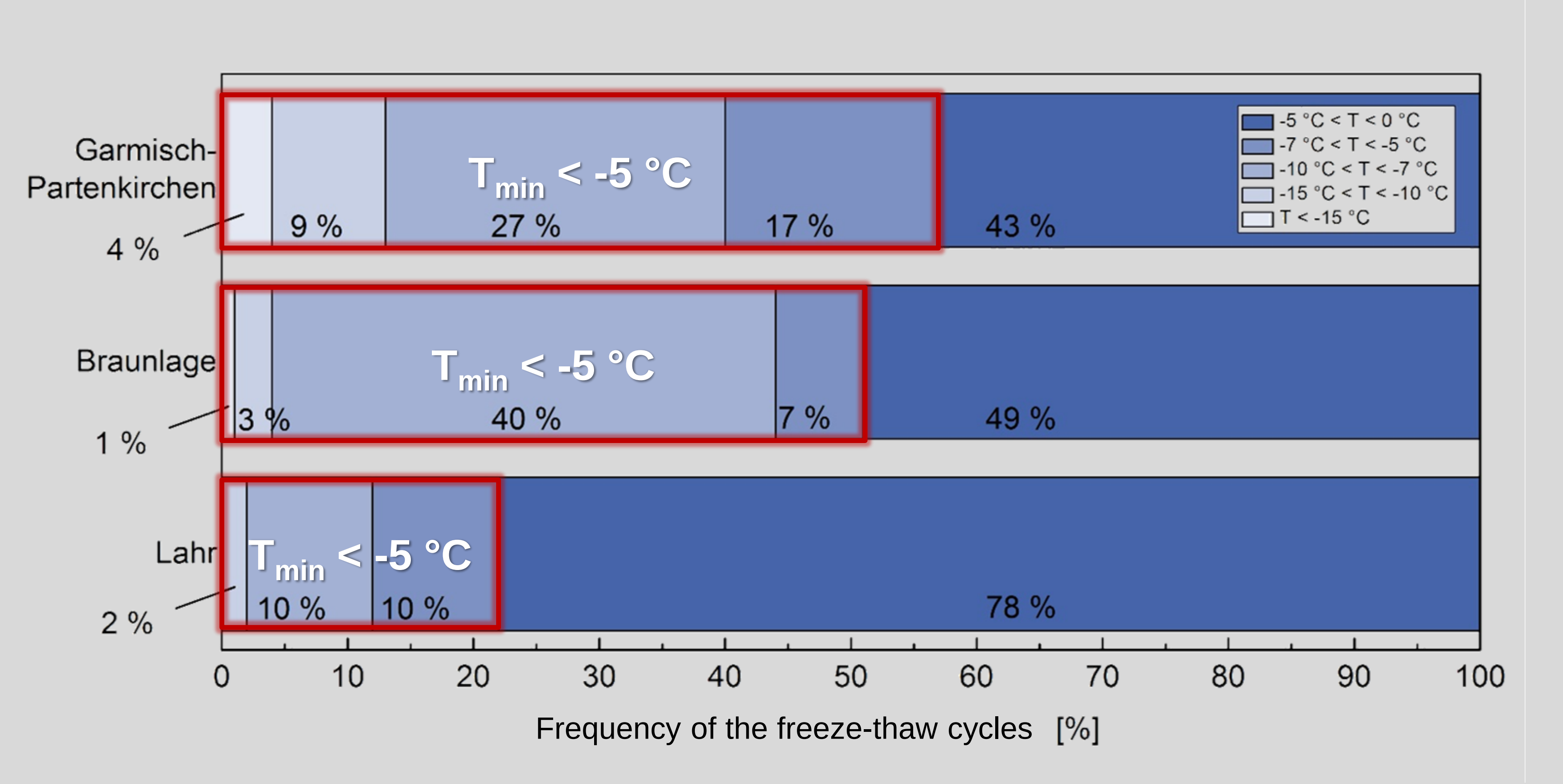
Garmisch-Partenkirchen



total number: 1663
with precipitation: 1449

⇨ **precipitation at approx. 85 % of all frost periods**

Classification of the freeze-thaw cycles by means of the minimum temperature T_{min}



The minimum temperature depends pronouncedly on the location.
In Braunlage and Garmisch: Majority of FTC with T_{min} < -5 °C

Empirical models for the threeze-thaw attack

Model by Vesikari

$$r(t) = c_{env} \cdot c_{cur} \cdot c_{age} \cdot a^{-0,7}(f_{ck} + 8)^{-1,4} \cdot t$$

with

$r(t)$	spalling at time t [mm]
c_{env}	const. – intensity and likeliness of a freeze-thaw attack [-]
c_{cur}	const. – influence of curing [-]
c_{age}	const. – maturity of concrete and additon of additives [-]
a	air void content [-]
f_{ck}	concrete compressive strength [MPa]

Model by Lowke, Schiessl & Brandes

$$r(FTC) = k \cdot f_s \cdot f_{Tmin} \cdot f_{wc} \cdot f_{bin} \cdot f_{aea} \cdot f_{carb}$$

with

r	spalling after number of freeze-thaw-cycles [m]
k	max. allowable spalling per FTC [m/FTC]
fs	const. – salt concentration [-]
f_{Tmin}	const. – min. temperature [-]
f_{wc}	const. – w/c-ratio [-]
f_{bin}	const. – type of binder [-]
f_{aea}	const. – air void content [-]
f_{carb}	const. – carbon. bound. zone [-]

Low accuracy due to:

- physical mechanisms are ignored
- affecting parameters are not interrelated
- basic deficiencies of the product-type approach

Mechanisms of the frost damage

Physical mechanisms

volume expansion of water during freezing to ice 9 vol.-%

⇩

water is non-compressible } ⇨ tensile concrete strains occur

⇩

$$\varepsilon_{lin} = \sqrt[3]{1{,}09}$$

$$\approx 1{,}03 \;\square\; 3\ \% \quad > \quad \varepsilon_{c,t} = 0{,}3\ ‰$$

⇩

Expansion space necessary

otherwise ⇩

Crack formation in concrete

Prerequisite for the damage: critical saturation

Saturation degree S of the pores:

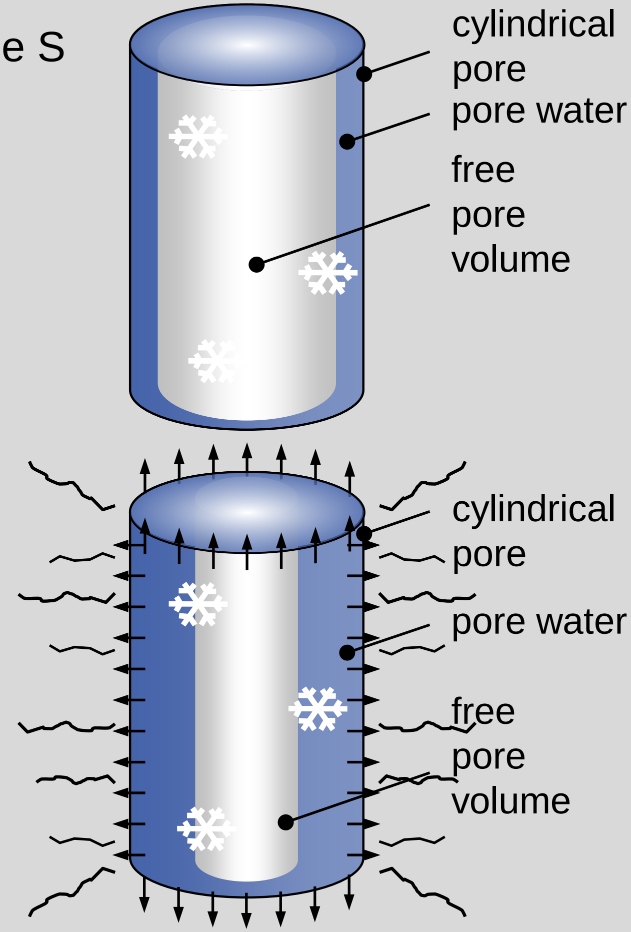
$$S = \frac{V_{water}}{V_{pore}}$$

no damage:

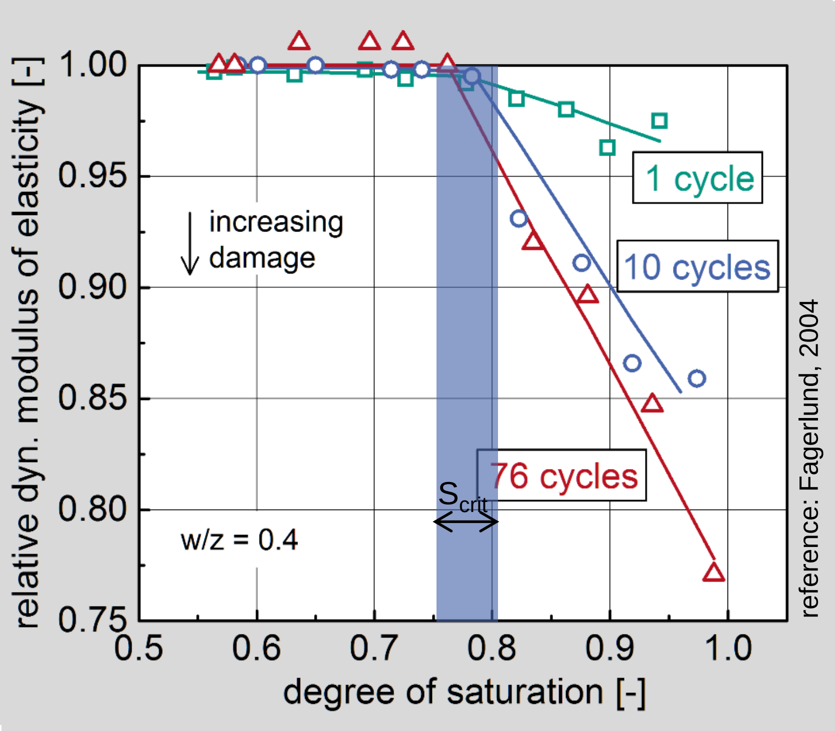
$$S < S_{crit}$$

damage:

$$S \geq S_{crit}$$



Limit state for the occurence of damage S_{crit}



reference: Fagerlund, 2004

- significant concrete damage initiated for $S > S_{crit} = 0.7 - 0.9$
- critical saturation S_{crit} well investigated
- insufficient knowledge on time development of saturation S(t) before damage occurs

time until critical saturation S_{crit} is reached is unknown

Model approach: $S(t_{failure}) = S_{crit} \rightarrow t_{failure}$

Current fib model: $S(t) = S_b + a \cdot t^{d}$

(Model Code for Service Life Design, 2006)

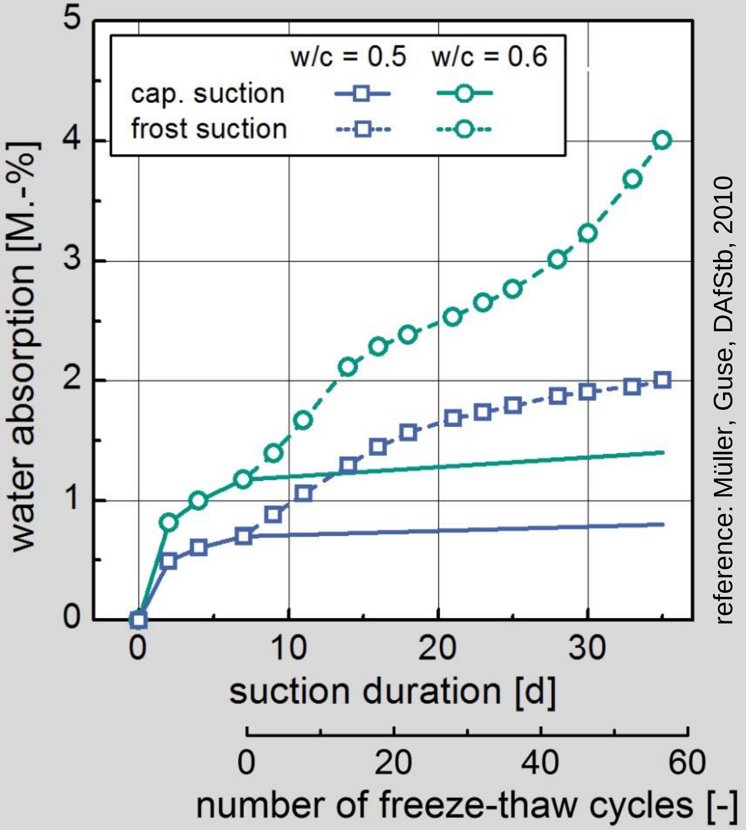
material coefficients

saturation degree due to the fast capillary suction

frost suction is ignored!

Consequences of cyclic freeze-thaw loading

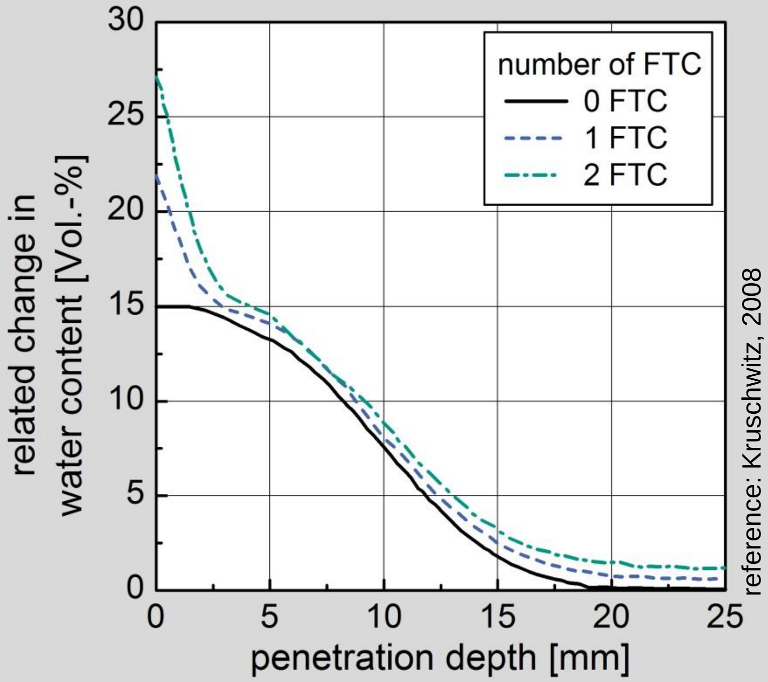
Concrete frost suction at T_{min} = -20°C



reference: Müller, Guse, DAfStb, 2010

Water uptake resulting from freezing-thawing action outweighs the one from capillary suction

Distribution of water absorption

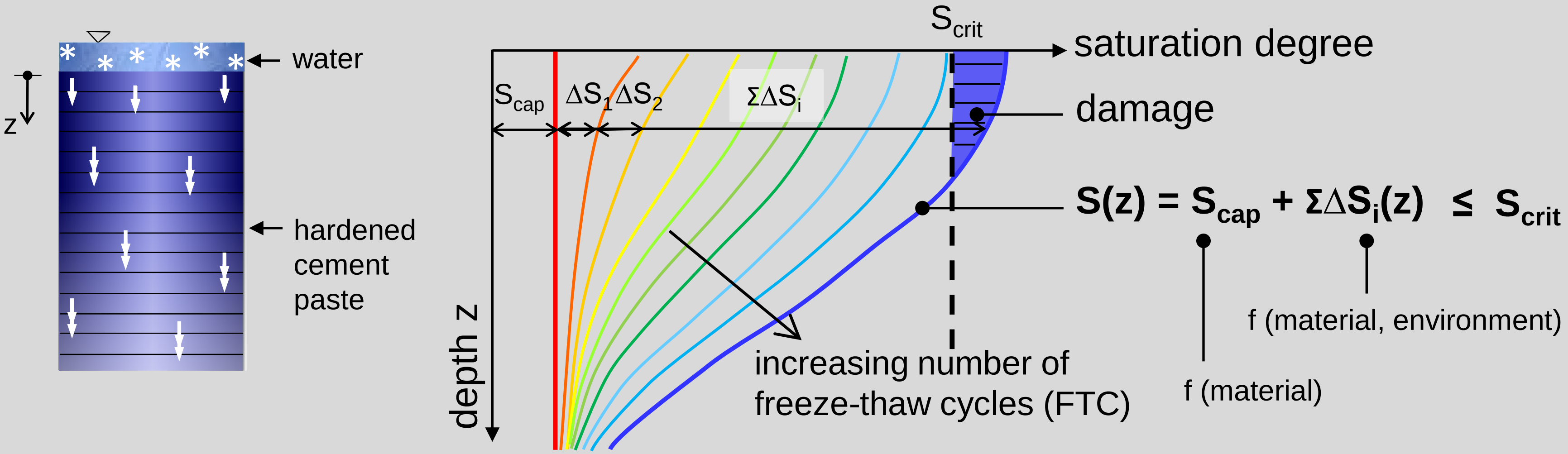


reference: Kruschwitz, 2008

Frost suction is limited to the top millimeters of the concrete's surface

Basis idea of modelling

Determination/prognosis of the water uptake depending on time and location during freeze-thaw actions



$$S(z) = S_{cap} + \Sigma\Delta S_i(z) \leq S_{crit}$$

ΔS dependent from:

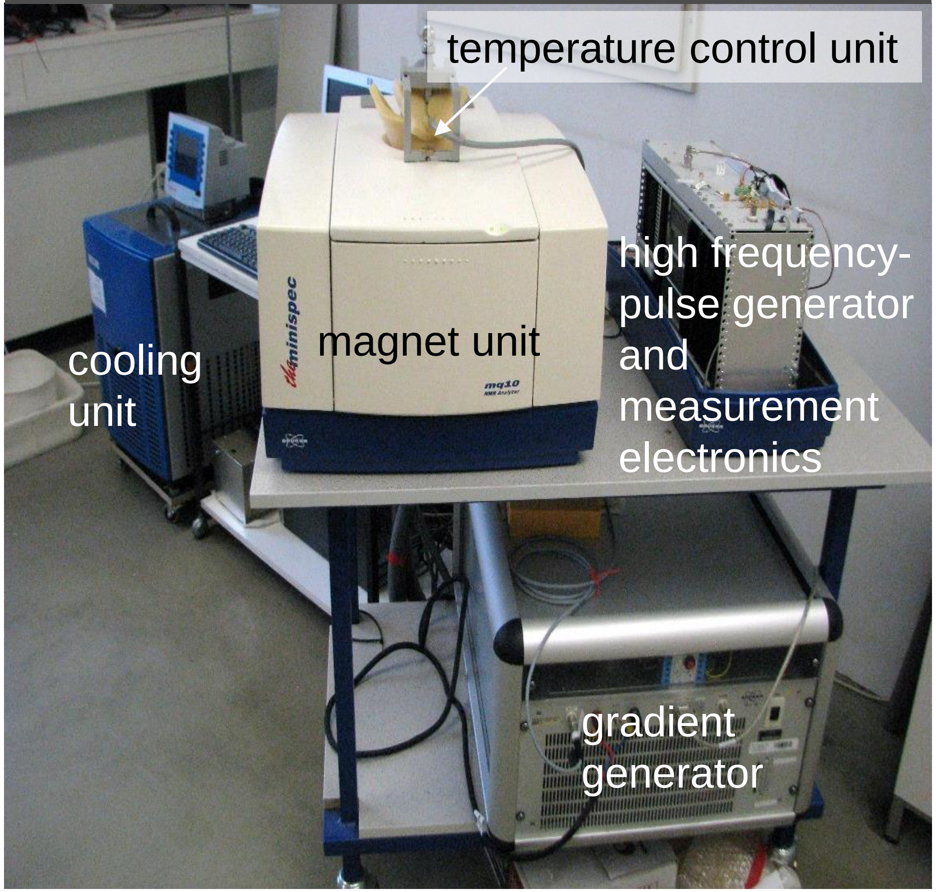
- w/c-ratio
- age, …
- minimum temperatur T_{min}
- temperature change rate

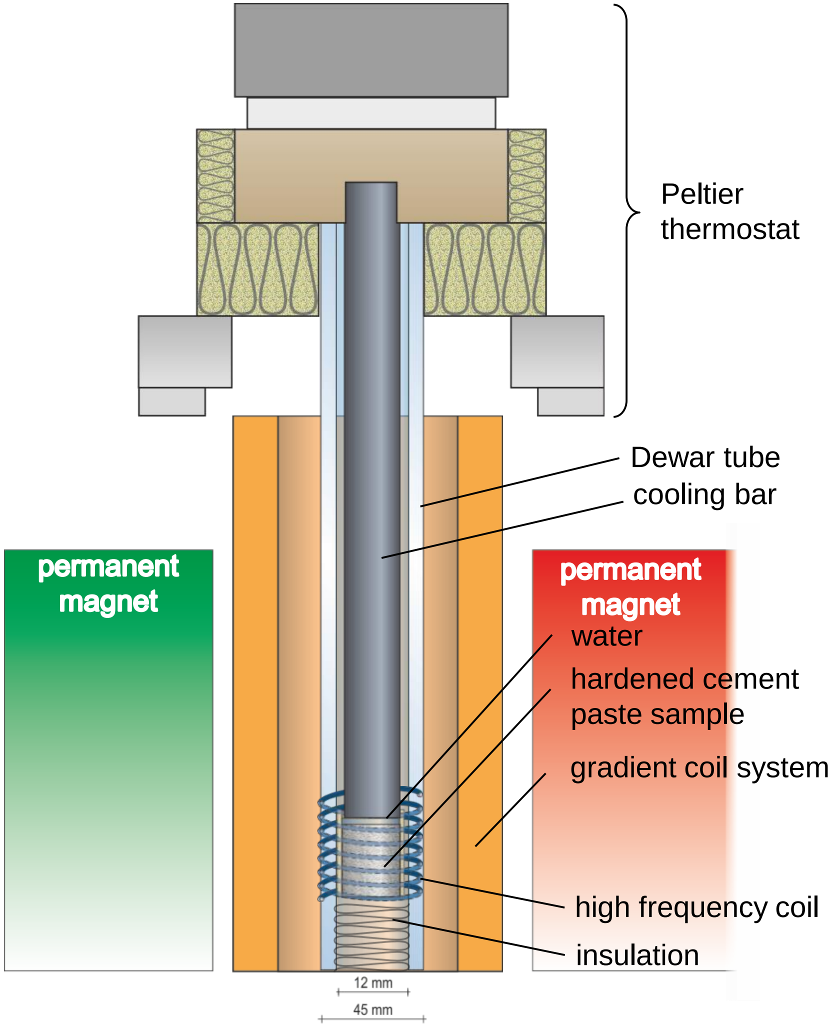
} material parameters

} environmental parameters

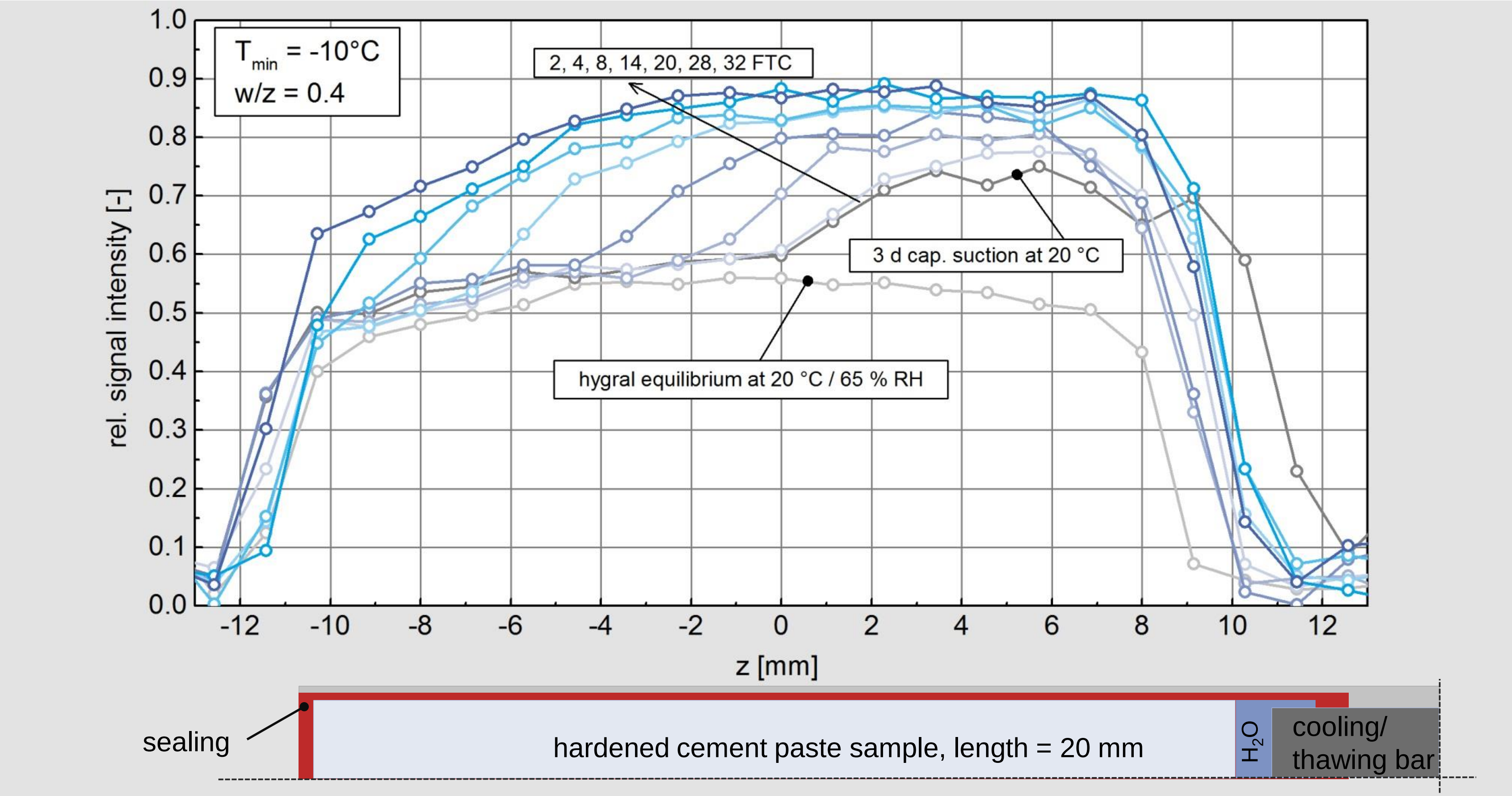
Measurement of frost suction

NMR measurement unit





Result of the NMR measurement

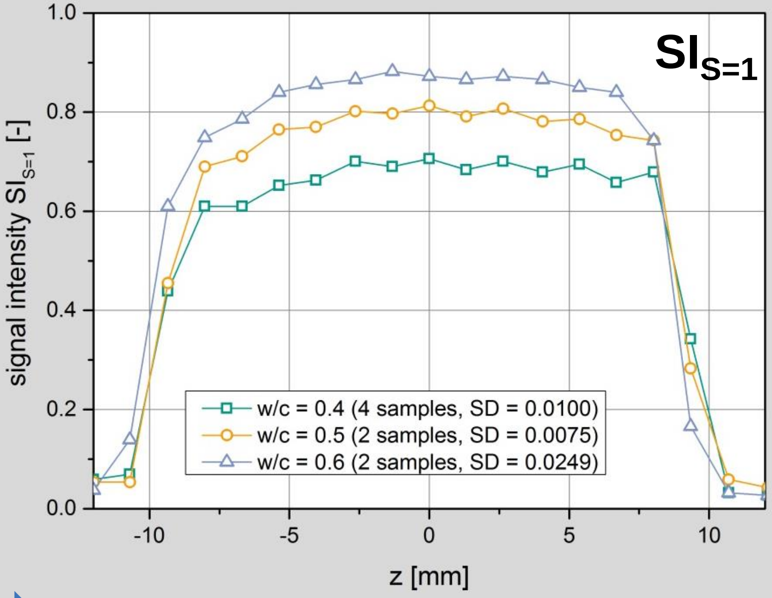


Conversion of signal intensity to saturation degree is possible

Conversion of the signal intensity SI to saturation degree S

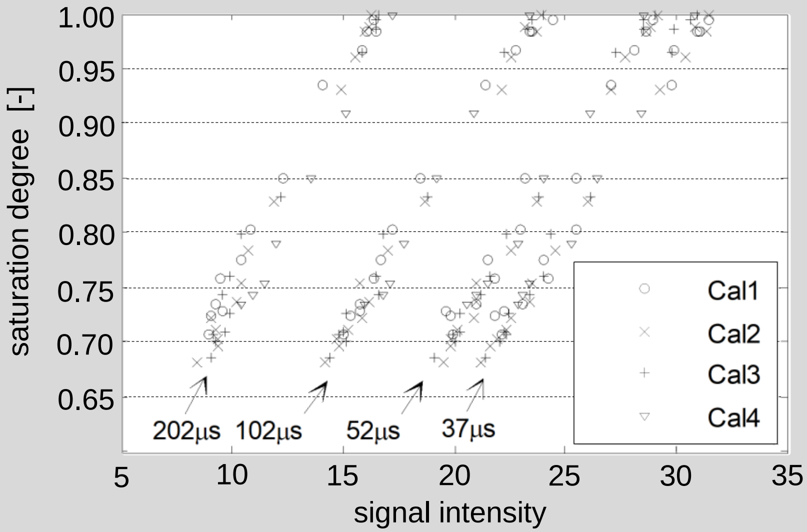
1 Saturation of calibration samples submerged in water at 150 bar → S = 1

2 Spatially resolved SI on fully saturated samples



➡ **Curve in good approximation equals pore volume**

3 Measurement of SI at different S-levels



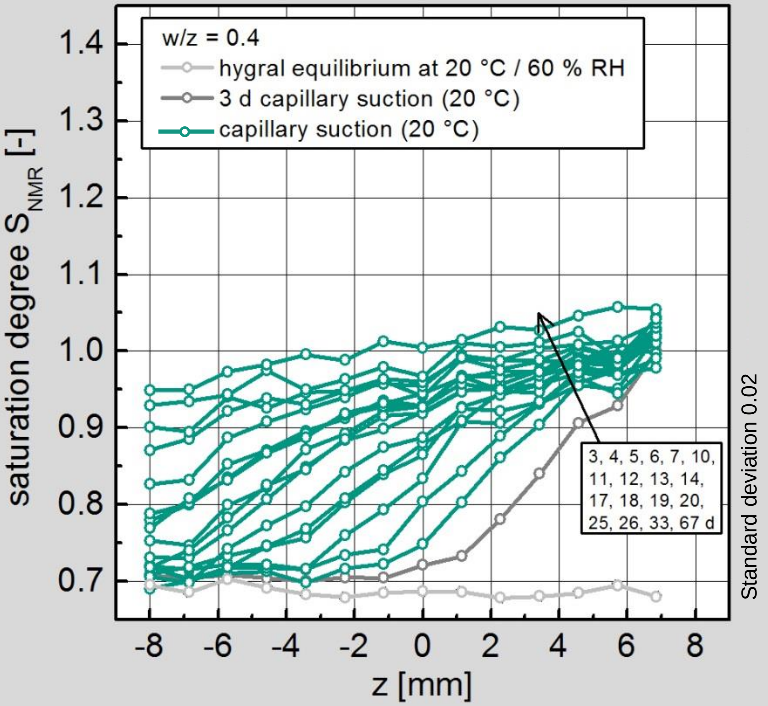
➡ **Linear correlation between signal intensity SI and saturation S**

4 Determination of saturation degree S_{NMR} of the sample

$$S_{NMR} = \frac{\text{total water volume}}{\text{pore volume}} = \frac{\text{spatially resolved SI of tested sample}}{\text{spatially resolved SI of fully saturated sample}}$$

Results: Water uptake for w/c = 0.4

Capillary suction at T = 20 °C (4 samples)

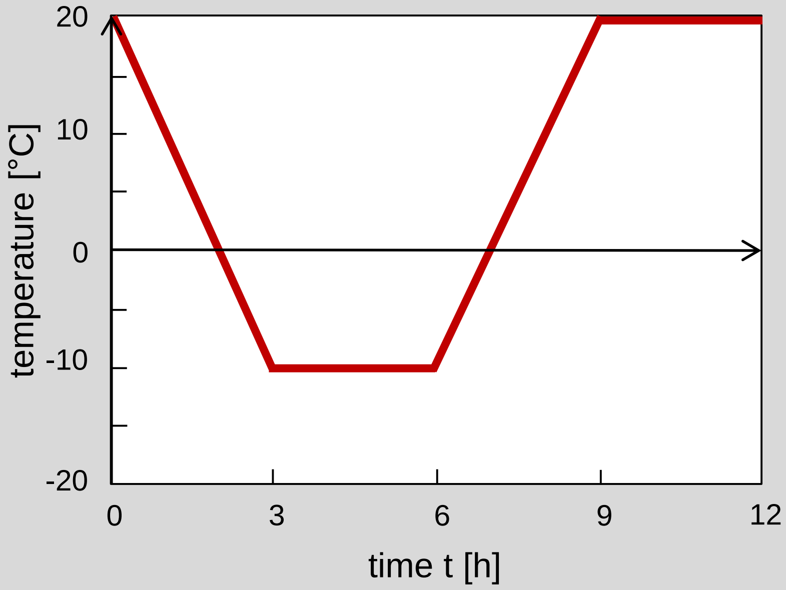


Major conclusions

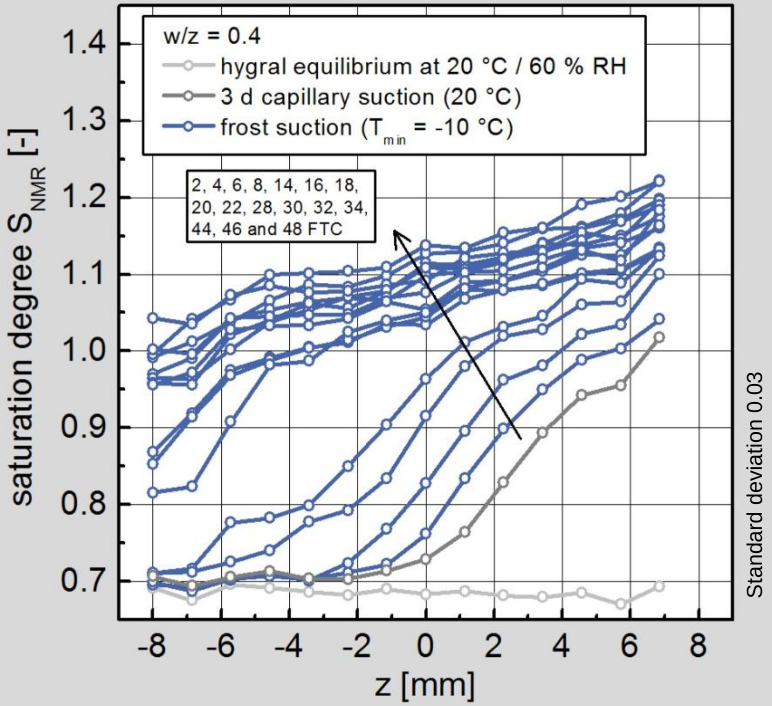
- increased saturation at the edge of the stressed surface (S > 0.9)
- waterfront penetrates the sample with time
- approximate homogeneous moisture distribution after capillary suction (about 40 days)

Results: Water uptake for w/c = 0.4

Temperature cycles including frost

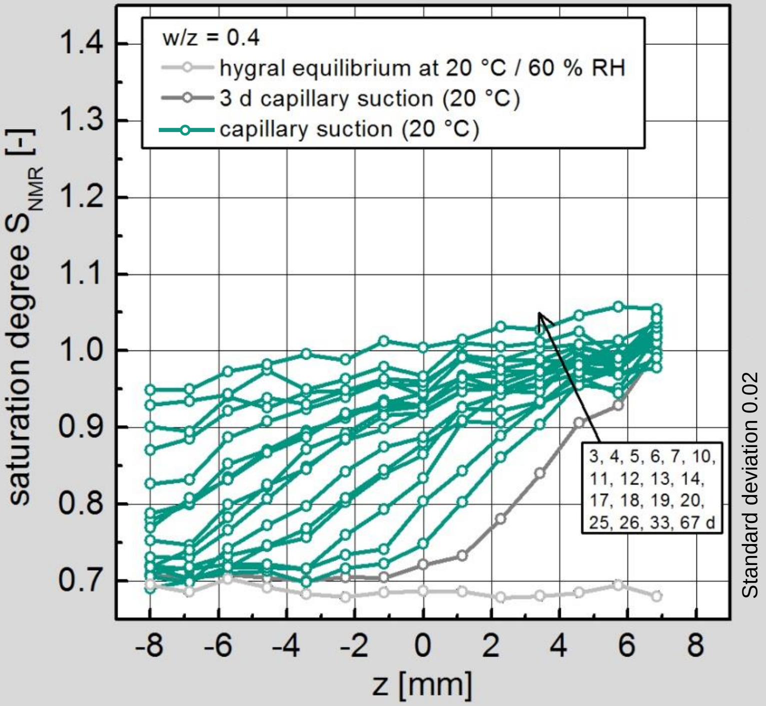


Frost suction T_{min} = -10 °C (4 samples)

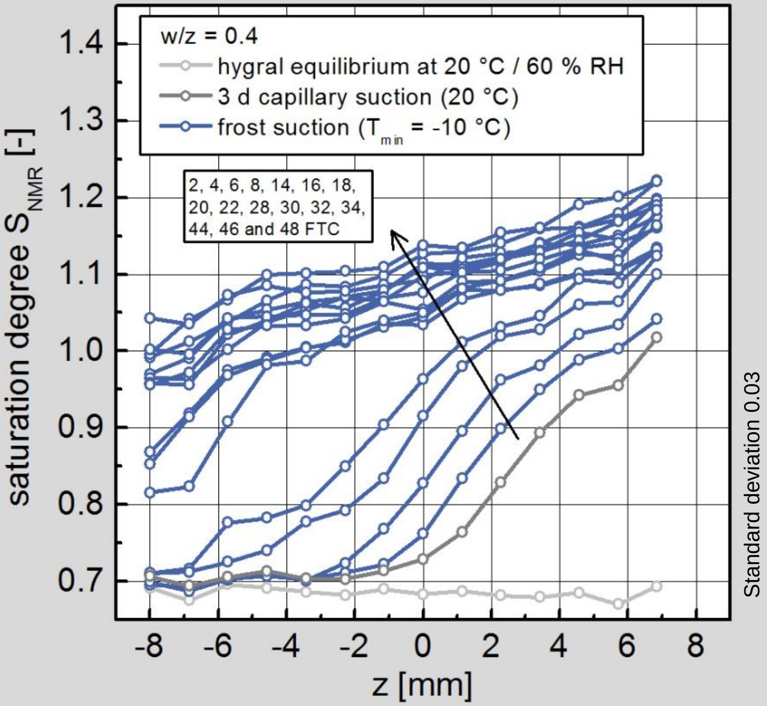


Results: Water uptake for w/c = 0.4

Capillary suction T = 20 °C (4 samples)



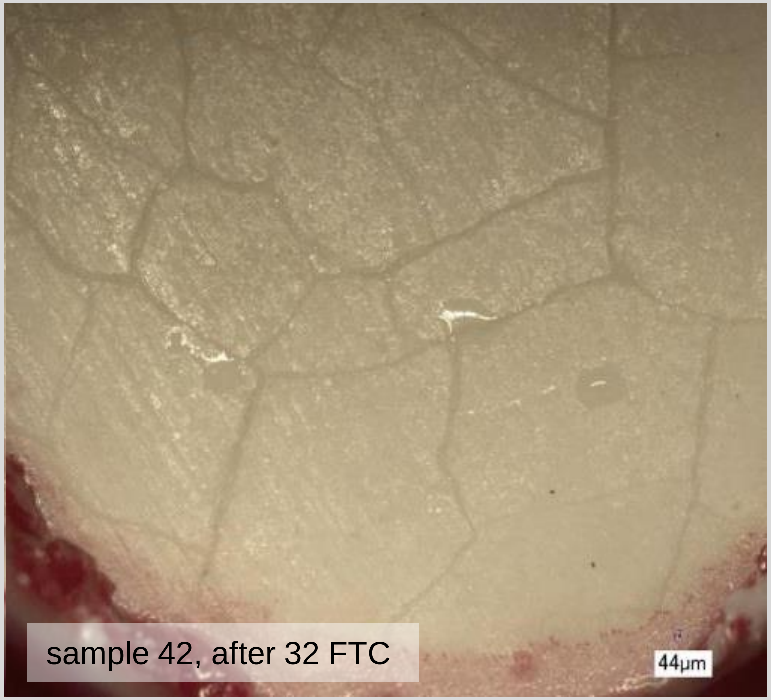
Frost suction T_{min} = -10 °C (4 samples)



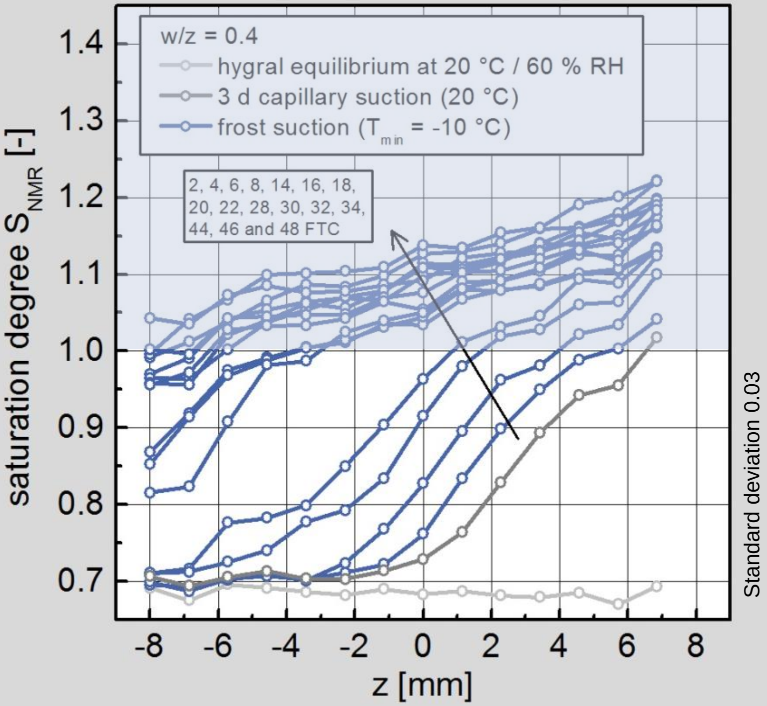
Temperature cycles including freeze-thaw phases cause an accelerated saturation of the sample and an increased amount of uptaken water (mechanism: mirco-ice-lens pump acc. to Setzer)

Results: Water uptake w/c = 0.4

Frost damage



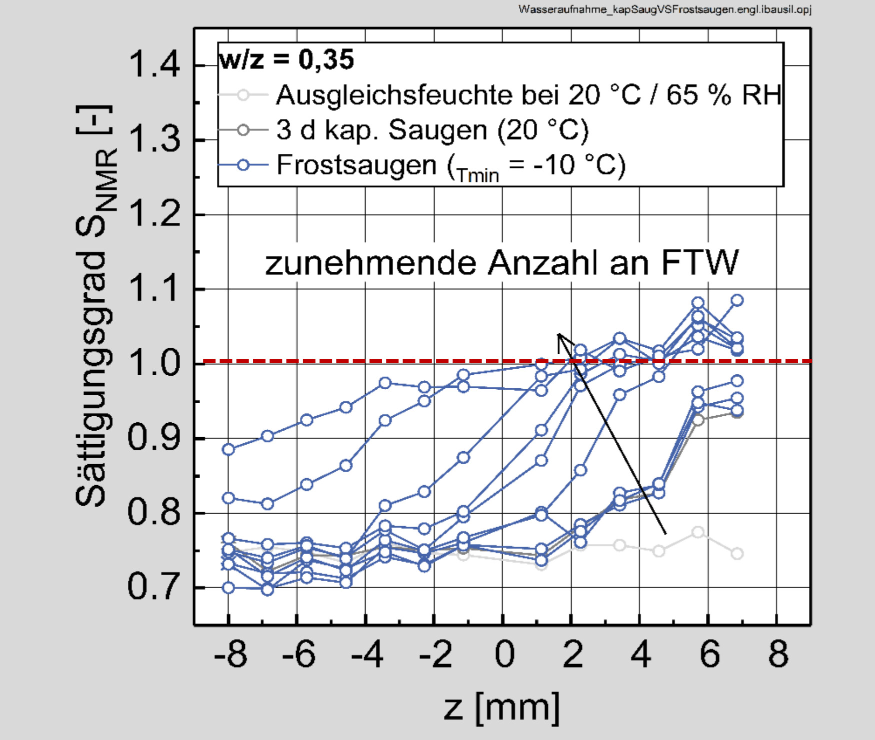
Frost suction T_{min} = -10 °C (4 samples)



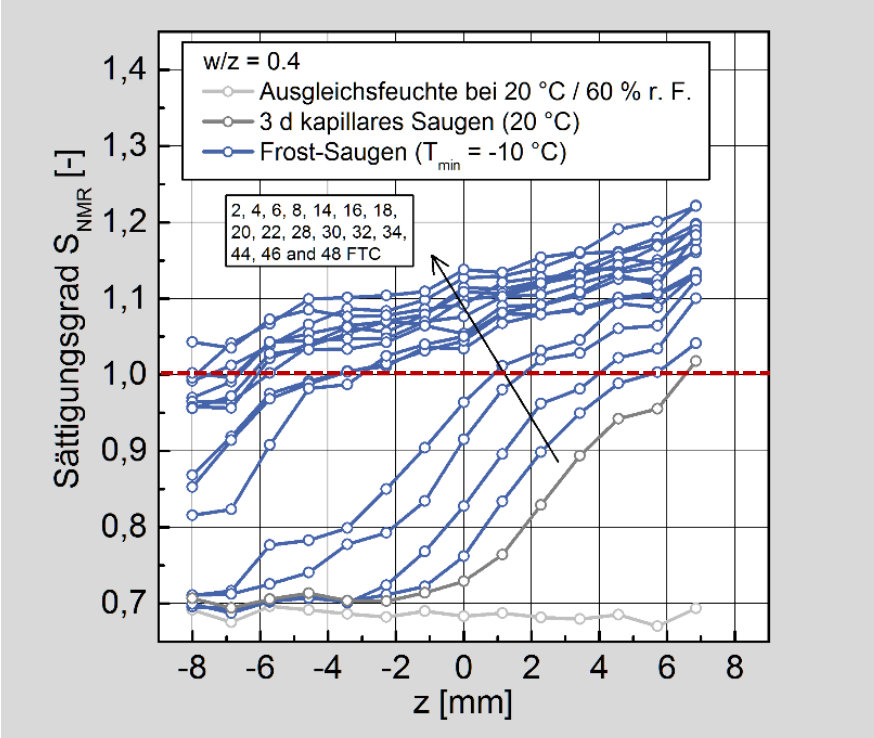
S ≥ 1 indicates damage corresponding to microcrack formation

Effect on frost suction characteristics

Frost suction for w/c = 0.35; T_{min} = -10 °C



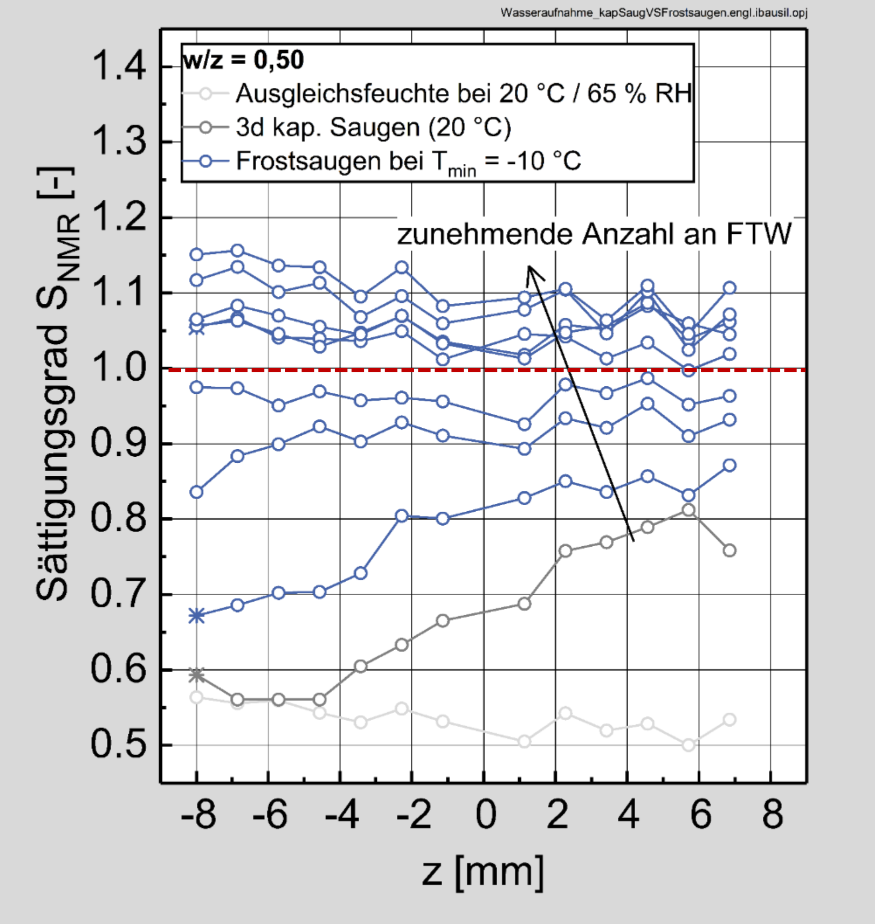
Frost suction for w/c = 0.4; Tmin = -10 °C



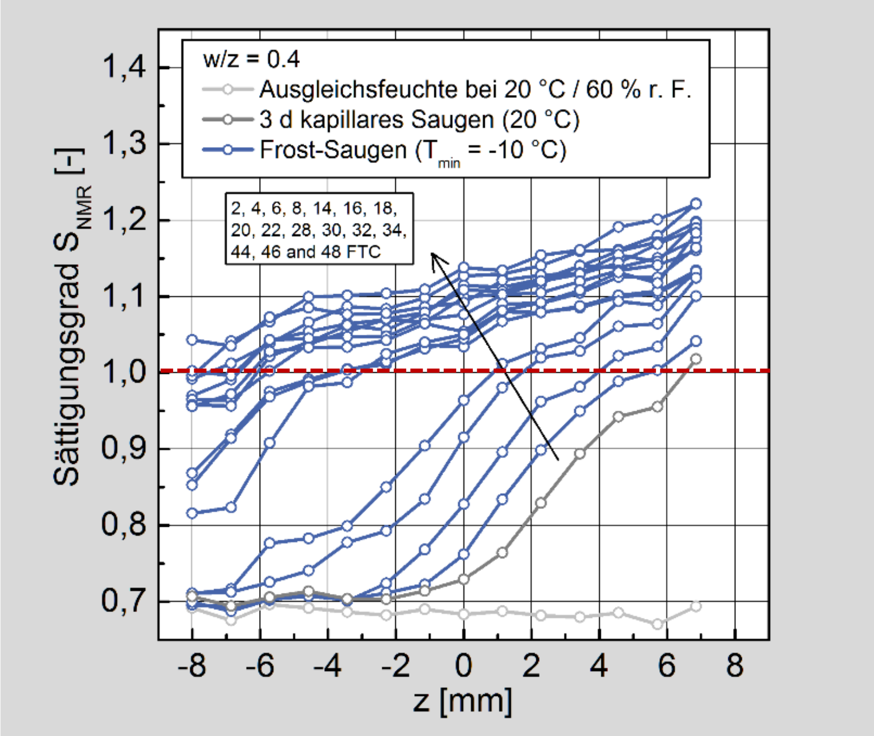
Effect of frost suction decreases with decreasing w/c ratio

Effect on frost suction characteristics

Frost suction for w/c = 0.5; T_{min} = -10 °C



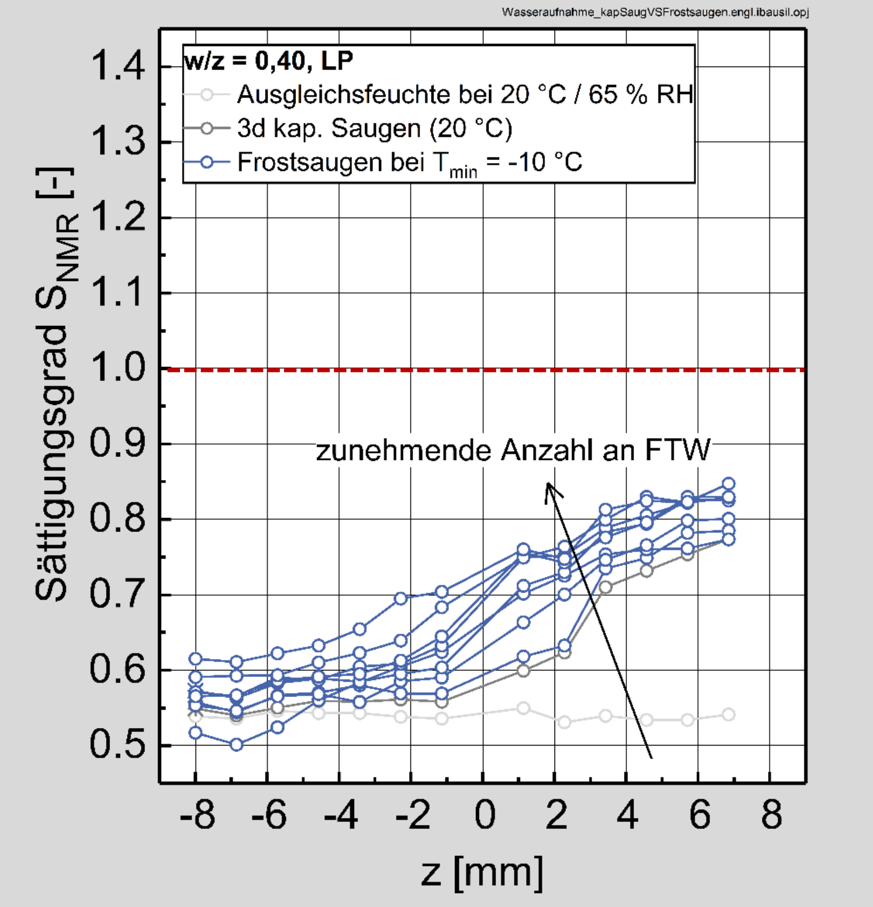
Frost suction for w/c = 0.4; Tmin = -10 °C



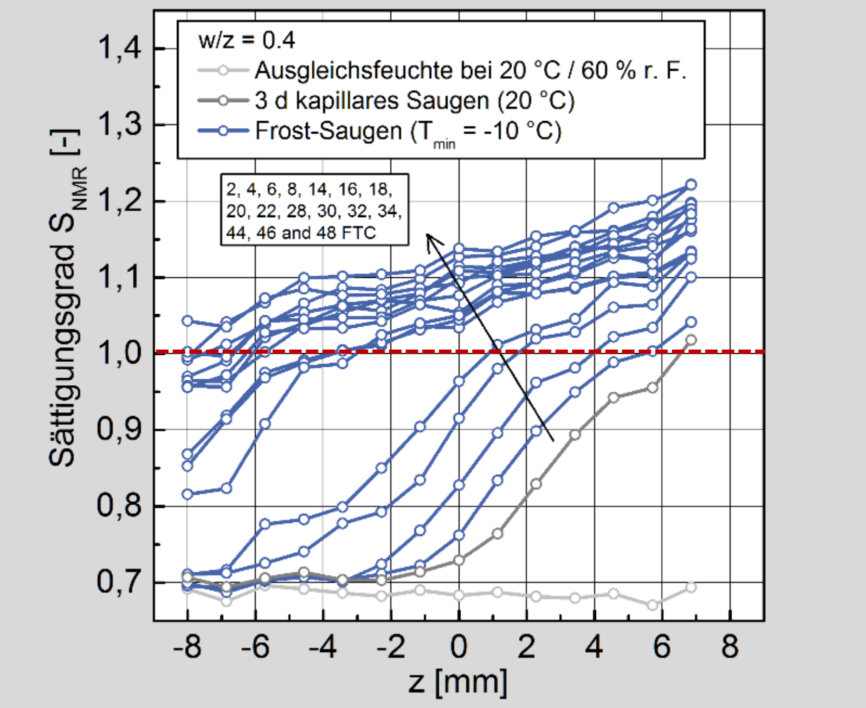
Effect of frost suction decreases with decreasing w/c ratio

Effect on frost suction characteristics

Frost suction, w/c = 0.4, AE, T_{min} = -10 °C



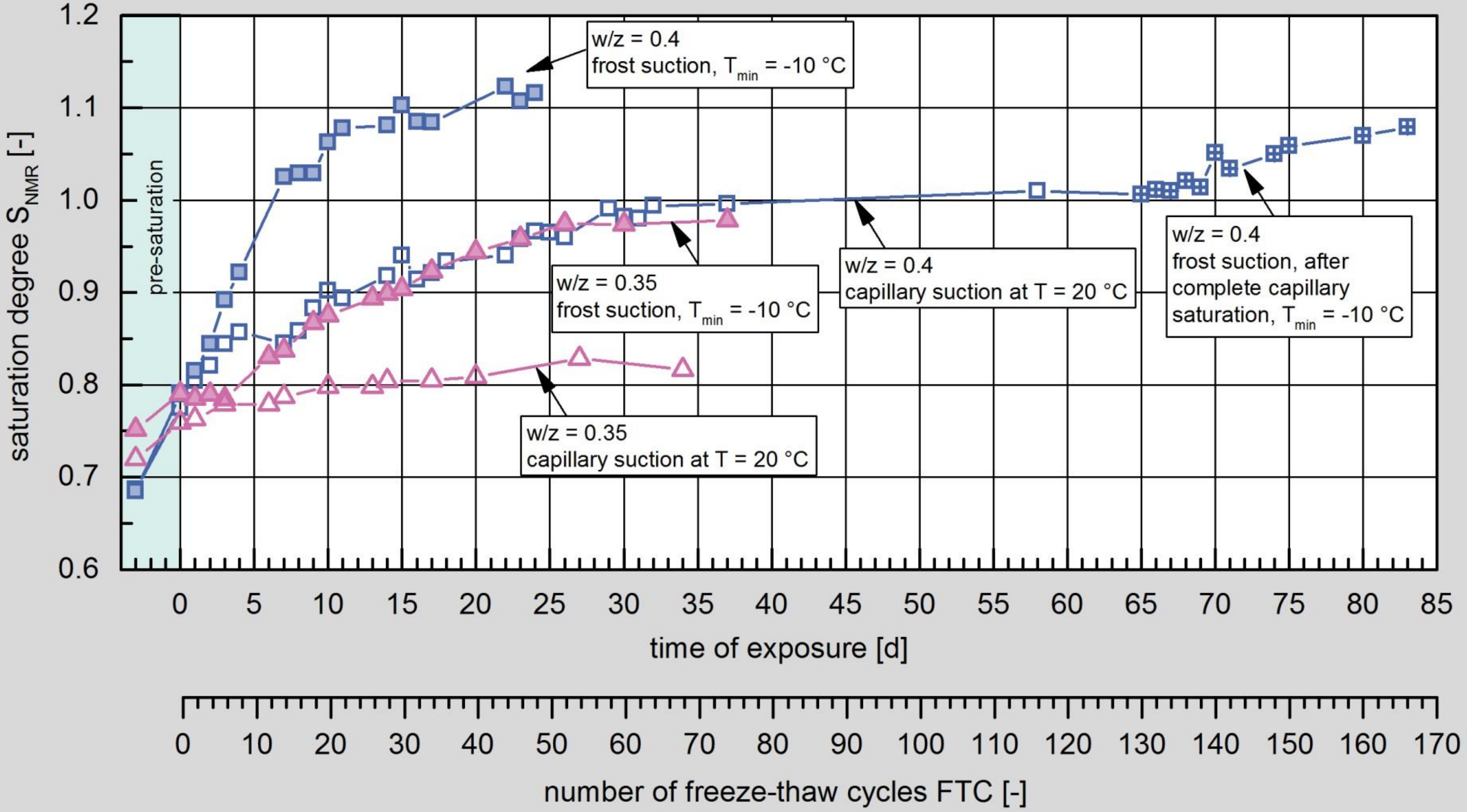
Frost suction, w/c = 0.4, T_{min} = -10 °C



Addition of air entraining agents reduces the frost suction considerably

Integral saturation for w/c = 0.35 and w/c = 0.40

Capillary suction vs. frost suction



w/z = 0.4
frost suction, T_{min} = -10 °C

w/z = 0.35
frost suction, T_{min} = -10 °C

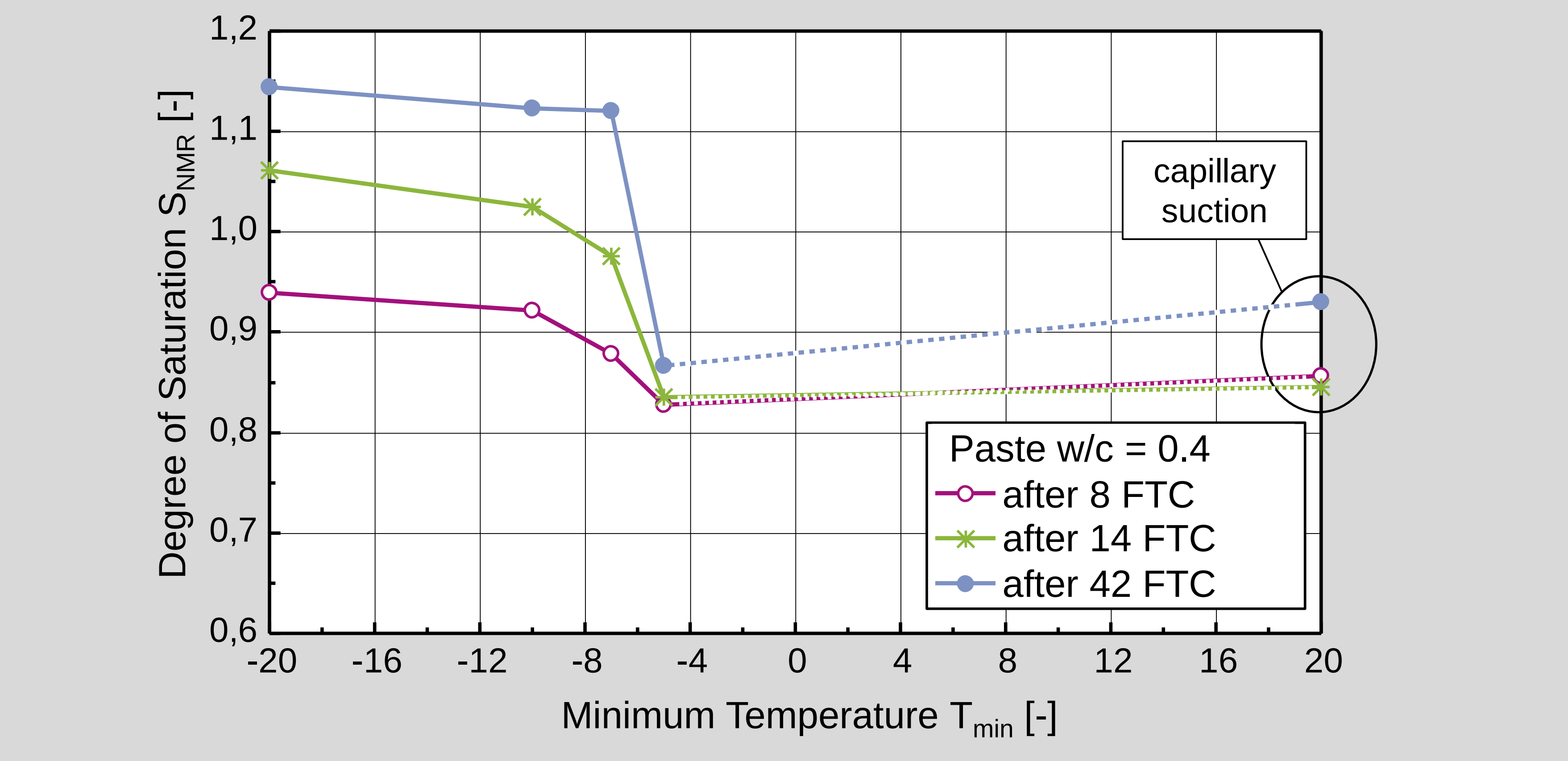
w/z = 0.4
capillary suction at T = 20 °C

w/z = 0.4
frost suction, after complete capillary saturation, T_{min} = -10 °C

w/z = 0.35
capillary suction at T = 20 °C

Frost suction can be quantified with high spatial resolution using NMR technique

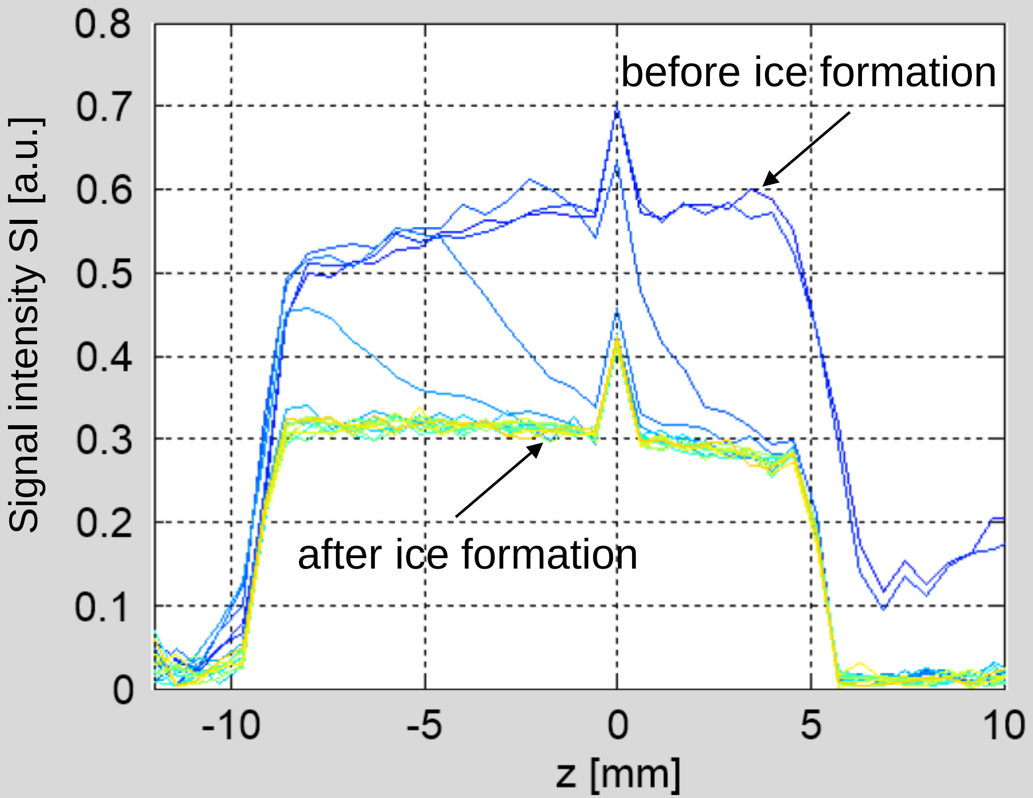
Influence of minimum temperature T_{min}



Saturation increases with decreasing frost temperature T_{min}, in particular for -10 °C < T_{min} < -5 °C

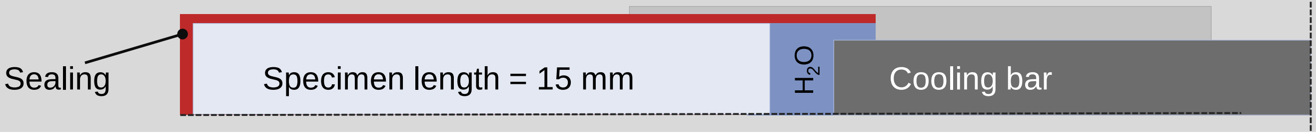
In-situ observation of the freezing process

Hardened cement paste, w/c = 0.6, T_{min} ≈ -10 °C



Conclusions:

- The freezing of water to ice reduces the intensity of the signal proportional to the amount of frozen water (ice)
- Changes in the intensity of the signal can also be used to determine the freezing temperature of the water

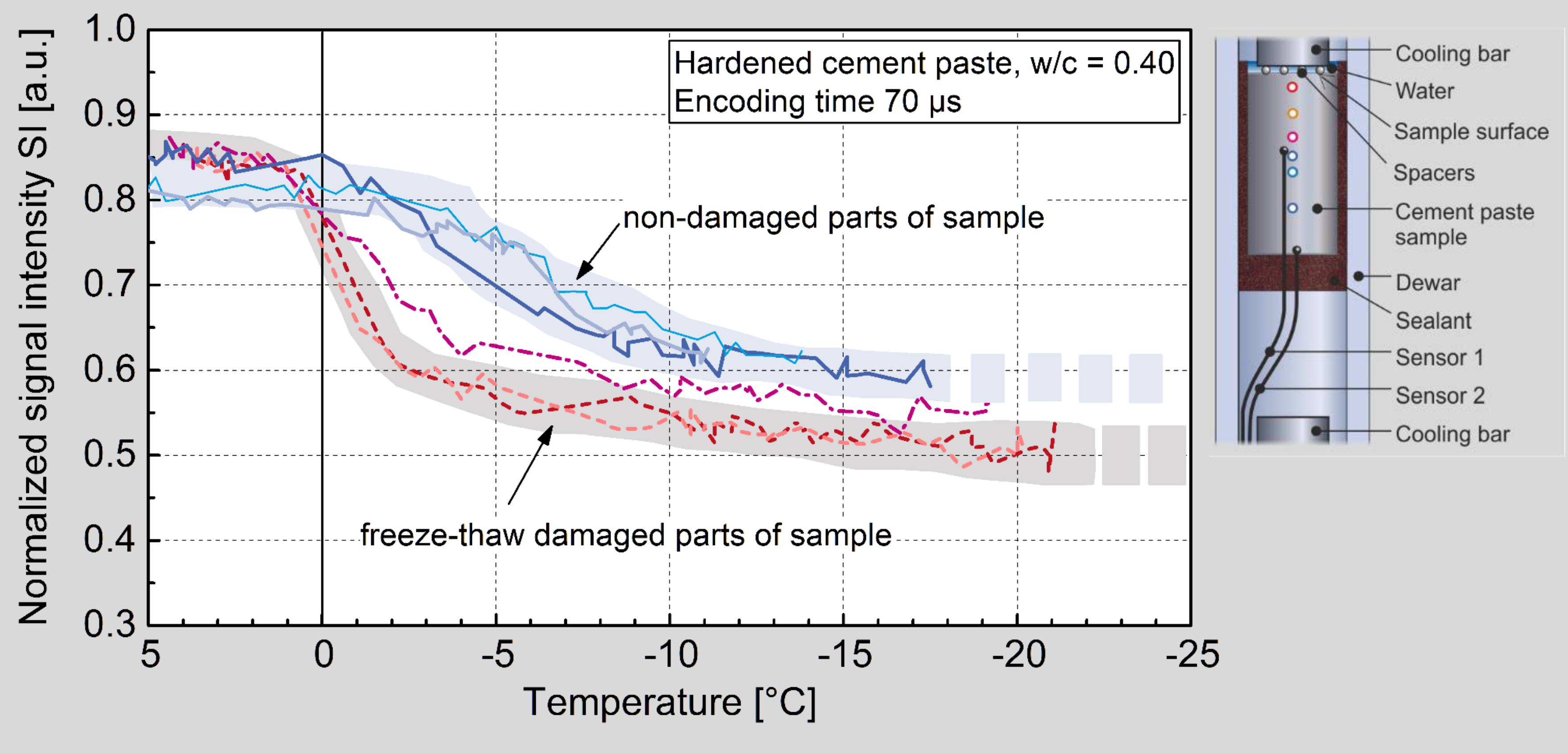

Sealing

Specimen length = 15 mm

H_2O

Cooling bar

Freezing temperature of water as function of microstructural damage



Water in freeze-thaw damaged parts of sample freezes at significantly higher temperatures than in undamaged parts

Development of the model

Summary of key findings

- Sample boundary zone reaches values of $S \approx 1.0$ by capillary suction
- Frost suction significantly exceeds capillary suction (water uptake)
- Saturation degree $S > 1.0$ indicate damage (cracking)

Criterion for frost damage

$S(x,t) \geq S_{crit}$

S(x,t) to be calculated by means of a suitable approach

Model describing S(x,t) due to combined capillary and frost suction

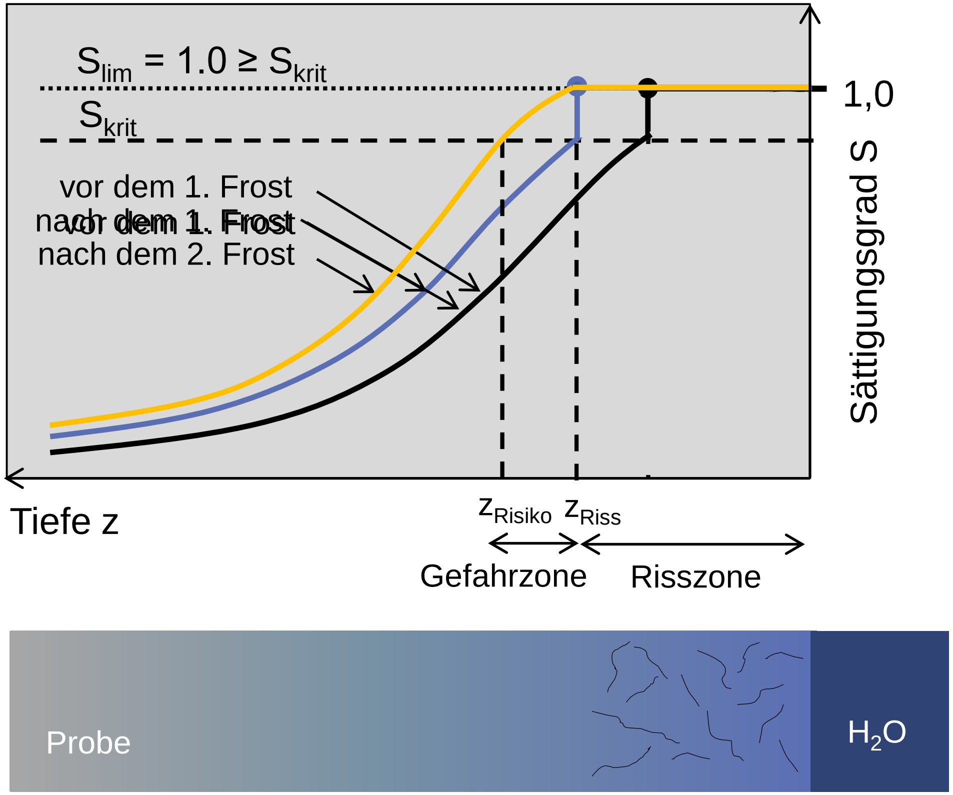
$$\frac{\partial S}{\partial t} = \frac{\partial}{\partial x}\left(W(S) \cdot (1 + F_{MELP}) \cdot \frac{\partial S}{\partial x}\right)$$

$$W(S) = W_1 \underbrace{\left(\alpha_0 + \frac{1 - \alpha_0}{1 + \left(\frac{1-S}{1-S_W}\right)^n}\right)}$$

Bažant et al., Materials & Structures 5 (1972), pp. 709-720

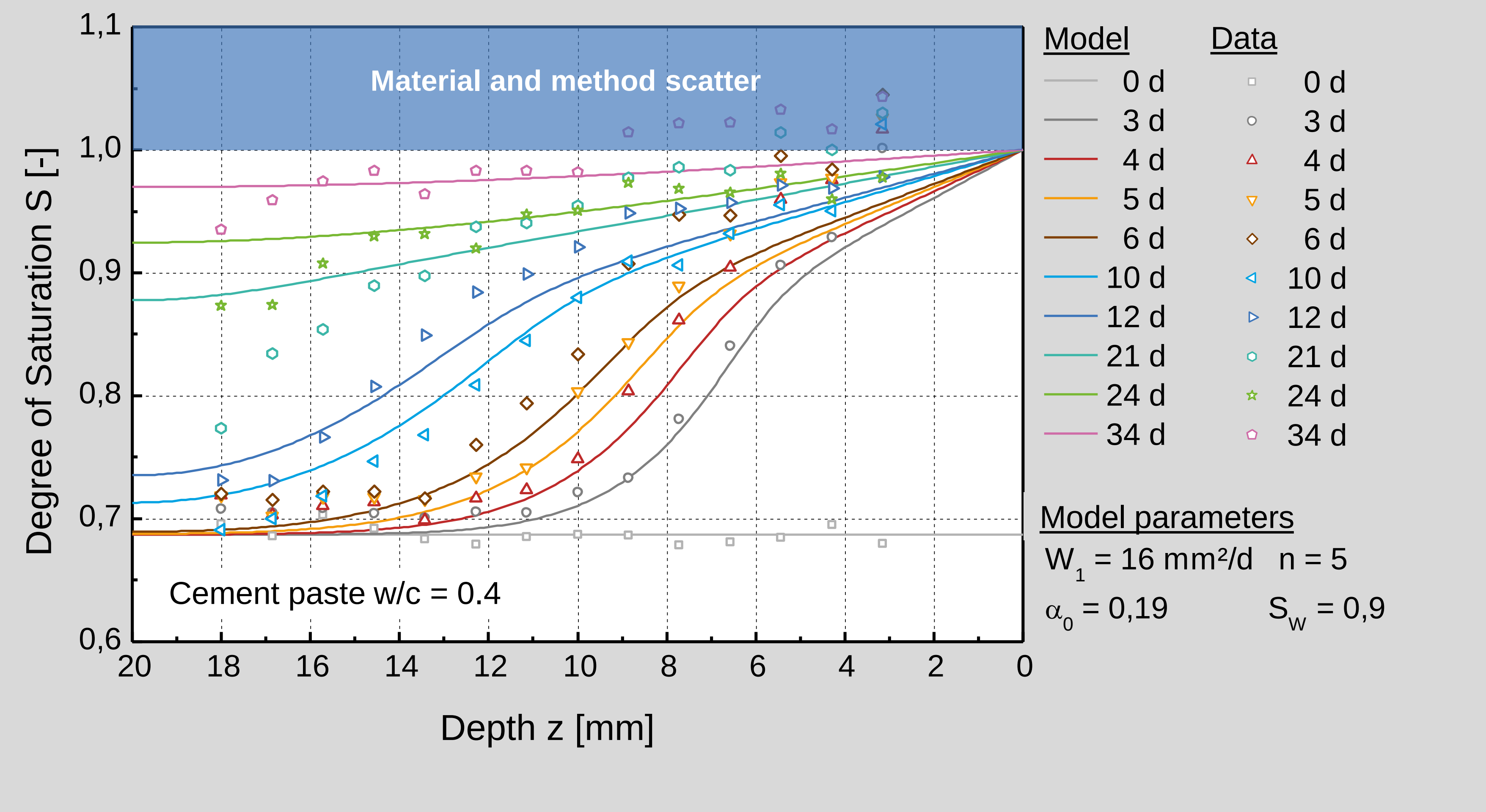
S	degree of saturation [-]
t, x	duration of suction process [d], location (depth from surface [mm]
W(S)	water transport coefficient [mm²/d] (fit coefficients α_0, S_W, n [-])
W_1	water transport coefficient [mm²/d] for S = 1.0
F_{MELP}	factor [-] describing additional frost suction due to micro-ice-lens pump

Schematic illustration of the model approach



- $S = V_W / V_{P,gesamt}$
- Definition des Grenzzustandes des Sättigungsgrades $S_{lim} \geq S_{krit}$

Model validation – capillary suction

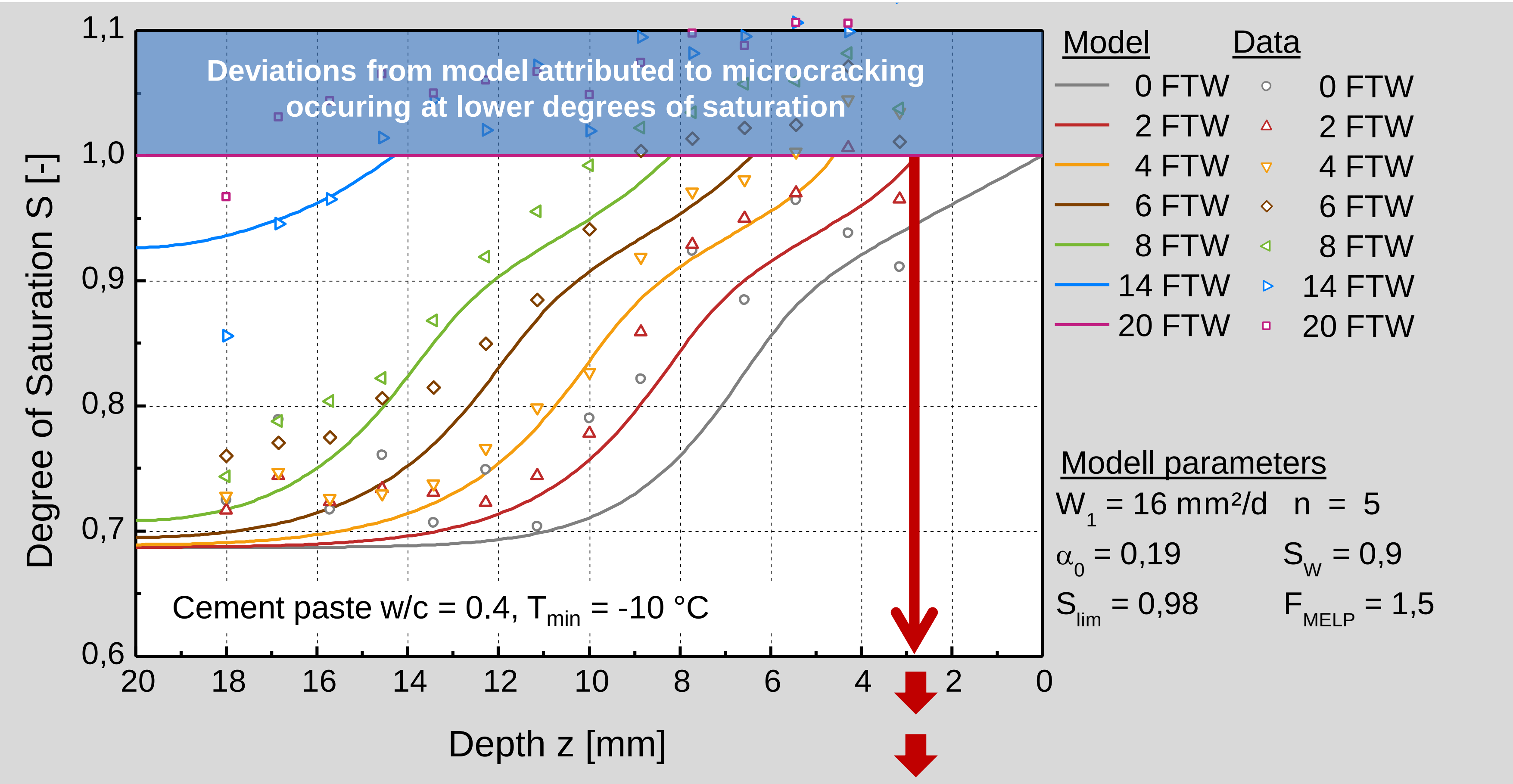


Model parameters

W_1 = 16 mm²/d n = 5

α_0 = 0,19 S_W = 0,9

Model validation – frost suction



Deviations from model attributed to microcracking occuring at lower degrees of saturation

Cement paste w/c = 0.4, T_{min} = -10 °C

Modell parameters

W_1 = 16 mm²/d n = 5

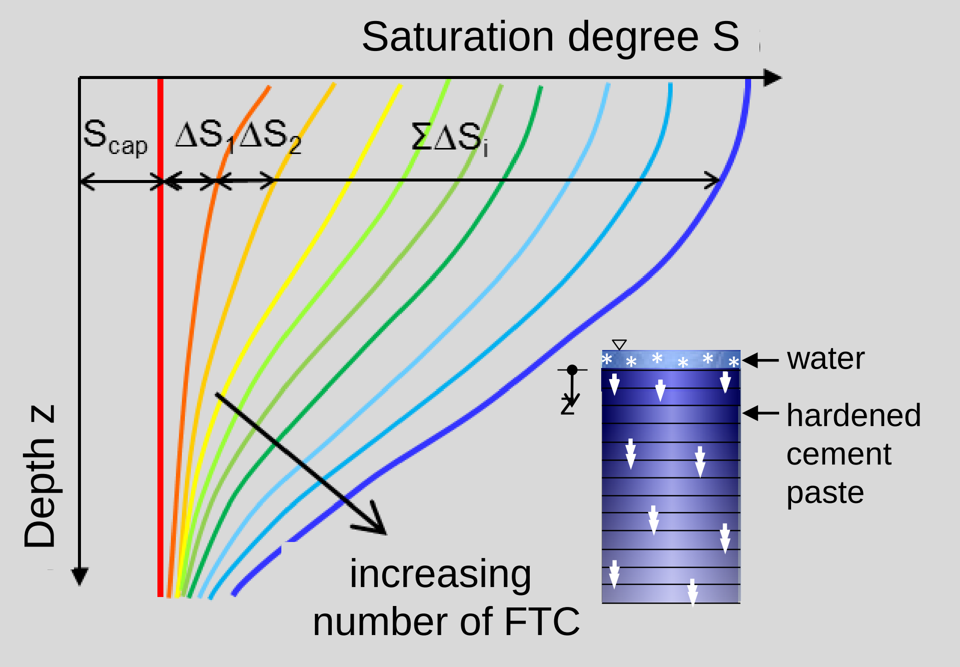
α_0 = 0,19 S_W = 0,9

S_{lim} = 0,98 F_{MELP} = 1,5

Process zone depth as function of FTC

Calculation of spalling depth possible

New model at a glance



Data basis to quantify the frost suction for w/c ratios 0,35 ≤ w/z ≤ 0,50 und T_{min} values 0 °C ≥ T_{min} ≥ -20 °C are available

z_{crack} und t_{crit} may be estimated!

Model to predict frost damage of cement mortars

$$S(z, t) = S_{cap}(z, t) + \Sigma\Delta S_i(z, t) \leq S_{crit}$$

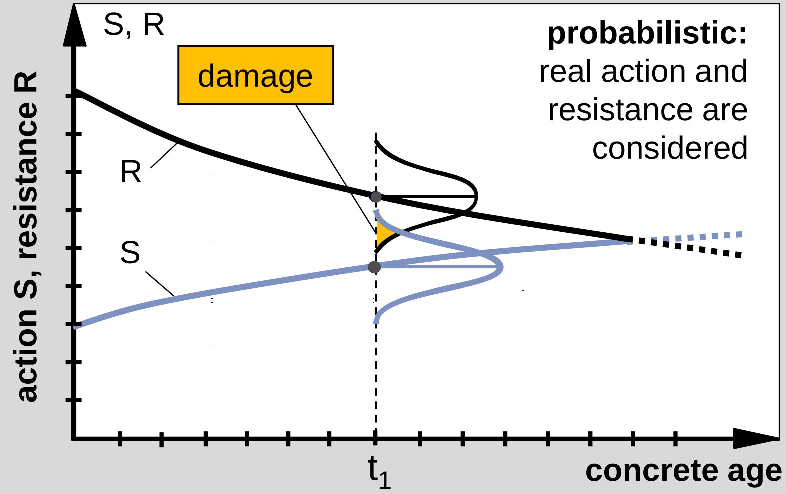
may be estimated by means of the model

first approximation $S_{crit} \geq 0.9$

Service life design for frost attack – outlook

Performance concept (models)

approach: $p_f(t) = p_f\,[R(t) - S(t) \leq 0] \leq p_{target}$



Future relations in guidelines

physical model for frost damage *)	**S** = Sat(z,t) = f (climate, environment, material)
	R = Sat_{crit} = f (material)

*) To avoid confusion, saturation is expressed here as „Sat“ (not as S as before)

Open questions / future works

- Classification of the actions related to geographical regions, e.g. classified due to climate
- Extension of the model for concrete and for frost de-icing agents attack
- Verification of the hypothesis that the model needs no failure criterion
- Development of simplyfied approaches, e.g. using partial safety factors, defined/given service lifes etc.
- ……..

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Thank you very much