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BEST4 Conference
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Questions related to specific materials, methods, and services will be addressed at the conclusion of this presentation.

Learning Objectives

Participants will :

1. Learn how to link the performance of individual building enclosure components in a holistic framework to achieve high-performance buildings.

2. Explore, through built case studies, how building envelope design determines overall energy conservation and sustainability capabilities

3. Learn innovative practices for avoiding heat loss as well as moisture and air infiltration in enclosure design for healthy new and existing buildings.

4. Understand the role of building enclosure commission-ing in the design, construction, and operation and maintenance of commercial facilities.

State of the Art in Evaluation Durability of Exterior Plasters

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University of Padova, Italy

Layout/1

- Durability of exterior plasters - introduction:
  - - Role of exterior plaster in a wall;
  - - Modes of plaster degradation in different climates;
- Factors influencing durability of plasters
  - - Inner structure (porosity, pore size distribution);
  - - Moisture retention (sorption isotherm);
  - - Hygro-thermal properties (capillary suction, permeability, thermal conductivity & capacity);
  - - Thermal expansion;
  - - Moisture induced expansion (shrinkage & swelling);
  - - Chemical composition;
- Durability of plasters in standards & recomendations
  - - Cyclic freezing/thawing test;
  - - Mechanical strength test & pull off test;
  - - Shrinkage & thermal dilatation test;
  - - Salt crystallization tests;
  - - Accelerated calcium leaching test;

Layout/2

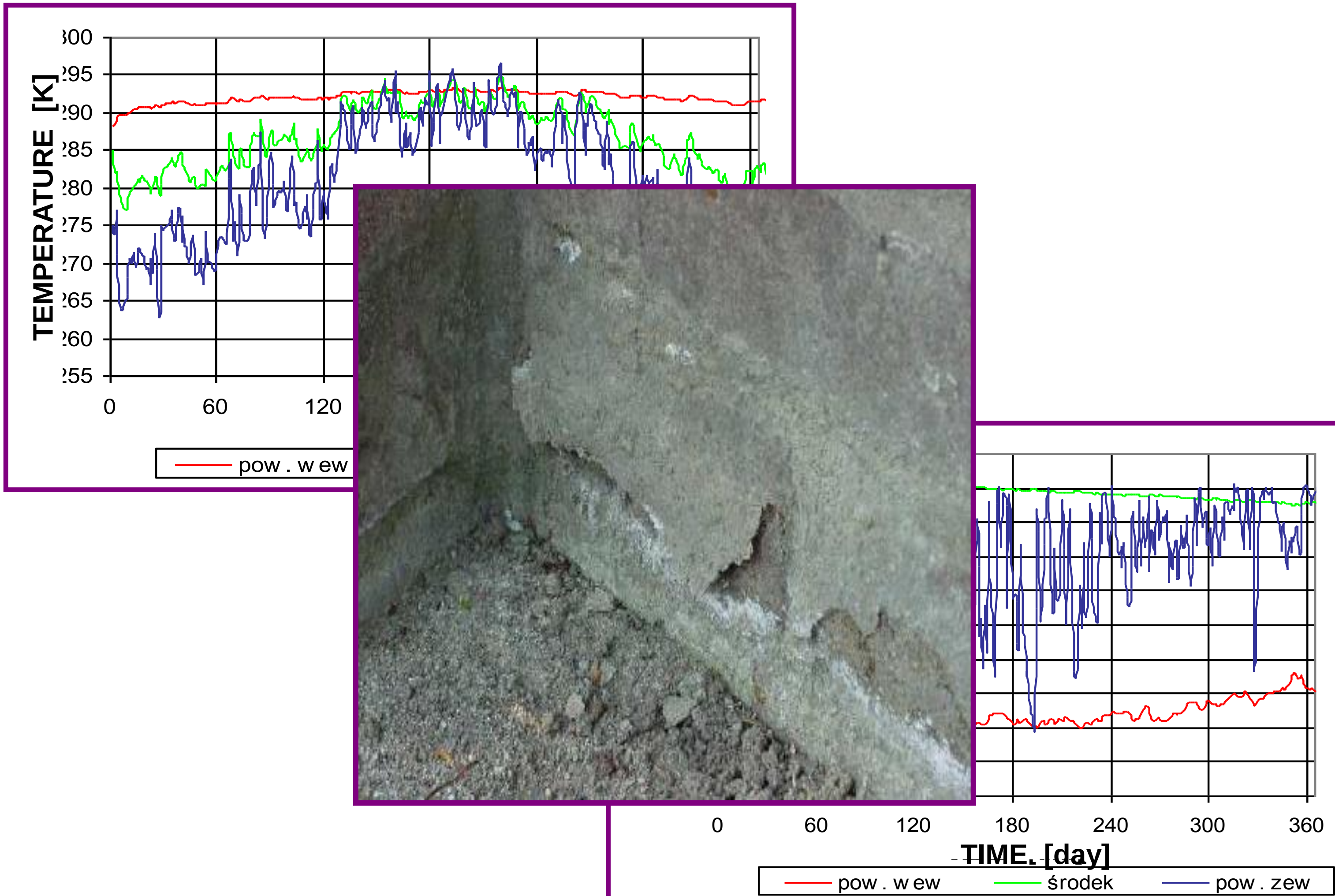
- Damage due to hygro-thermal expansion/shrinkage
  - - Physical mechanisms of degradation;
  - - Methods of experimental testing;
  - - Numerical modeling;
  - - Preventing hygro-thermally induced damage.
- Frost damage
  - - Physical mechanisms of degradation;
  - - Methods of experimental testing;
  - - Numerical modeling;
  - - Preventing frost damage.
- Damage due to calcium dissolution/leaching
  - - Physical mechanisms of degradation;
  - - Methods of experimental testing;
  - - Numerical modeling;
  - - Preventing degradation due to chemicals dissolution.

Layout/3

- Damage due to salt crystallization
  - - Physical mechanisms of degradation;
  - - Methods of experimental testing;
  - - Numerical modeling;
  - - Preventing damage due to expanding-salts.
- Conclusions & Final Remarks

Introduction

Degradation due to variable hygrothemal conditions



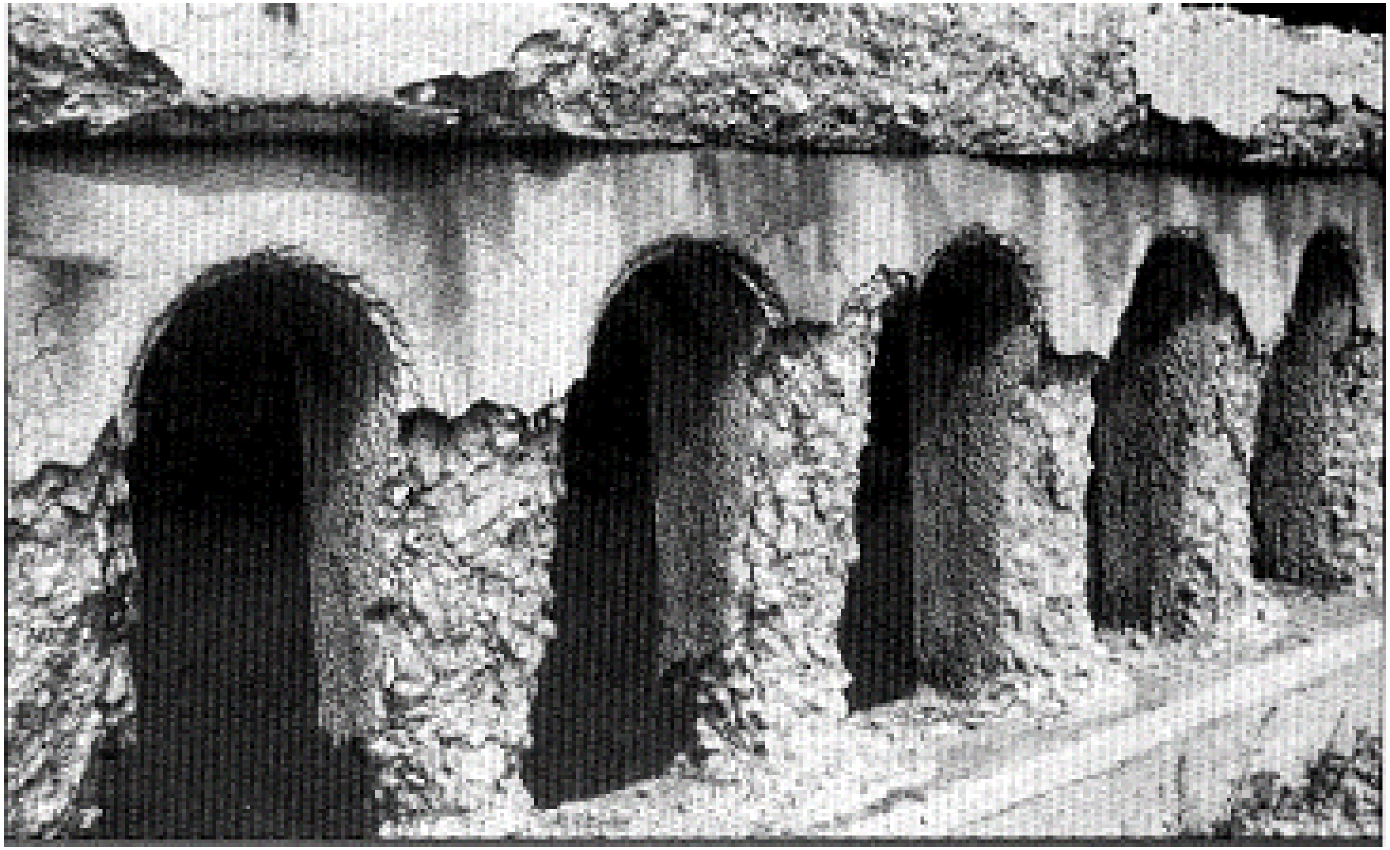
Introduction

Frost damage due to water freezing / thawing

Frost degradation of the plaster in the climatic conditions of Poland, due to excessive moisture content and negative temperatures.

Introduction

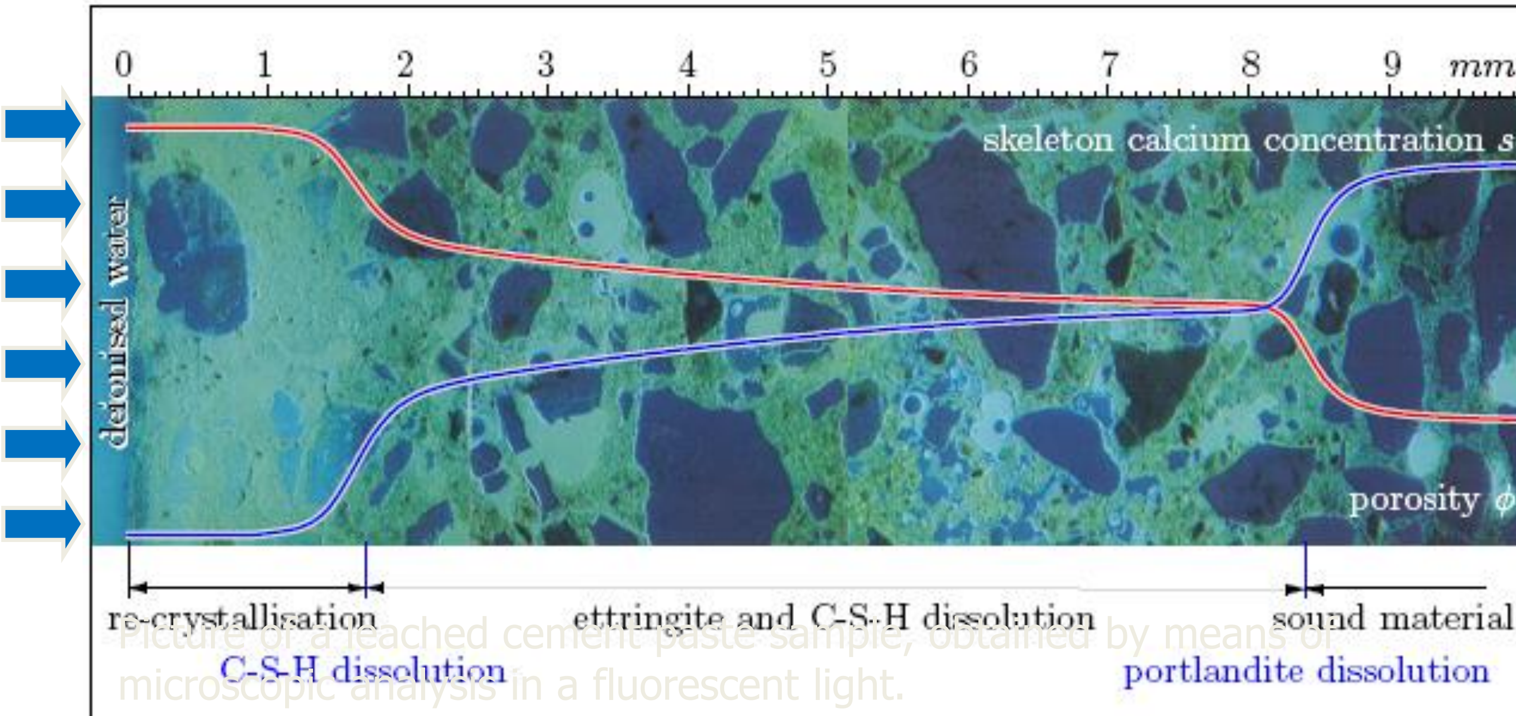
Frost and moisture damage



Introduction

Leaching of cement based materials (dissolution of calcium)

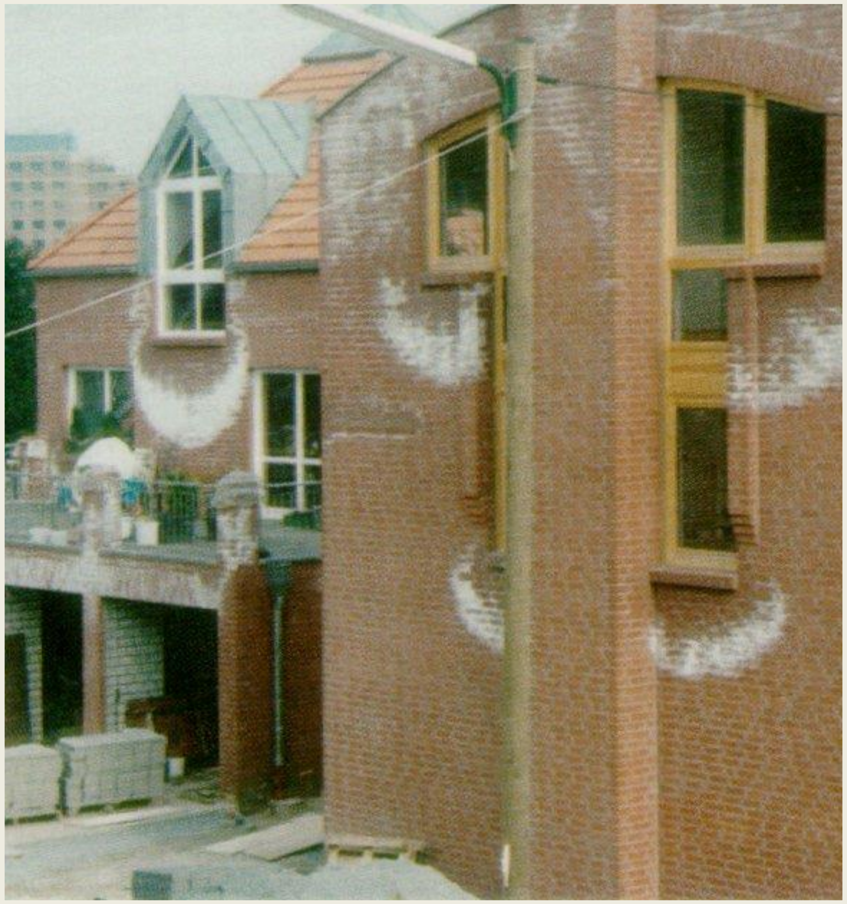
Demineralized water



Picture of a leached cement paste sample, obtained by means of microscopic analysis in a fluorescent light.

Introduction

Efflorescence on a wall surface



Salt crystallisation & material damaging

Exterior plaster

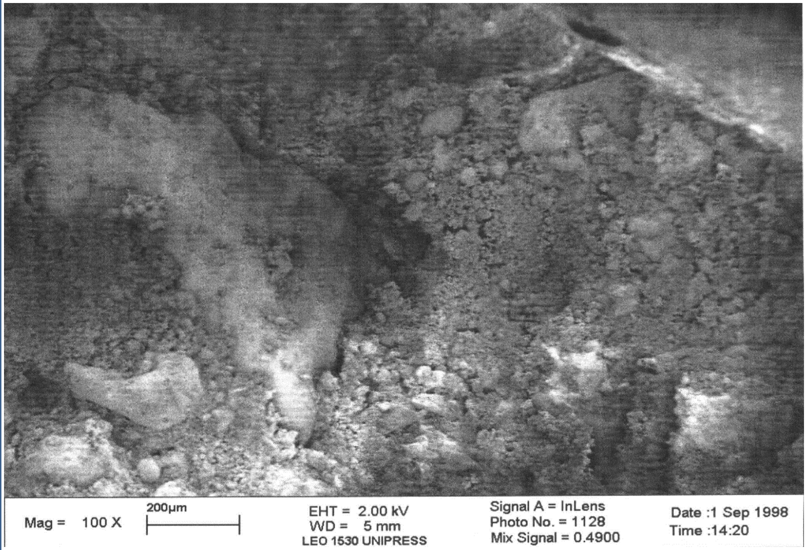
Functions in a wall

- External finishing and aesthetic role
- Protection and buffer layer for moisture
- Attenuation of temperature variations
- Protection against deteriorating factors

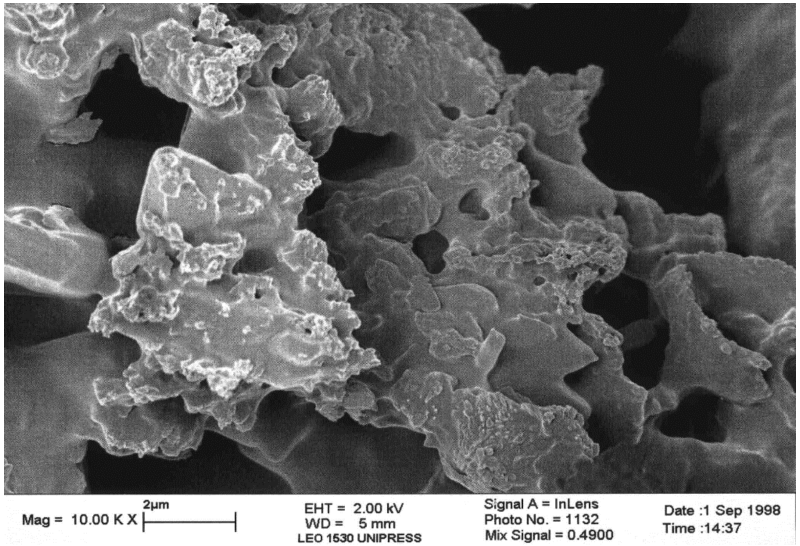
Porous materials

Inner structure of porosity

Scanning Electron Microscopy



100 x

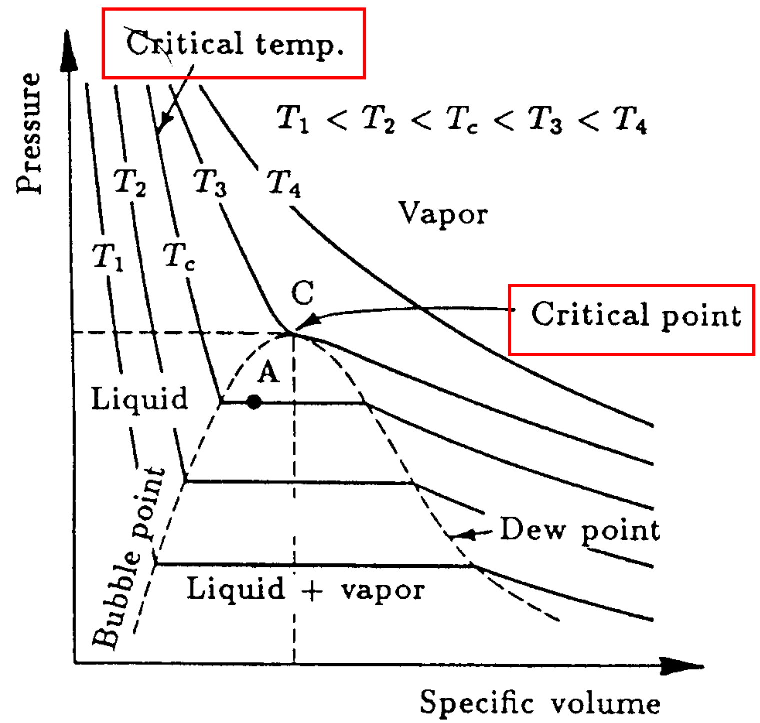


10 000 x

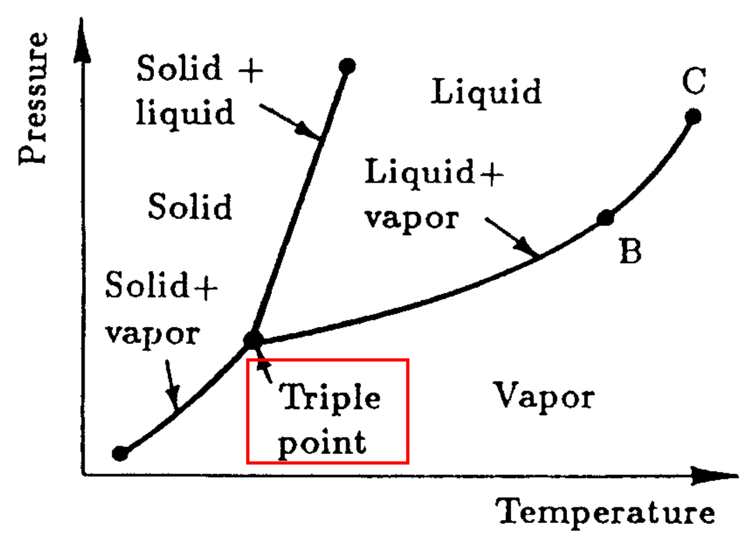
Moisture in porous materials

Phases of water

Critical temperature & critical point



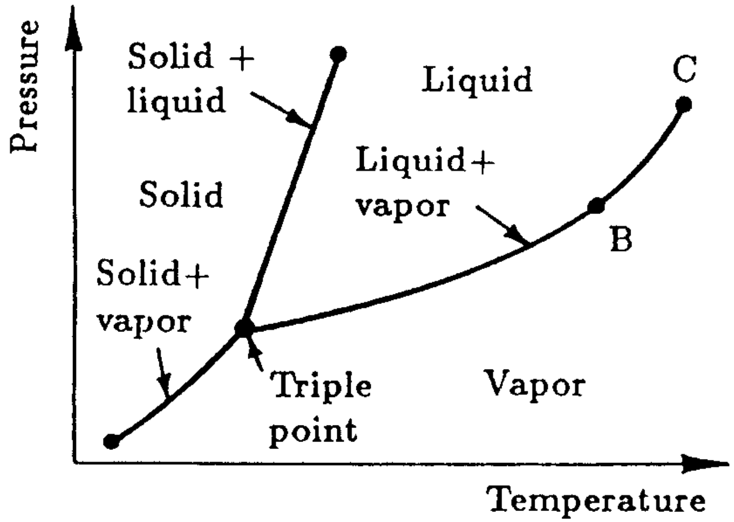
Phases of water & triple point



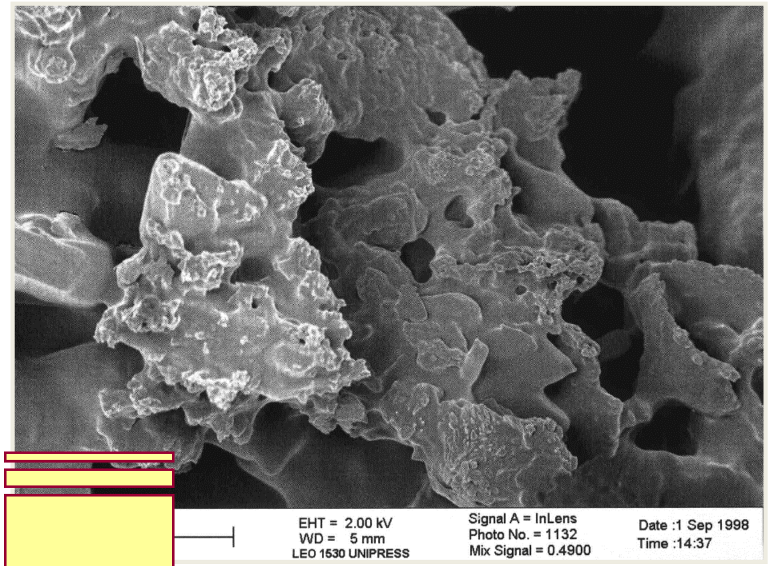
Porous materials

Multi-phase porous materials

Phases of moisture



Scanning Electron Microscopy



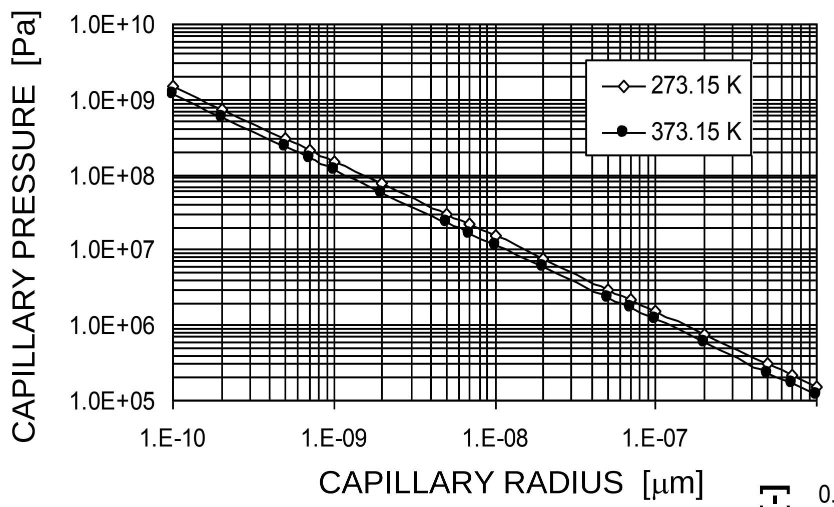
10 000 x

Mechanics of multiphase porous media

Moisture in porous materials

Inner structure of porosity

Laplace equation



$$p^c = \frac{\sigma}{R}$$

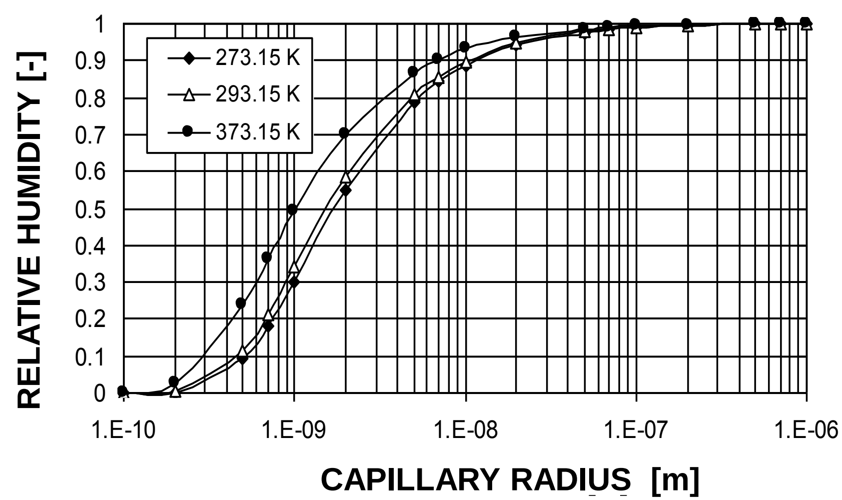
$$\frac{1}{R} = \frac{1}{r'} + \frac{1}{r''}$$

p^c – capillary pressure .
R – meniscus curvature.

Kelvin equation

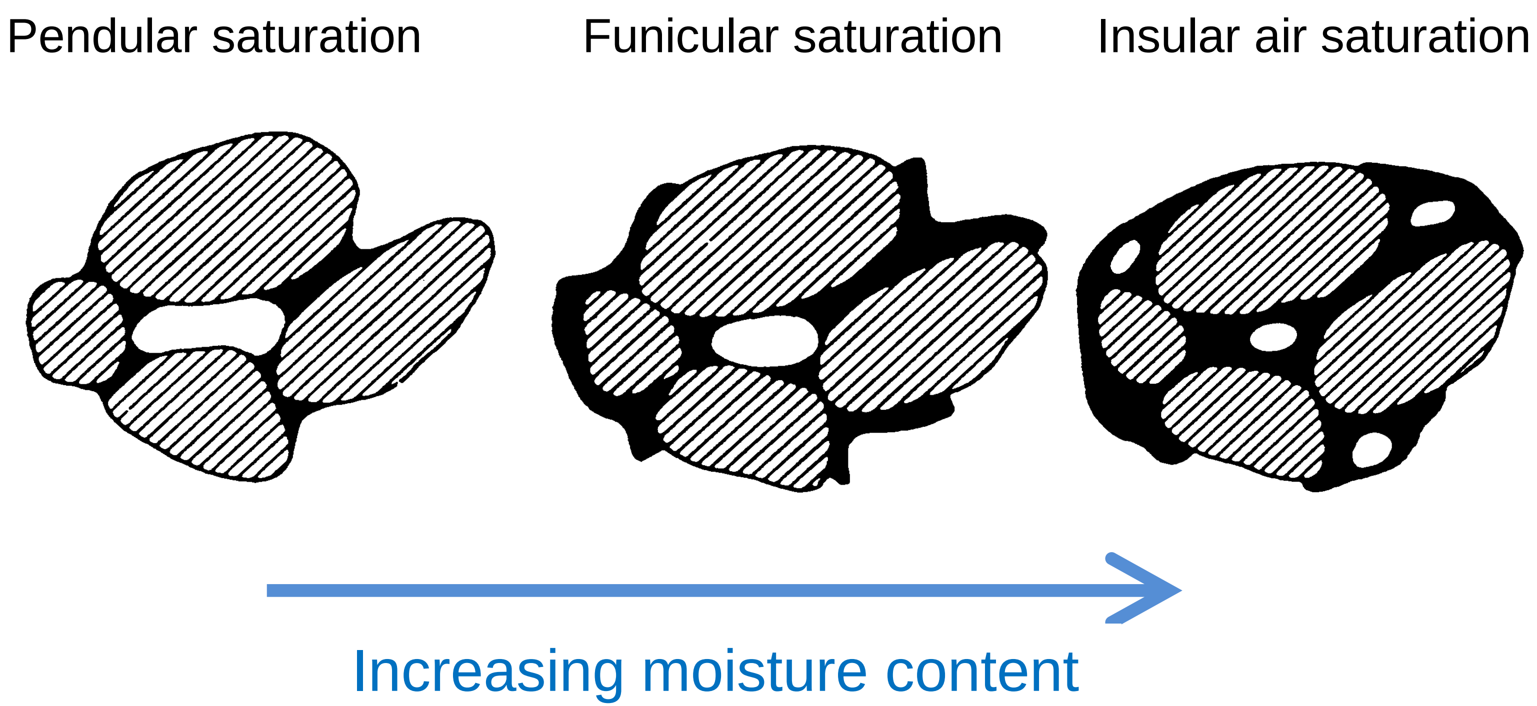
$$\varphi = \frac{p^v}{p^{vs}} = \exp\left(-\frac{p^c M_w}{\rho^w RT}\right)$$

φ – relative humidity .
p^v – vapor pressure
p^{vs} – saturated vapor pressure .



Moisture in porous materials

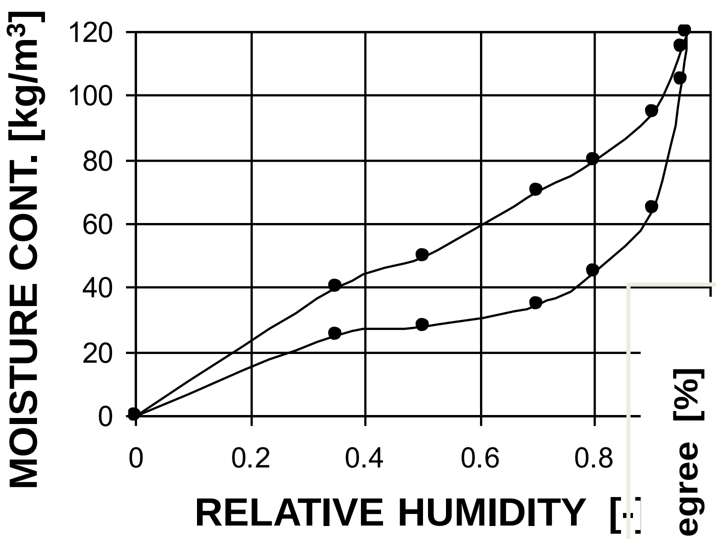
Moisture content vs. pore size



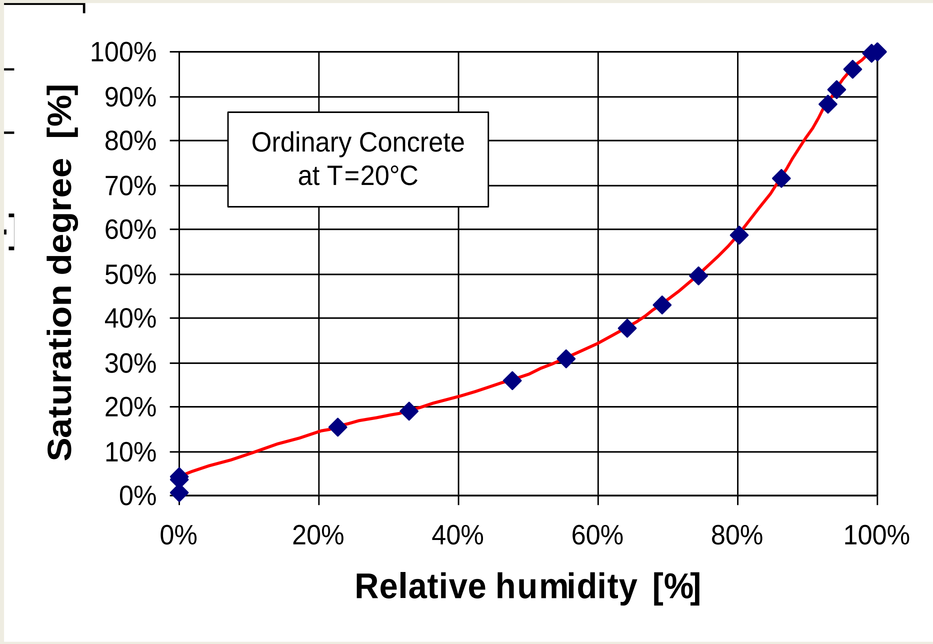
Moisture in porous media

Sorption isotherms

Concrete w/c=0.4 (exp.)



Concrete (math. model)



Structure of porous materials

Simplified models of porosity

Physical reality

Simplified model

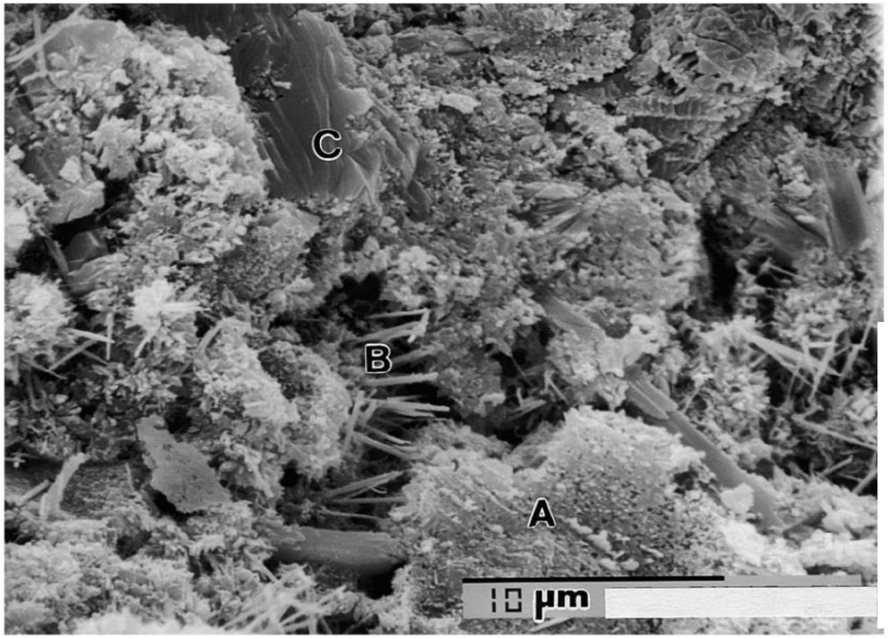
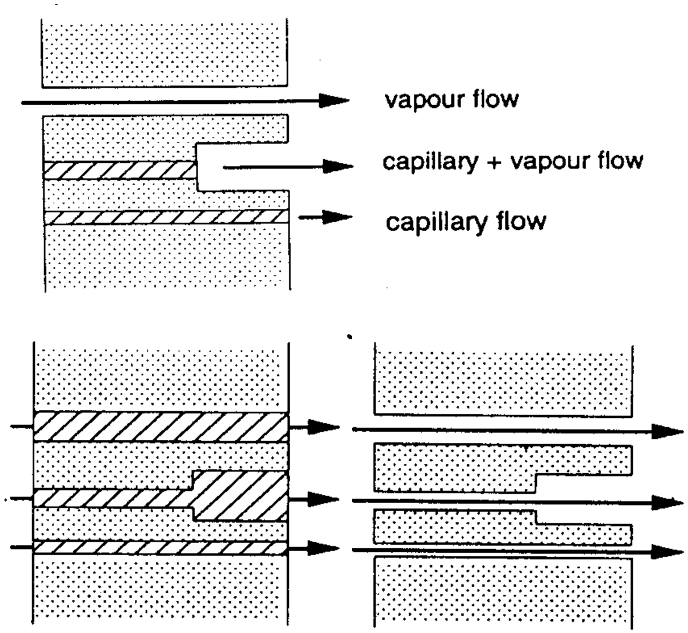


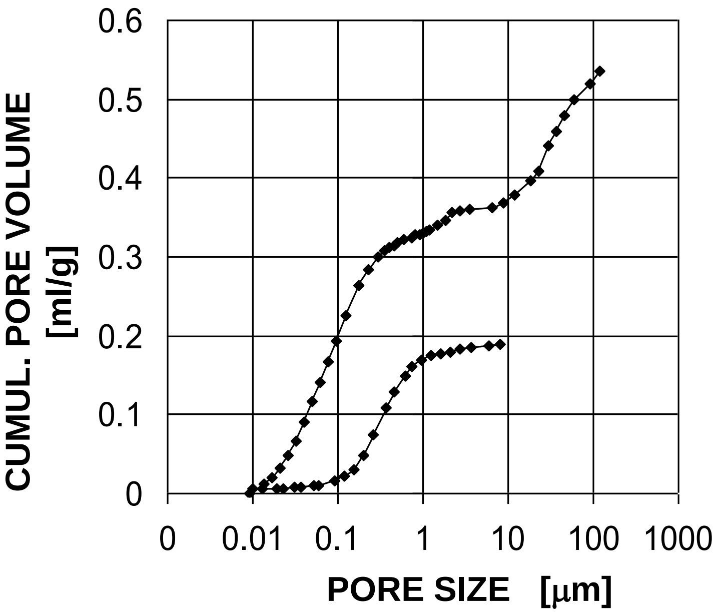
Fig. 2. S.E.M. image of porous paste of Type III cement at 28 days A = C–S–H, B = ettringite, C = $Ca(OH)_2$.

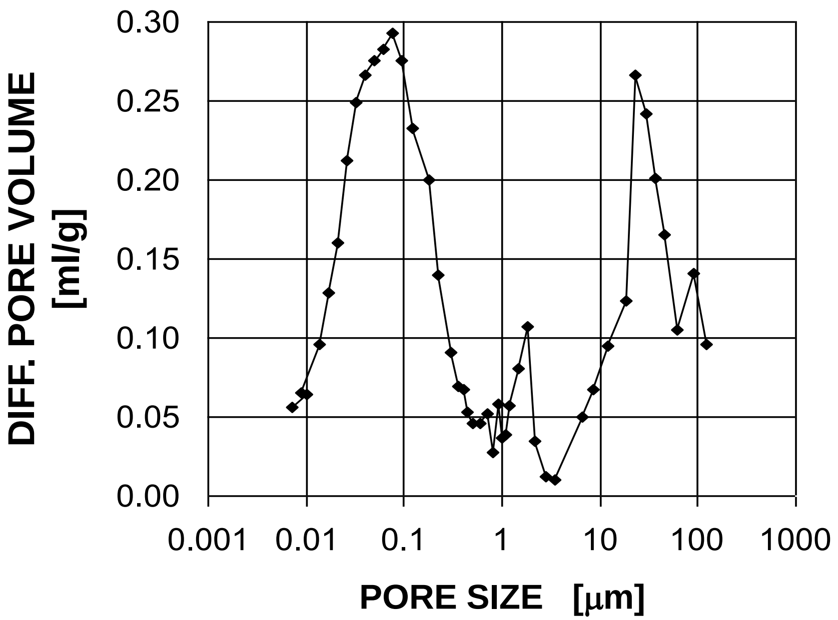


Structure of porous materials

Mercury Intrusion Porosimetry

Cumulative & differential pore size distribution curve





Description of porosity structure

Pores clasiffication

Pore designation	Diameter	Remarks
Micropores	< 2.5 nm (< 25 Å)	Part of C-S-H ← Gel pores
Mesopores	2.5–50 nm (25–500 Å)	Capillary pores
Macropores	50 nm–10 μm	Capillary pores
Entrained air voids	10 μm–0.1 mm	Not directly linked to shrinkage mechanisms
Entrapped air voids		Not directly linked to shrinkage mechanisms
Pre-existing microcracks		Not directly linked to shrinkage mechanisms

Moist material as multi-phase medium

Phases & constituents

- solid matrix
- chemically bound water

} Solid phase

- physically adsorbed water
- capillary water (free water)

} Liquid phases

- water vapour
- dry air

} Gas phase = moist air

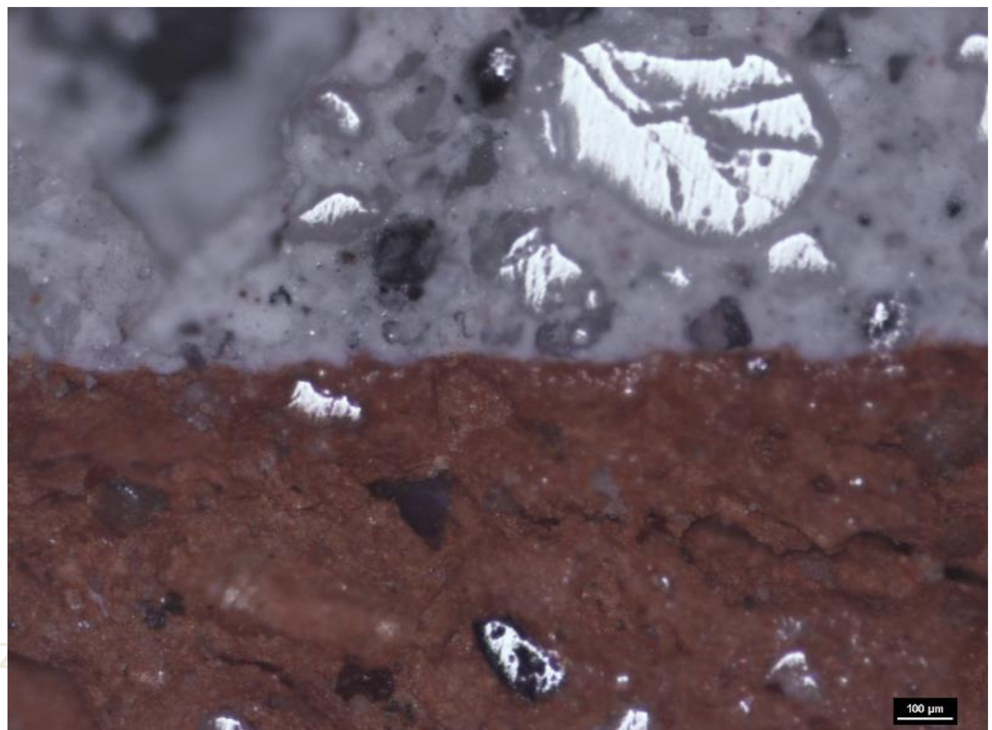
Inter-Material Transition Zone

Experimental Study

Exterior plaster

<u>Inter-material transition zone</u>

Wall material (ceramic brick, concrete blocks

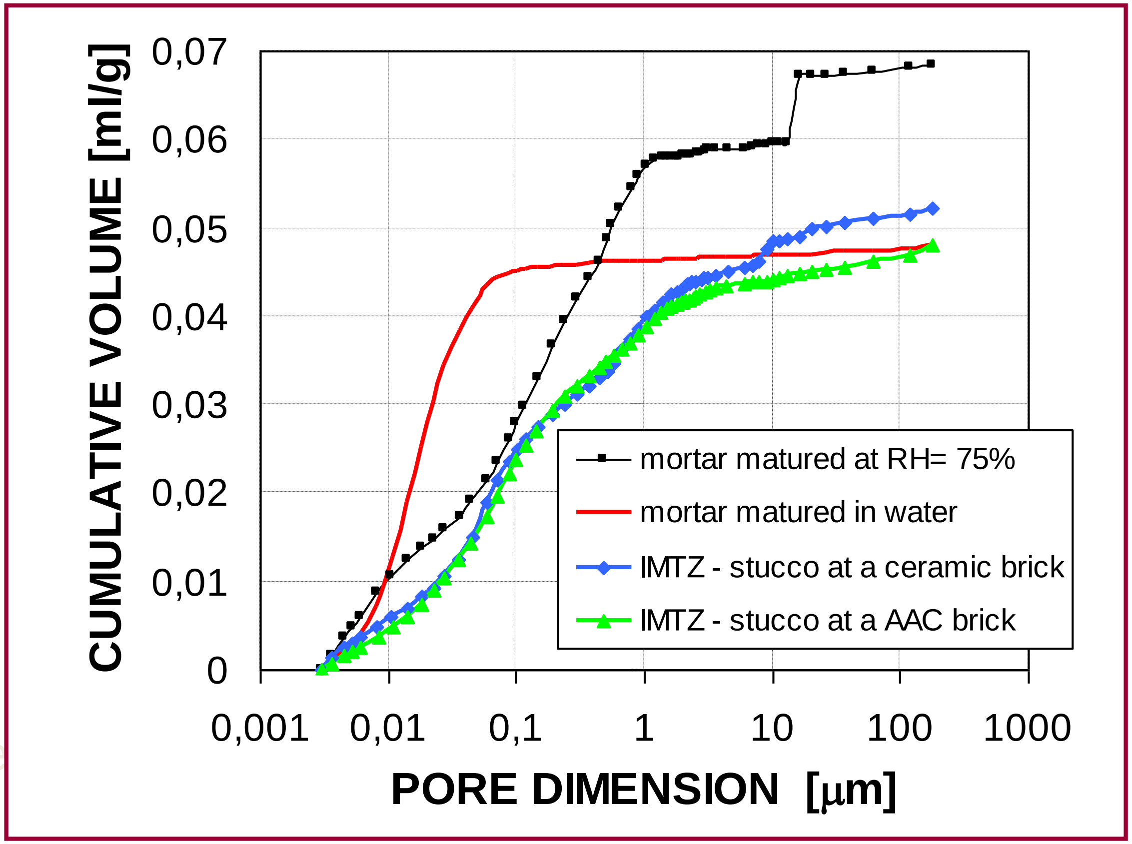


Pore siz

Inter-Material Transition Zone

Experimental Study

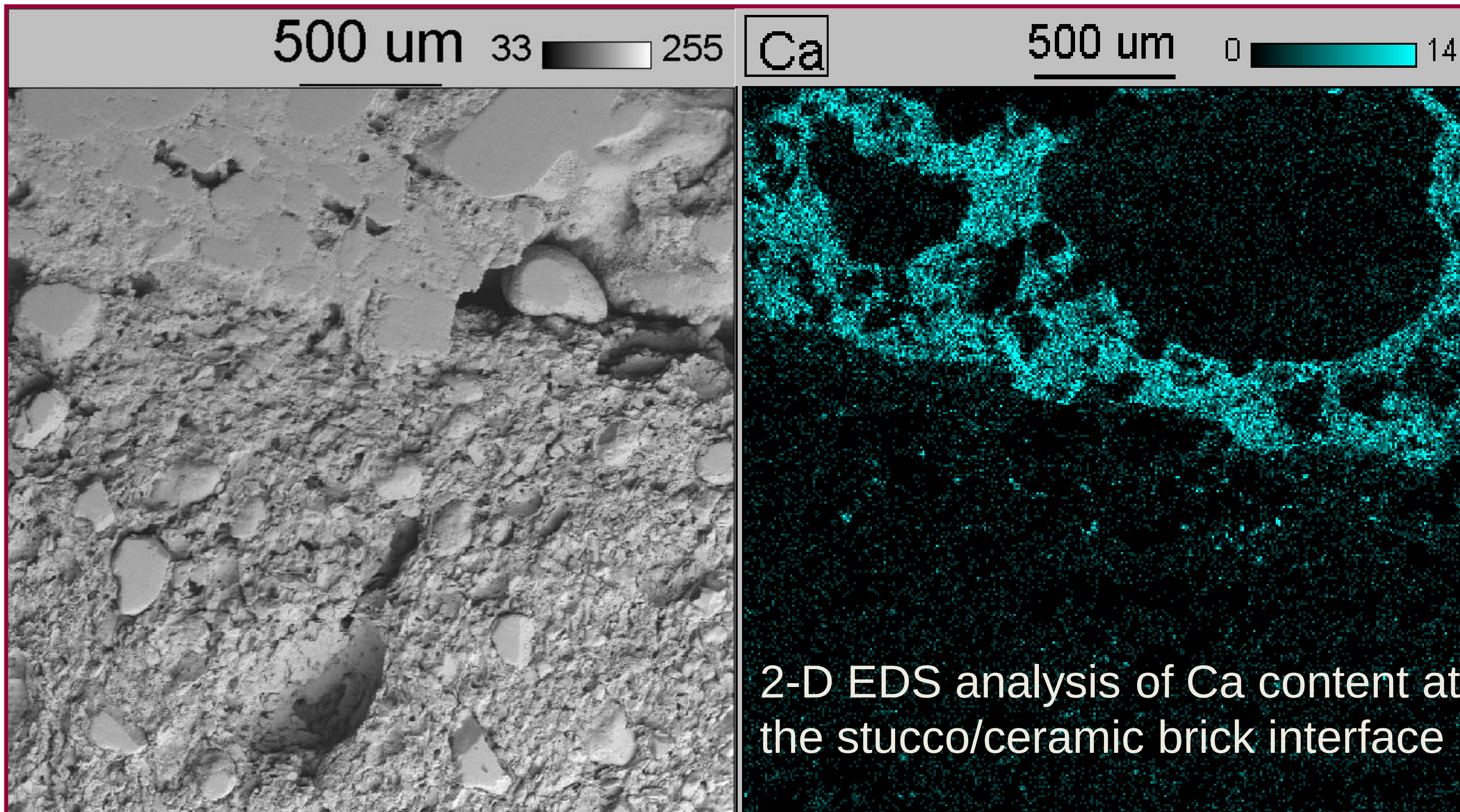
Inter-material transition zone



Pore size

Inter-Material Transition Zone

Experimental Study

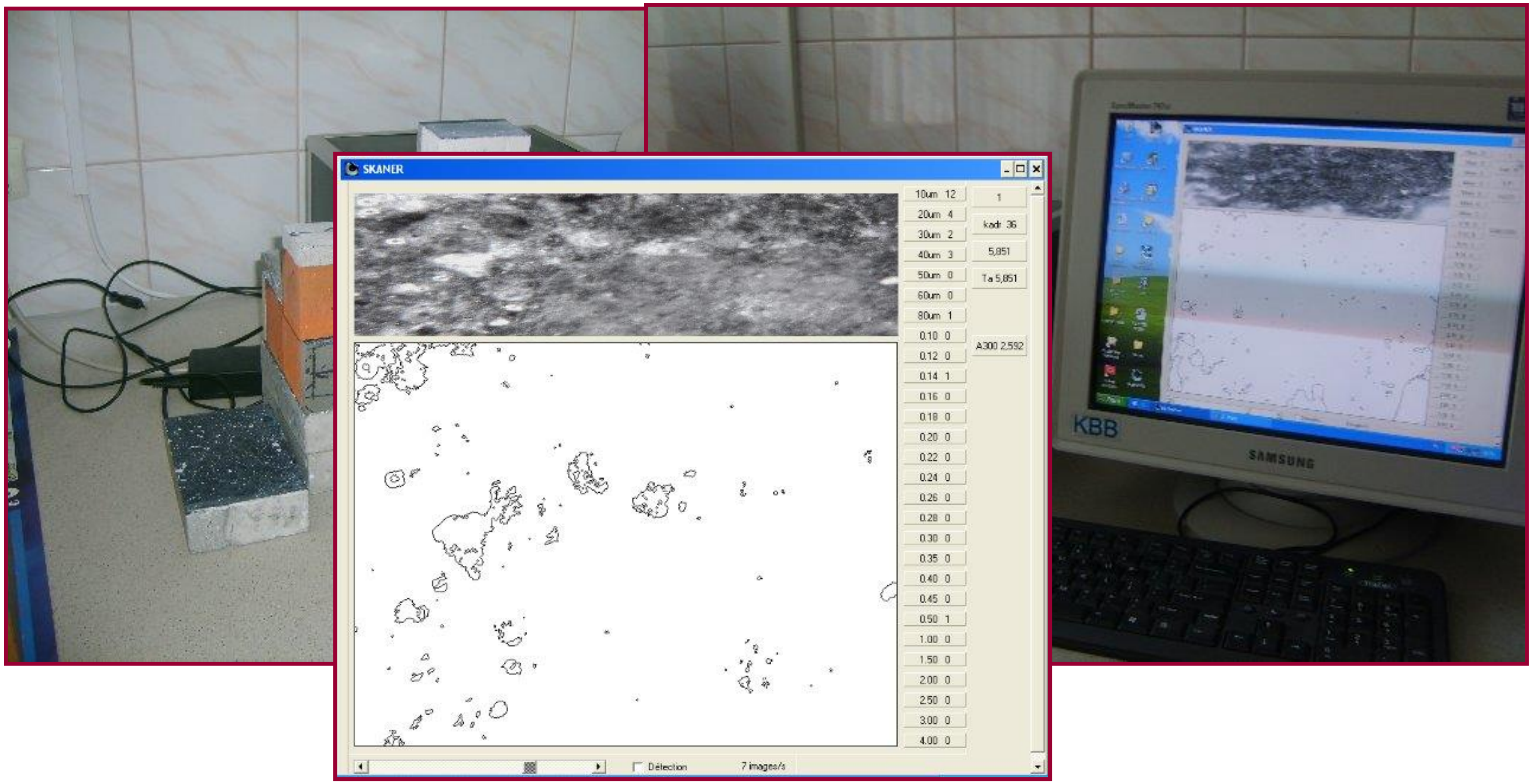


2-D EDS analysis of Ca content at the stucco/ceramic brick interface

SEM
stucco/ceramic brick interface

Inter-Material Transition Zone

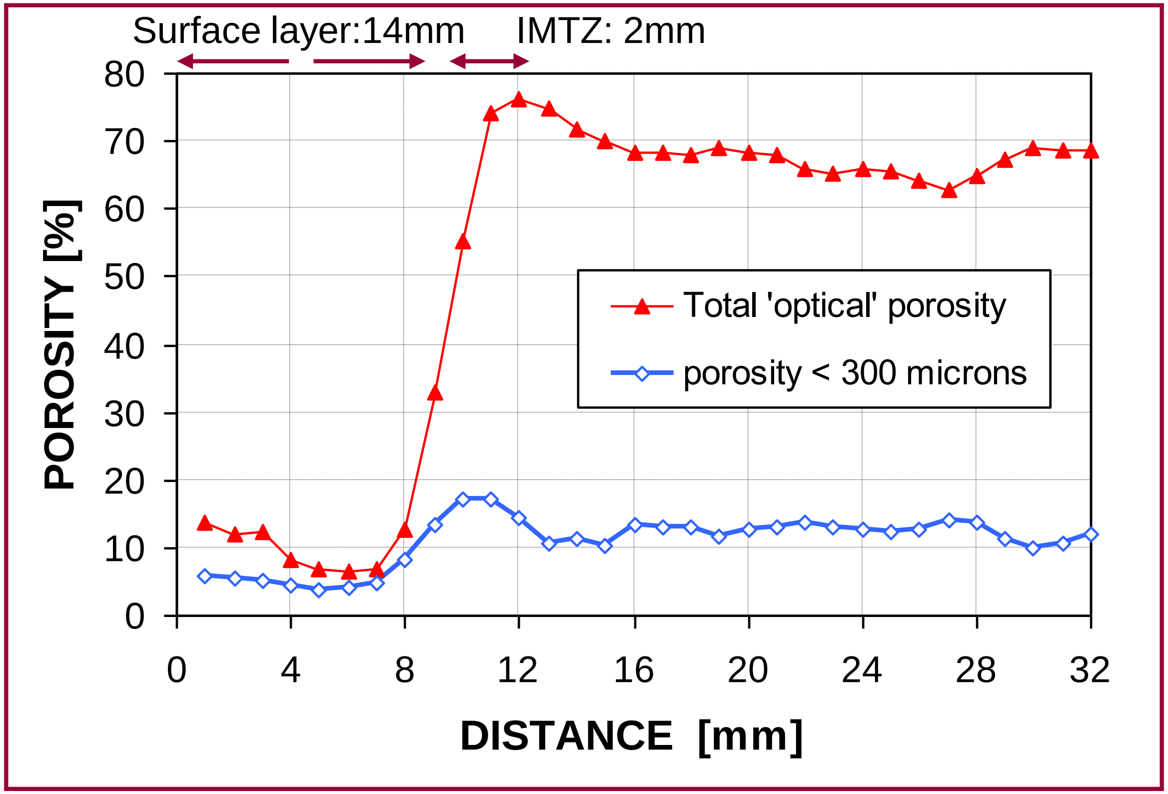
Experimental Study



Scanning Optical Microscopy analysis of the porosity for the stucco/material IMTZ (based on the EN 480 - 11)

Inter-Material Transition Zone

Experimental Study



Scanning Optical Microscopy analysis of the porosity at the stucco/AAC IMTZ (based on the EN 480 - 11)

Material properties

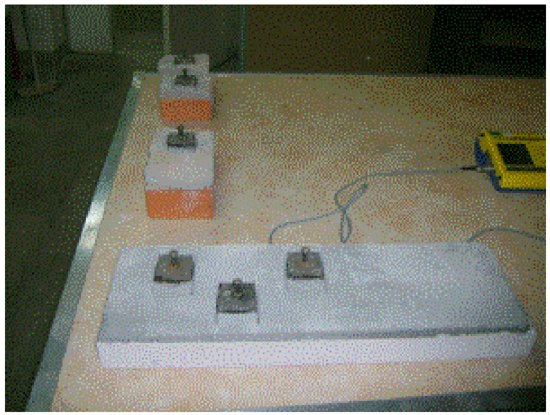
Different properties of the materials & IMTZ

Material	Total porosity [%]	Apparent density [kg/m^3]	Intrinsic permeability [m^2]	Thermal conductivity [W/m·K]
AAC	70	400	5.0×10^{-16}	0.14
Stucco	17	2200	9.0×10^{-19}	0.80
IMTZ	25	1990	2.4×10^{-18}	0.80

Material	Young modulus [GPa]	Poisson ratio [-]	Compressive strength [MPa]	Tensile strength [MPa]
AAC	2.4	0.20	4.50	0.50
Stucco	8.0	0.175	7.40	0.82
IMTZ	7.8	0.175	7.04	0.78

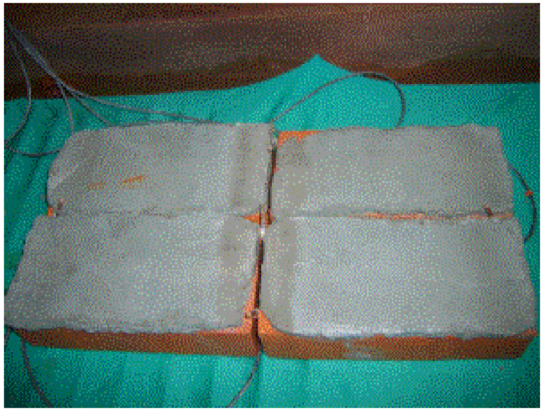
Durability of exterior plaster

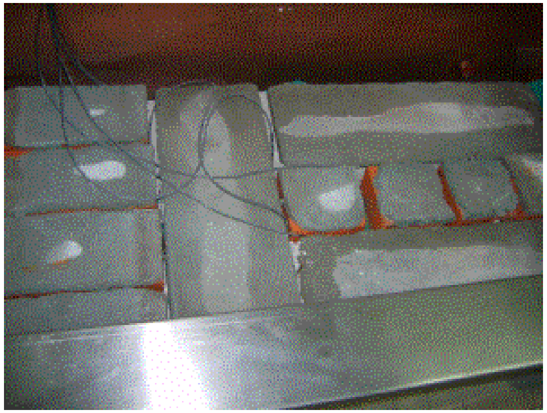
Pull off test

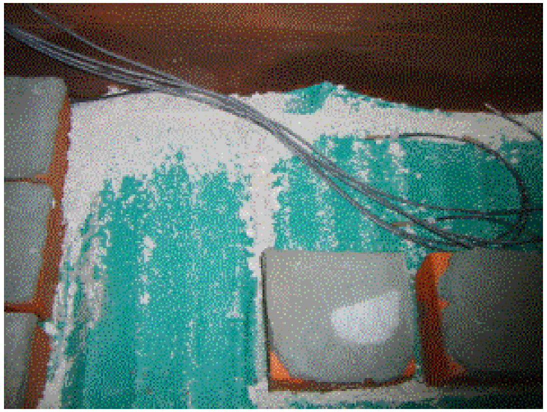


Freezing of water in porous materials

Cyclic freezing /thawing test







Modeling

Phenomenological & mechanistic approach

Phenomenological approach

- description of the final results of the process only, without profound entering into details of the physico-chemical phenomena involved and their interactions
- usually based on Thermodynamics (of Irreversible Processes)
- often uses inverse solution technique

(assumed model vs. experimental results ⇒ model parameters)

Mechanistic approach

- description of the physical processes involved, taking into account their complicated interactions, effect of the material structure, phase changes of particular constituents etc.

Modeling

Modeling coupled heat, air, moisture & chemicals transport (CHAMCT) in porous materials

Phenomenological approach

- ✓ Luikov - 1966
- ✓ Harmathy - 1969
- ✓ Bazant et al. – 1971-2006
- ✓ Krischer - 1978
- ✓ Huang – 1979
- ✓ Bazant & Wittmann - 1982
- ✓ Gawin - 1991
- ✓ Coussy – 1995, 2004, 2010
- ✓ Ulm & Coussy - 1995
- ✓ Sercombe, Hellmich, Ulm, Mang – 2000

Mechanistic approach

- ✓ Slattery - 1967
- ✓ Whitaker - 1977
- ✓ Hassanizadeh & Gray - 1979, 1990
- ✓ Bear, Bachmat - 1986
- ✓ Nasrallah & Perre - 1988
- ✓ Gawin & Schrefler – 1996, 1999
- ✓ Lewis & Schrefler – 1998
- ✓ Gawin - 2000
- ✓ Gawin, Pesavento, Schrefler – 2003-2012

Modeling

Modeling material degradation (cracking + chemical)

Modeling calcium leaching

- ✓ Adenot and Buil - 1992
- ✓ Gerard - 1996
- ✓ Ulm, Torrenti, Adenot - 1999
- ✓ Kuhl, Bangert, Meschke - 2004
- ✓ Kuhl & Meschke – 2007

Nonequil. Calcium leaching

- ✓ Gawin, Pesavento & Schrefler -2008, 2009

Frost damage

- ✓ Bazant – 1998
- ✓ Scherer – 1999, 2005, 2010
- ✓ Setzer – 2001
- ✓ Coussy – 2005, 2006, 2007
- ✓ Pentalla – 1998, 2002, 2006

Modeling material degradation

- damage theory:

- ✓ Mazars - 1984
- ✓ Pijaudier-Cabot & Mazars - 1989
- ✓ Pijaudier-Cabot, Gerard, Molez– 1998

- chemo-poro-plasticity:

- ✓ Ulm, Torrenti, Adenot - 1999

- theory of reactive porous media:

- ✓ Kuhl, Bangert, Meschke - 2004

Modeling salt transport & precipitation

- ✓ Samson et al. - 2007
- ✓ Koniorczyk & Gawin –2008, 2011, 2012
- ✓ Koniorczyk – 2009, 2010, 2012

Modeling

Balance equations & evolution equation

- ✓ Dry air mass balance
- ✓ Water species mass balance
- ✓ Salt mass balance
- ✓ Multiphase medium energy balance
- ~~✓ Electrical charge balance equation~~
- ✓ Multiphase medium momentum balance
- ✓ Multiphase medium angular momentum balance
- ✓ Second law of Thermodynamics for multiphase medium

- ✓ Evolution equation for deterioration (chemical, thermal…)
- ✓ Evolution equation for damage (cracking)
- ✓ Evolution equation for chemical reaction / phase change

Modeling

State variables & internal variables

- ✓ **Dry air** – gas pressure
- ✓ **Water** – moisture content, capillary pressure, relative humidity
- ✓ **Salt** – salt concentration
- ✓ **Heat** – temperature
- ✓ ~~Electrical charge – electrical pptential~~
- ✓ Mechanical equilibrium – **strain** tensor, displacement vector
- ✓ Angular momentum – summetry of stress tensor
- ✓ 2nd law of Thermodynamics – restrictions for constitutive relations

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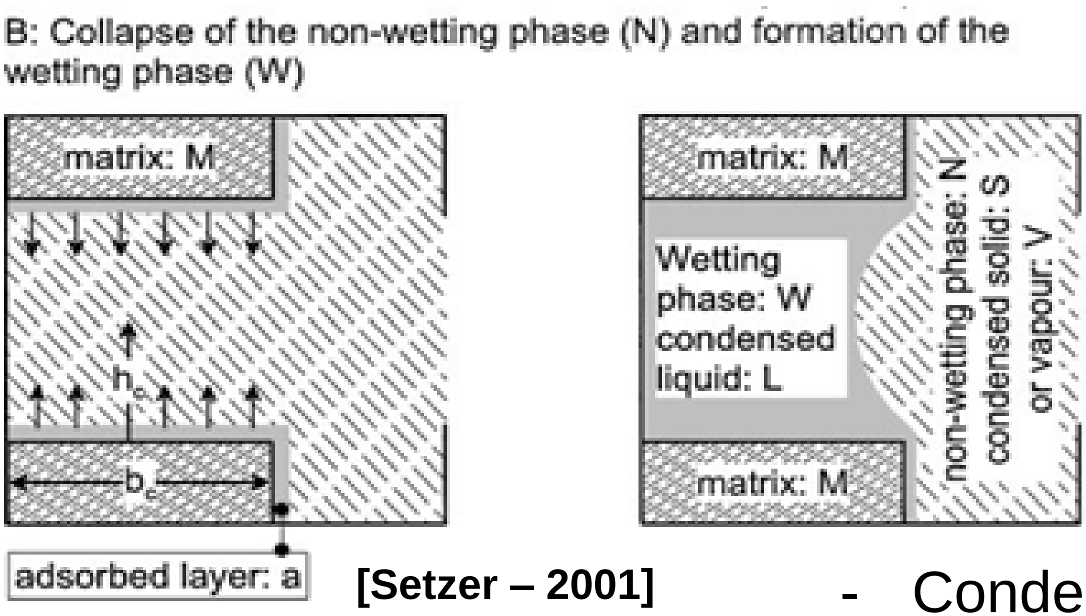
- ✓ **Damage** (mechanical, chemical, thermal, …) parameter
- ✓ **Mechanical damage** parameter
- ✓ **Chemical reaction / phase change** – degree of advancement

Modeling

Phase changes in porous materials

$$\gamma_{MV} > \gamma_{MS} > \gamma_{ML}$$

Less → more wetting phases: vapour, ice, water



[Setzer – 2001]

from nonwetting to wetting phase

Stable phase change at equil. conditions:

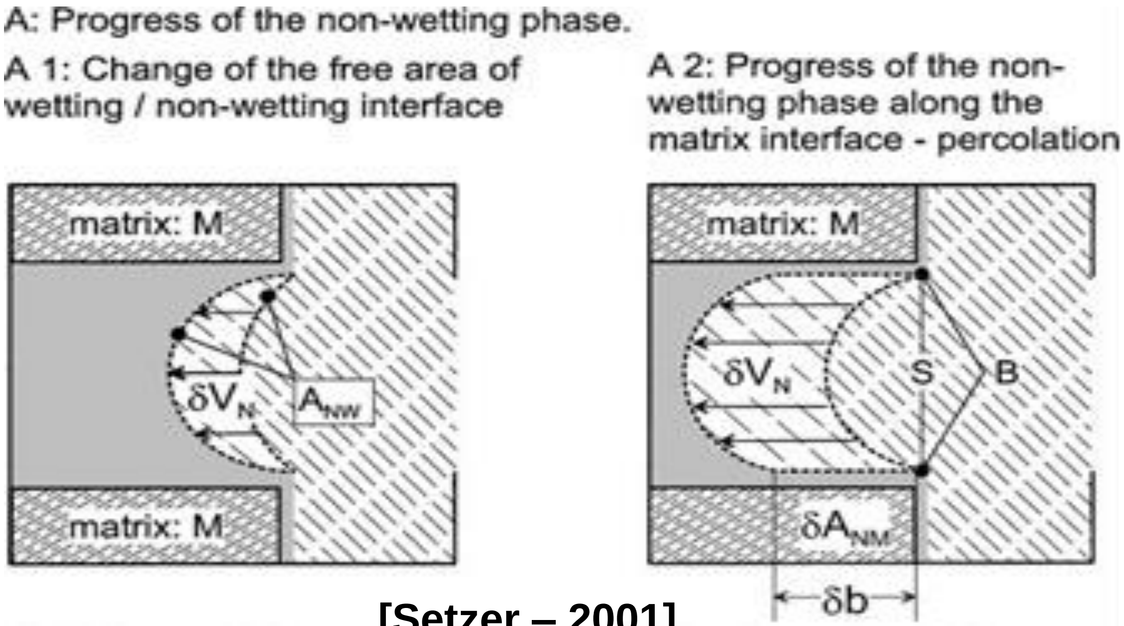
- Condensation of vapor
- Thawing of ice

Modeling

Phase changes in porous materials

$$\gamma_{MV} > \gamma_{MS} > \gamma_{ML}$$

Less → more wetting phases: vapour, ice, water



[Setzer – 2001]

from wetting to nonwetting phase

Unstable phase change below equil. conditions:

- Evaporation of water
- Freezing of ice

Modeling

Mass transport mechanisms

Capillary water (free water):

- ✓ advective flow *(water pressure gradient)*

Physically adsorbed water:

- ✓ diffusive flow *(water concentration gradient)*

Chemically bound water:

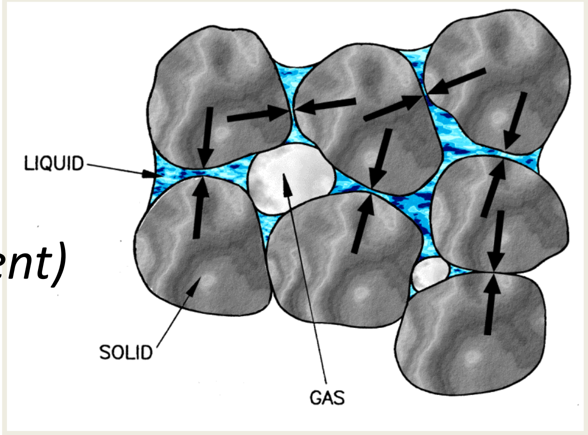
- ✓ no transport

Water vapour:

- ✓ advective flow *(gas pressure gradient)*
- ✓ diffusive flow *(water vapour concentration gradient)*

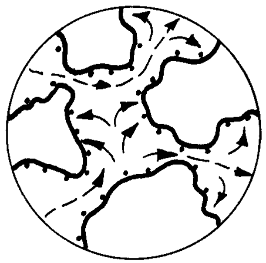
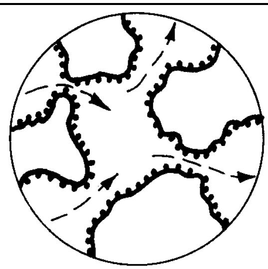
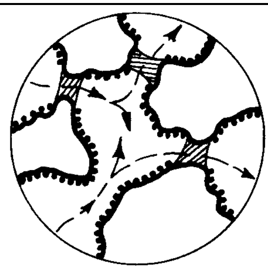
Dry air:

- ✓ advective flow *(gas pressure gradient)*
- ✓ diffusive flow *(dry air concentration gradient)*



Modeling

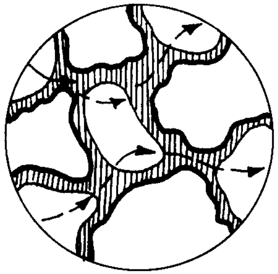
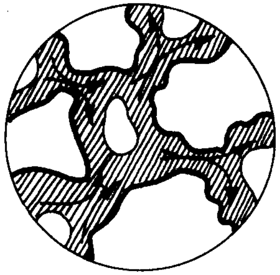
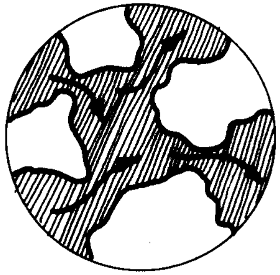
Moisture trnasport in porous materials - summary

	1) 0% < φ < ~20% 2) vapour + mono-layer of physically adsorbed water 3) adsorption ↔ desorption 4) diffusion and advective flow of vapour + surface diffusion in adsorbed water film
	1) ~20% < φ < ~60% 2) vapour + poly-layer of physically adsorbed water 3) adsorption ↔ desorption 4) diffusion and advective flow of vapour + surface diffusion in adsorbed water film
	1) ~60% < φ < ~95% 2) capillary water + vapour + poly-layer of physically adsorbed water 3) capillary condensation ↔ evaporation & adsorption ↔ desorption 4) „condensation – capillary flow - evaporation” + diffusion and advective flow of vapour + (surface diffusion in adsorbed water film)

1) Relative humidity, 2) moisture forms, 3) phase changes,
4) mechanisms of moisture transfer, (phenomenon of less importance)

Modeling

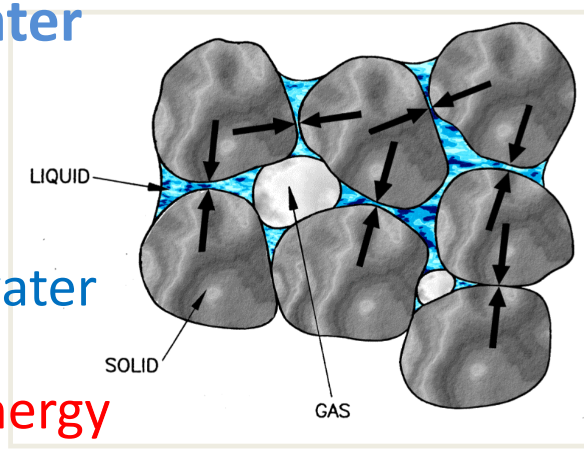
Moisture trnasport in porous materials - summary

	1) ~95% < φ < ~99% 2) capillary water + vapour (+ poly-layer of physically adsorbed water) 3) capillary condensation ↔ evaporation & (adsorption ↔ desorption) 4) capillary & advective flow of capillary water +„condensation – capillary flow - evaporation” + (diffusion of vapour in air)
	1) ~99% < φ < 100% 2) free water + vapour 3) capillary condensation ↔ evaporation 4) capillary & advective flow of free water + (diffusion of vapour in air)
	1) φ = 100% 2) free water 3) - 4) advective flow of free water

1) Relative humidity, 2) moisture forms, 3) phase changes,
4) mechanisms of moisture transfer, (phenomenon of less importance)

Modeling

Phase changes of water



- ***Thawing:*** ice + energy ⇒ capillary water
- ***Freezing:*** capillary water ⇒ ice + energy
- ***Evaporation:*** capillary water + energy ⇒ water vapor
- ***Condensation:*** water vapor ⇒ capillary water + energy
- ***Desorption:*** phys. adsorbed water + energy ⇒ water vapor
- ***Adsorption:*** water vapor ⇒ phys. adsorbed water + energy

Modeling

Phase changes of water

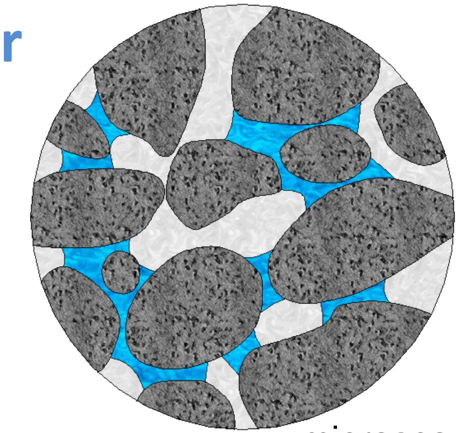
Microscopic balance equations
(differential equations)

Spatial averaging

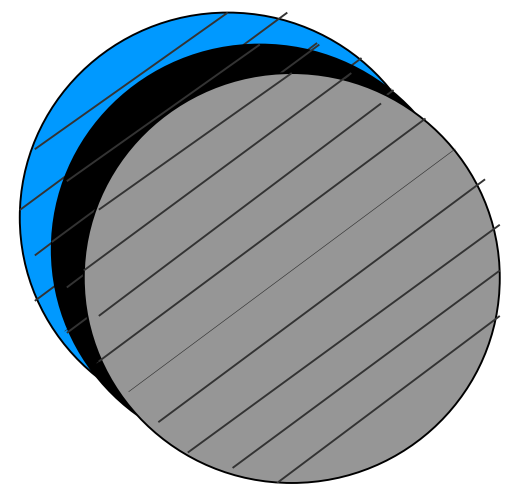
Macroscopic balance equations
(differential equations)

Weighted residual method
& time discretisation

F.E. model
(algebraic equations)



microscopic view



macroscopic view of averaged overlapping continua

Modeling

Numerical solution

$$\mathbf{C}_{gg}\frac{\partial \overline{\mathbf{p}}^{g}}{\partial t}+\mathbf{C}_{gc}\frac{\partial \overline{\mathbf{p}}^{c}}{\partial t}+\mathbf{C}_{gs}\frac{\partial \overline{\mathbf{c}}_{\mathbf{Ca}}}{\partial t}+\mathbf{C}_{gt}\frac{\partial \overline{\mathbf{T}}}{\partial t}+\mathbf{C}_{gu}\frac{\partial \overline{\mathbf{u}}}{\partial t}+\mathbf{K}_{gg}\overline{\mathbf{p}}^{g}+\mathbf{K}_{gc}\overline{\mathbf{p}}^{c}+\mathbf{K}_{gs}\overline{\mathbf{c}}_{\mathbf{Ca}}+\mathbf{K}_{gt}\overline{\mathbf{T}}=\mathbf{f}_{g}$$

$$\mathbf{C}_{cc}\frac{\partial \overline{\mathbf{p}}^{c}}{\partial t}+\mathbf{C}_{cs}\frac{\partial \overline{\mathbf{c}}^{Ca}}{\partial t}+\mathbf{C}_{ct}\frac{\partial \overline{\mathbf{T}}}{\partial t}+\mathbf{C}_{cu}\frac{\partial \overline{\mathbf{u}}}{\partial t}+\mathbf{K}_{cg}\overline{\mathbf{p}}^{g}+\mathbf{K}_{cc}\overline{\mathbf{p}}^{c}+\mathbf{K}_{gs}\overline{\mathbf{c}}^{Ca}+\mathbf{K}_{ct}\overline{\mathbf{T}}=\mathbf{f}_{c}$$

$$\mathbf{C}_{tc}\frac{\partial \overline{\mathbf{p}}^{c}}{\partial t}+\mathbf{C}_{ts}\frac{\partial \overline{\mathbf{c}}^{Ca}}{\partial t}\mathbf{C}_{tt}\frac{\partial \overline{\mathbf{T}}}{\partial t}+\mathbf{C}_{tu}\frac{\partial \overline{\mathbf{u}}}{\partial t}+\mathbf{K}_{tg}\overline{\mathbf{p}}^{g}+\mathbf{K}_{tc}\overline{\mathbf{p}}^{c}+\mathbf{K}_{ts}\overline{\mathbf{c}}^{Ca}\mathbf{K}_{tt}\overline{\mathbf{T}}=\mathbf{f}_{t}$$

$$\mathbf{C}_{sc}\frac{\partial \overline{\mathbf{p}}^{c}}{\partial t}+\mathbf{C}_{ss}\frac{\partial \overline{\mathbf{c}}^{Ca}}{\partial t}+\mathbf{C}_{st}\frac{\partial \overline{\mathbf{T}}}{\partial t}+\mathbf{C}_{su}\frac{\partial \overline{\mathbf{u}}}{\partial t}+\mathbf{K}_{sg}\overline{\mathbf{p}}^{g}+\mathbf{K}_{sc}\overline{\mathbf{p}}^{c}+\mathbf{K}_{ss}\overline{\mathbf{c}}^{Ca}+\mathbf{K}_{st}\overline{\mathbf{T}}=\mathbf{f}_{s}$$

$$\mathbf{C}_{ug}\frac{\partial \overline{\mathbf{p}}^{g}}{\partial t}+\mathbf{C}_{uc}\frac{\partial \overline{\mathbf{p}}^{c}}{\partial t}+\mathbf{C}_{us}\frac{\partial \overline{\mathbf{c}}^{Ca}}{\partial t}+\mathbf{C}_{ut}\frac{\partial \overline{\mathbf{T}}}{\partial t}+\mathbf{C}_{uu}\frac{\partial \overline{\mathbf{u}}}{\partial t}+\mathbf{K}_{uu}\overline{\mathbf{u}}=\mathbf{f}_{u}$$

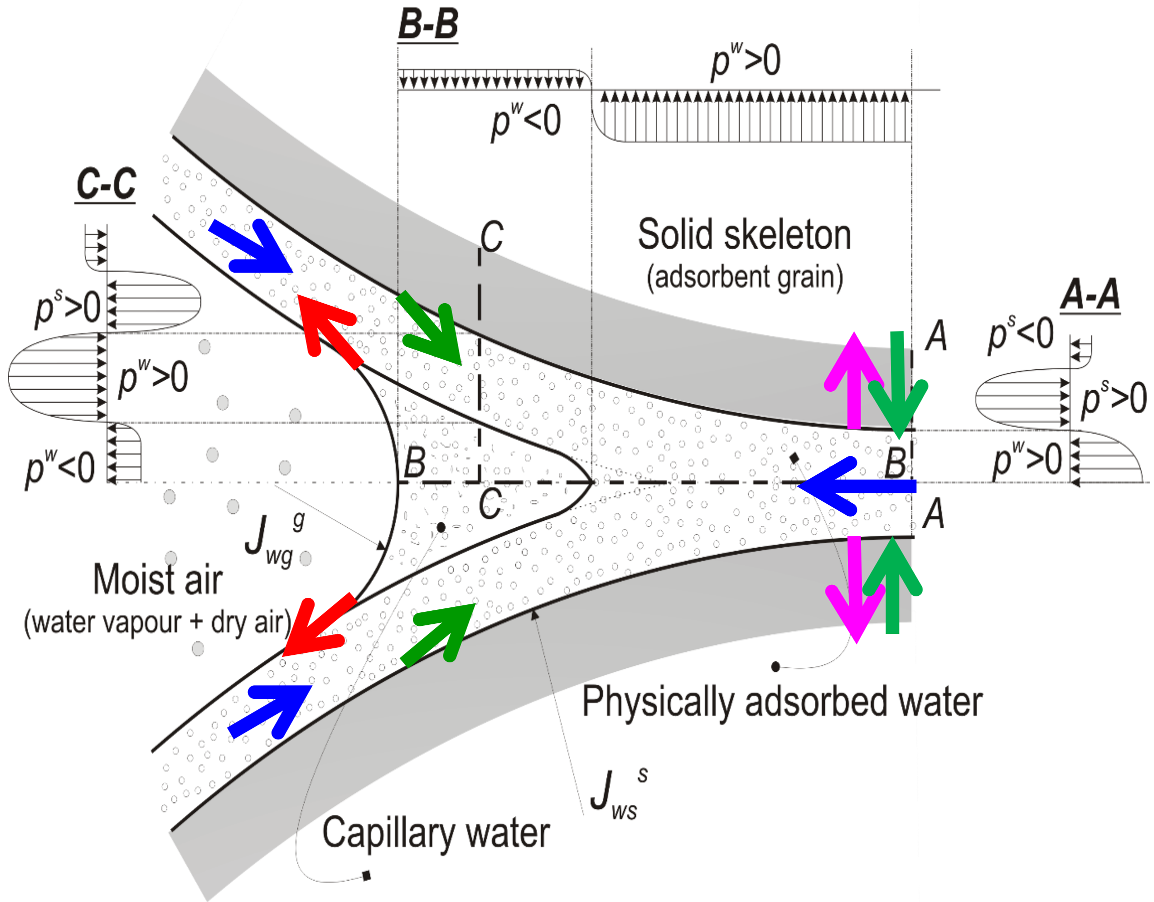
where **$\mathbf{K}_{ij}$** - related to the primary variables

$\mathbf{C}_{ij}$ - related to the time derivative of the primary variables

$\mathbf{f}_{i}$ - related to the other terms, eg. BCs *(i,j=g,c,t,s,**u**)*

Modeling

Physical origins of shrinkage



Forces:

in water

Capillary pressure

Disjoining pressure

in skeleton

Capillary pressure

Disjoining pressure

Modeling

Material strain decomposition

$$\boldsymbol{\varepsilon}_{mech} = \boldsymbol{\varepsilon}_{tot} - \boldsymbol{\varepsilon}_{c} - \boldsymbol{\varepsilon}_{th} - \boldsymbol{\varepsilon}_{ch}$$

- free thermal strain
- chemical strain
- creep strain
- mechanical strain *(caused by mechanical load and shrinkage)*

Shrinkage strain

$$\boldsymbol{\varepsilon}_{sh} = -\frac{\alpha}{3K_T}\left(\chi^{ws}\Delta p^{c}\right)\mathbf{I}$$

or

$$\boldsymbol{\varepsilon}_{sh} = \left(\beta_{sh}\Delta\varphi\right)\mathbf{I}$$

Free thermal strain strain

$$\boldsymbol{\varepsilon}_{t} = \beta_{s}\,\Delta T\,\mathbf{I}$$

Chemical strain

$$\boldsymbol{\varepsilon}_{ch} = \beta_{ch}\,\Gamma_{chem}\,\mathbf{I}$$

Modeling

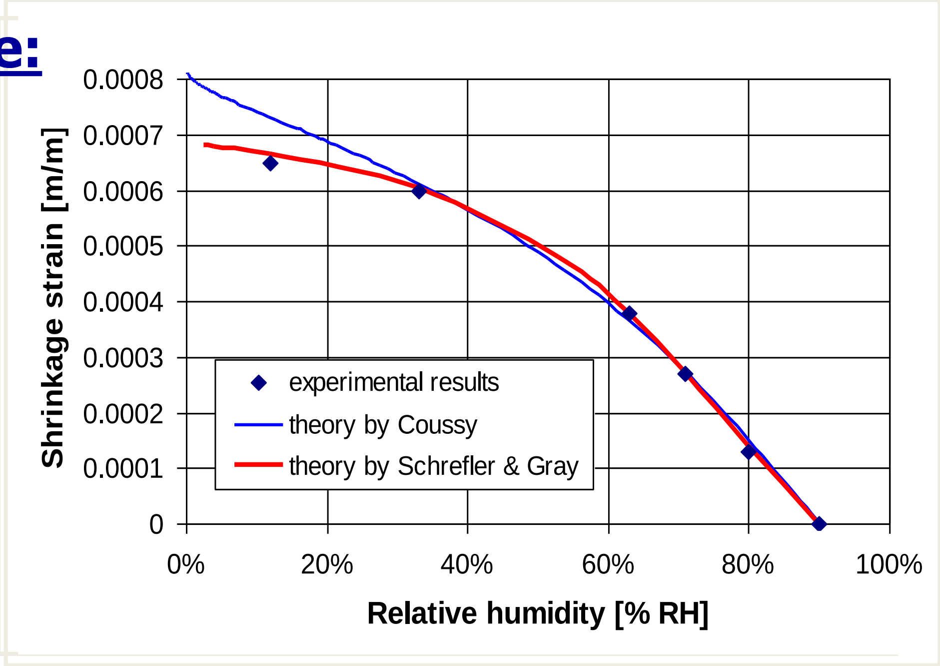
Shrinkage / swelling strains

Effective stress principle:

$$\boldsymbol{\sigma}_e^s = \boldsymbol{\sigma}^s + \alpha \mathbf{I} p^s$$

$$p^s = p^g - \chi_s^{ws} p^c$$

- *[Gray & Schrefler, 2001]*
- *[Gray & Schrefler 2006]*



where χ_s^{ws} is the solid surface fraction in contact with the wetting film,

I - unit, second order tensor, α - Biot's coefficient,

p^s - pressure in the solid phase and p^c is given by $p^c = \Pi^f - s^{wg} J_{wg}^w$

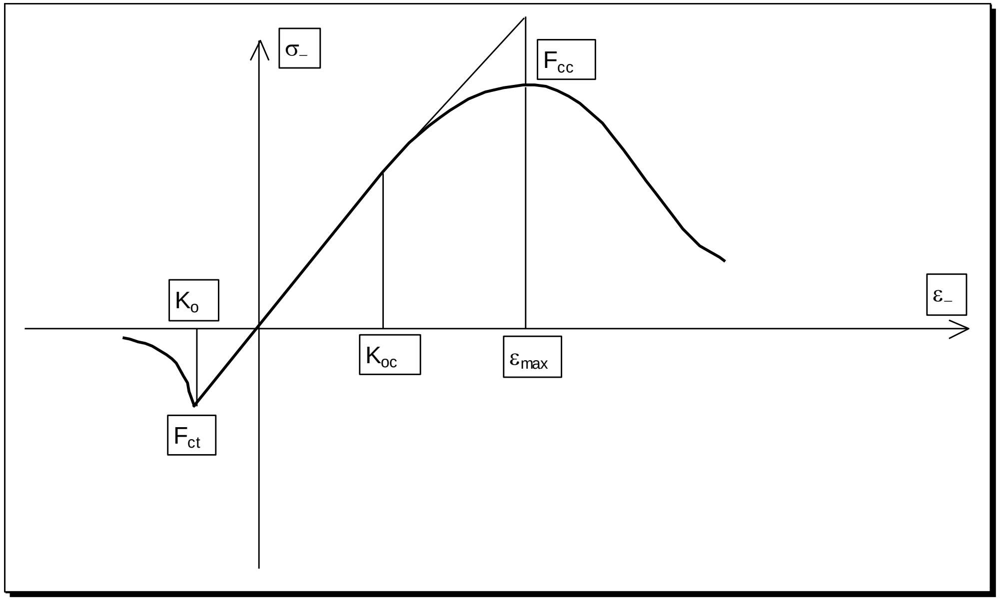
with Π^f - disjoining pressure

Modeling

Material damage (cracking)

Non-local isotropic damage theory

[Mazars & Pijaudier-Cabot, 1989]



$$d = \alpha_t d_t + \alpha_c d_c$$

$$\tilde{\varepsilon} = \sqrt{\sum_{i=1}^{3} \left(\langle \varepsilon_i \rangle_+ \right)^2}$$

$$\bar{\varepsilon}(x) = \frac{1}{V_r(x)} \int_V \Psi(x-s)\tilde{\varepsilon}(s)\, dv$$

$$\Psi(x-s) = \Psi_o \exp\left(-\frac{\|x-s\|^2}{2l_c^2} \right)$$

Modeling

Chemical deterioration and Total damage

$$V = 1 - \frac{E_0(\Gamma_{leach})}{E_0(\Gamma_{leach} = 0)}$$

Joint effect of mechanical and chemical damage

[Pijaudier-Cabot, Gerard, Molez – 1998]

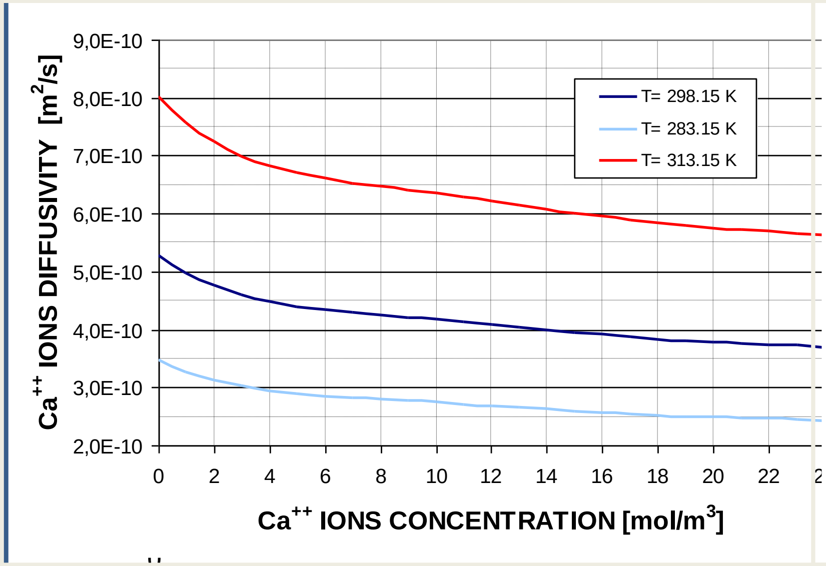
$$D = 1 - \frac{E(\Gamma_{leach})}{E_0(\Gamma_{leach} = 0)} = 1 - \frac{E(\Gamma_{leach})}{E_0(\Gamma_{leach})}\frac{E_0(\Gamma_{leach})}{E_0(\Gamma_{leach} = 0)} = 1 - (1 - d)(1 - V)$$

$$\boldsymbol{\sigma} = (1 - d)(1 - V)\boldsymbol{\Lambda}_0 : \boldsymbol{\varepsilon}^e = (1 - D)\boldsymbol{\Lambda}_0 : \boldsymbol{\varepsilon}^e$$

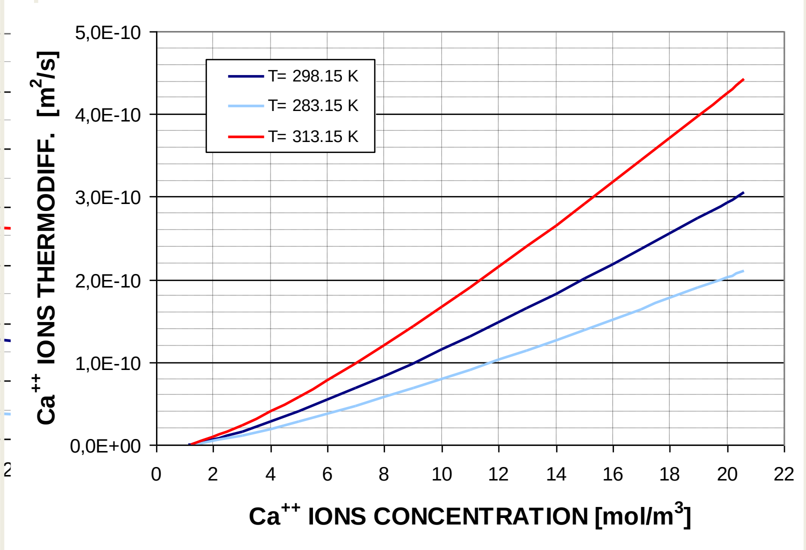
Modeling

Chemical deterioration and Total damage

Ions diffusion



Ions thermo-diffusion



$$\mathbf{D}_d^{Ca} = D_d^{Ca}\mathbf{I} = n S_w \tau D_{d0}^{Ca} \cdot \exp\left[A_4\left(T - T_{ref}\right)\right]\mathbf{I}$$

[Samson et al. - 2007]

$$\mathbf{D}_T^{Ca} = D_T^{Ca}\mathbf{I} = n S_w \tau D_{T0}^{Ca} \frac{c_{Ca}}{T} \cdot \exp\left[\alpha_T\left(T - T_{ref}\right)\right]\mathbf{I}$$

Material shrinkage

Tests of Bryant and Vadhanavikkit (1987)

Slab – thickness=30 cm

Material: concrete C50

- final porosity: 0.122, density: ρ= 1900 kg/m^3,
- intrinsic permeability: ko= 5·10^{-19} m^2,
- Young modulus: E= 49.2 GPa,
- water/cement ratio w/c=0.45.

Initial conditions: T_o= 293.15 K, φ_o= 99.8% RH, Γ_{hydr}=0.3;

Boundary conditions:

***Shrinkage** (from day 7)*

- convective heat exchange: α_c=5W/m^{2}K; T_{amb}=293.15K;
- convective moisture exchange: β_c=0.002m/s; RH_{amb}=60%
- surface mechanical load: unloaded or load=7 MPa at 8,28,84,182 days

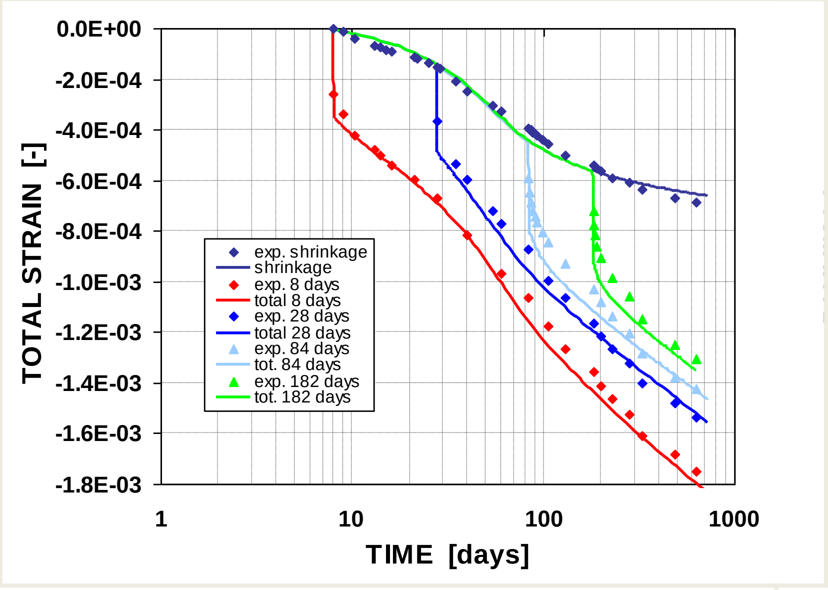
***Sealed** (for the first 7 days and basic creep)*

- convective heat and mass exchange: α_c=5W/m^{2}K; sealed
- surface mechanical load: unloaded or load=7 MPa at 8,28,84,182 days

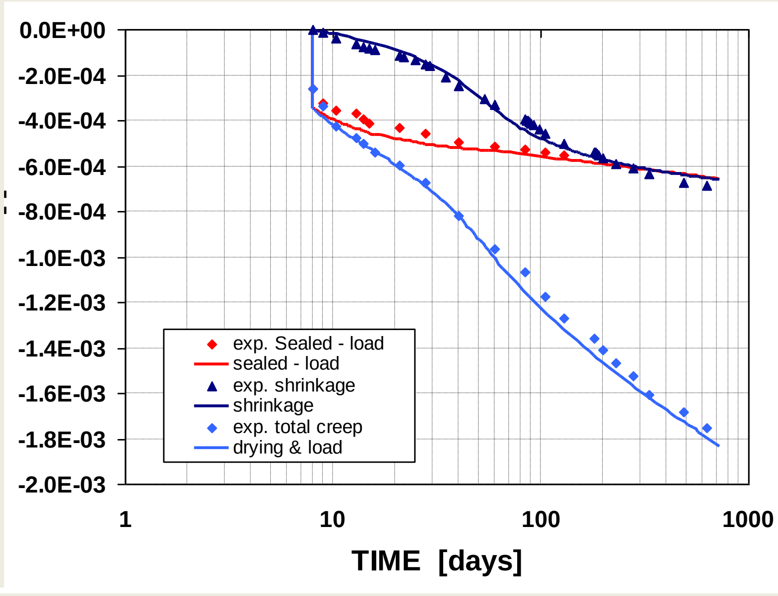
Material shrinkage

Tests of Bryant and Vadhanavikkit (1987)

Drying & Load



Pickett's effect (8 days)

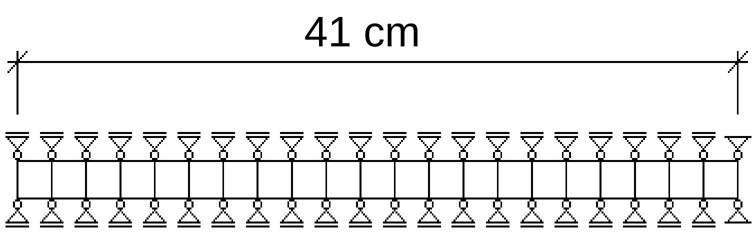


Material hygro-thermal strains

AAC wall exposed to the climatic conditions of Poland

Boundary conditions:

β_i= 0,008 m/s
h_i= 7.7 W/(m²K)
T_i= 20°C
RH_i= EN-13788



β_e= 0,023 m/s
h_e= 23.3 W/(m²K)
T_e= TMY (incl. solar rad.)
RH_e= TMY (incl. rain)

Initial conditions: RH =50%; T= 20°C;

Considered cases:

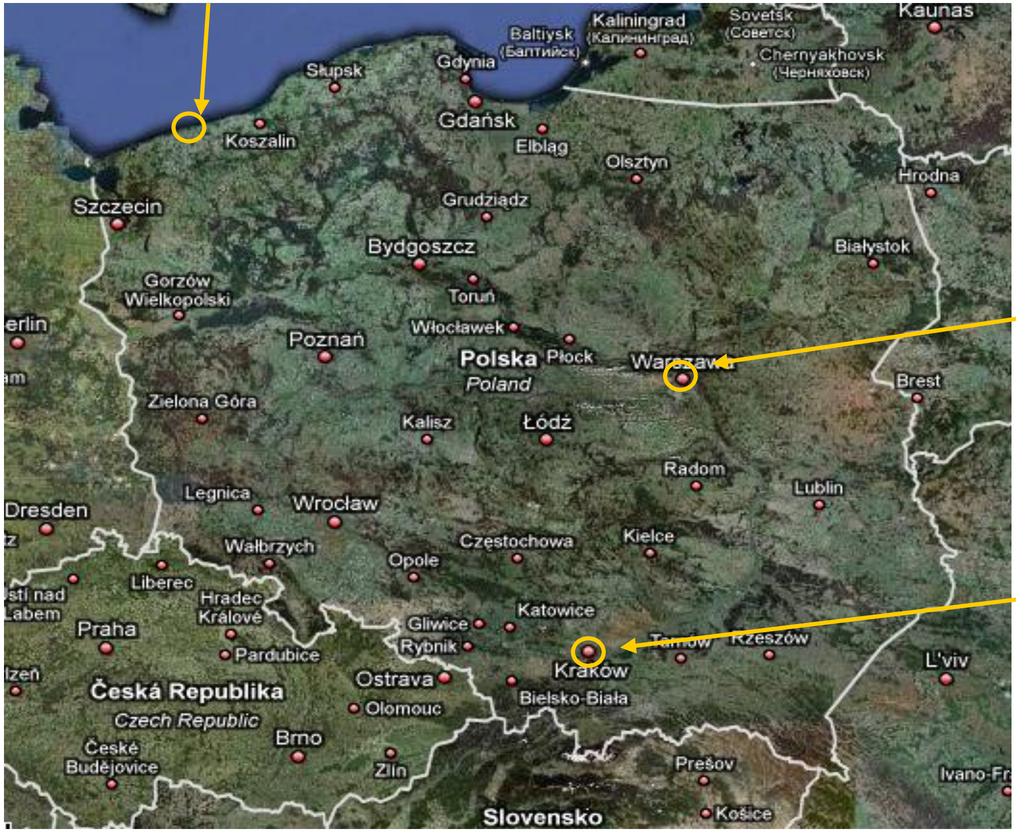
- AAC wall with external stucco and internal plaster;
- Brick wall with external stucco and internal plaster;
- Two levels of internal air humidity
- Considering & neglecting IMTZ in the stucco & plaster
- Climatic data of Warsaw, Cracow & Kolobrzeg

Material hygro-thermal strains

Wall exposed to the climatic conditions of Poland

Climatic data & location

Kolobrzeg: at the seaside of the Baltic Sea



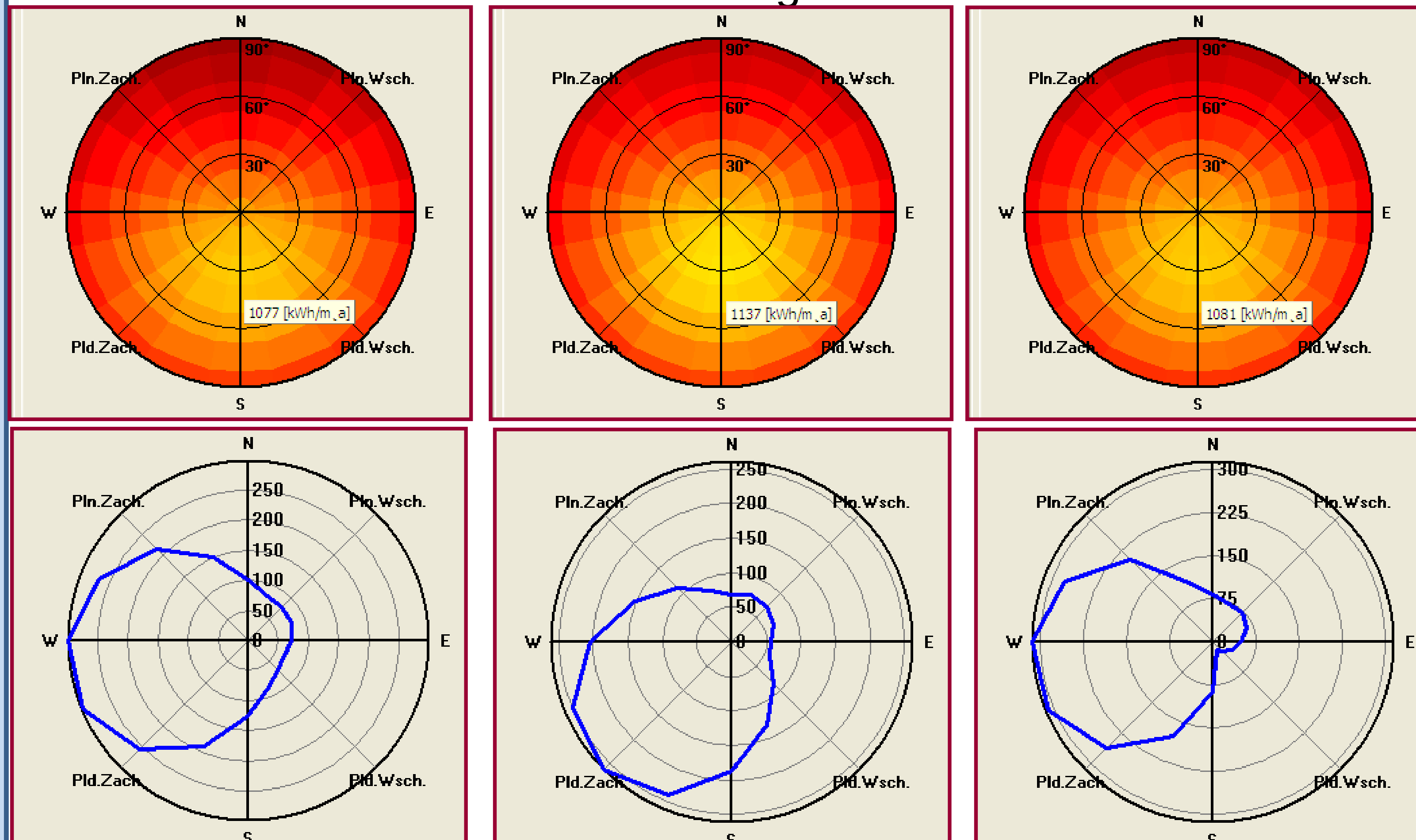
Warsaw: central part of Poland

Cracow: foreland of the Tatra Montains

Material hygro-thermal strains

Wall exposed to the climatic conditions of Poland

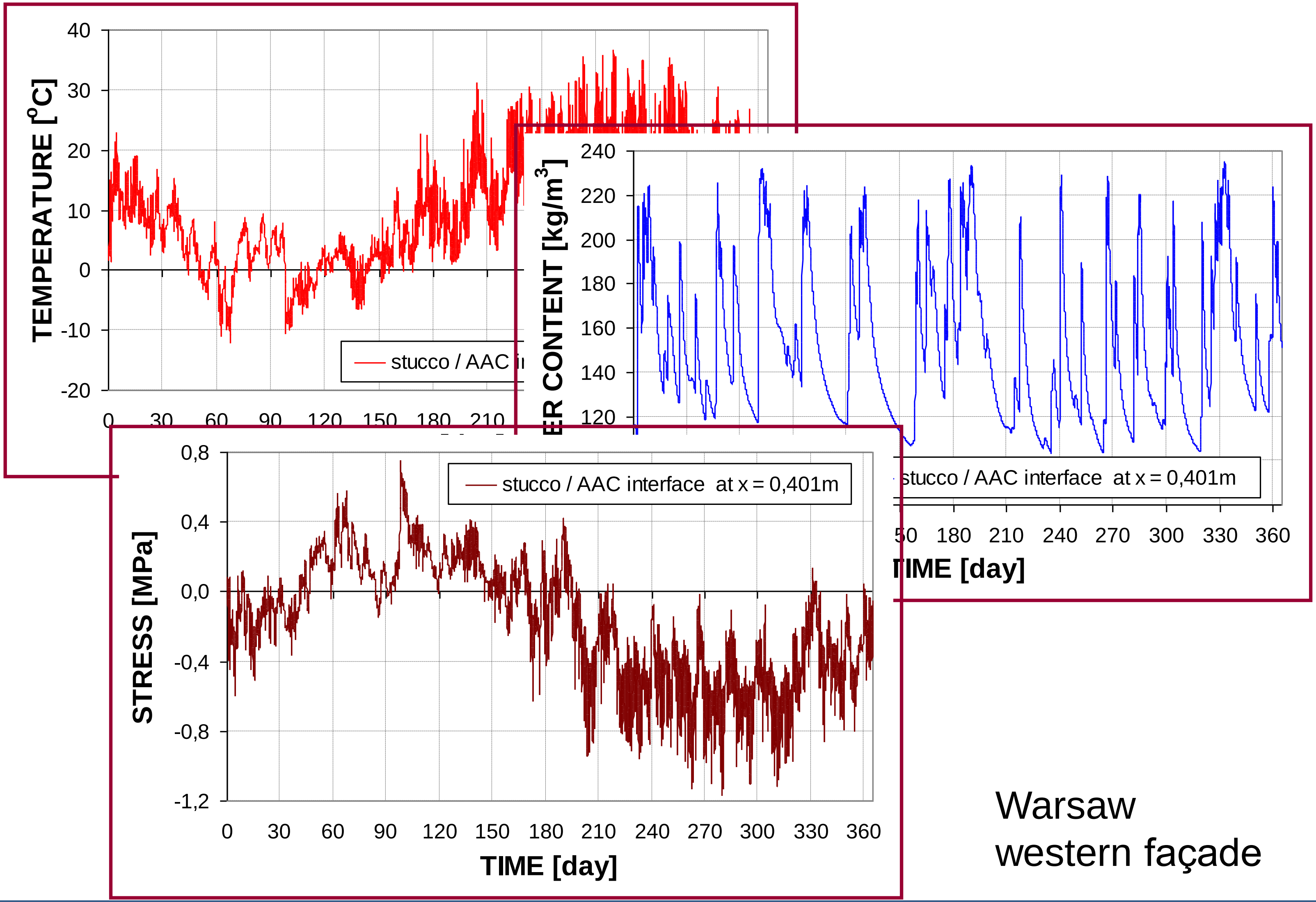
Warsaw | Kolobrzeg | Cracow



Total solar energy [kWh/m²year] and wind driven rain [mm/m²year] (from WUFI)

Material hygro-thermal strains

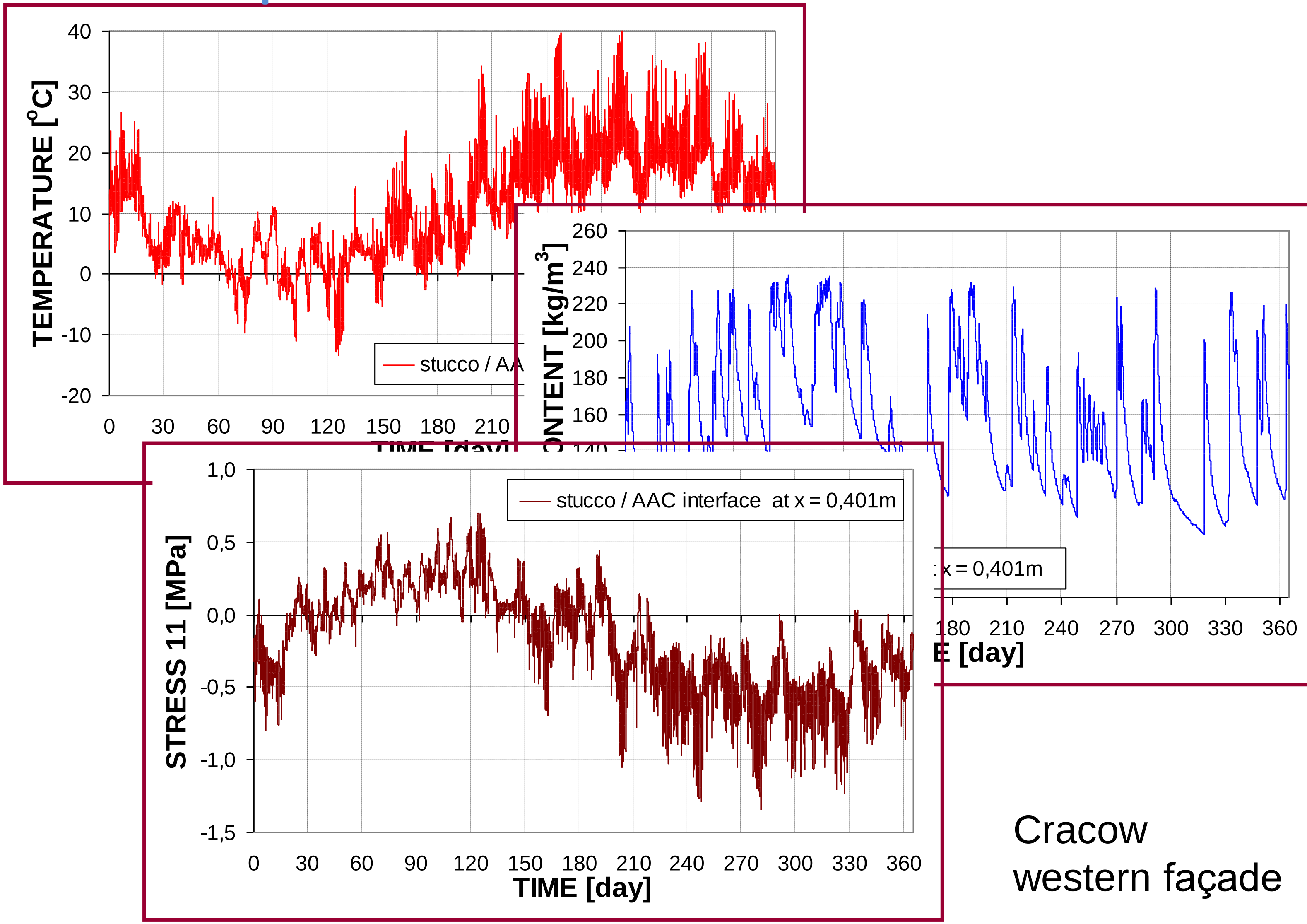
Wall exposed to the climatic conditions of Poland



Warsaw
western façade

Material hygro-thermal strains

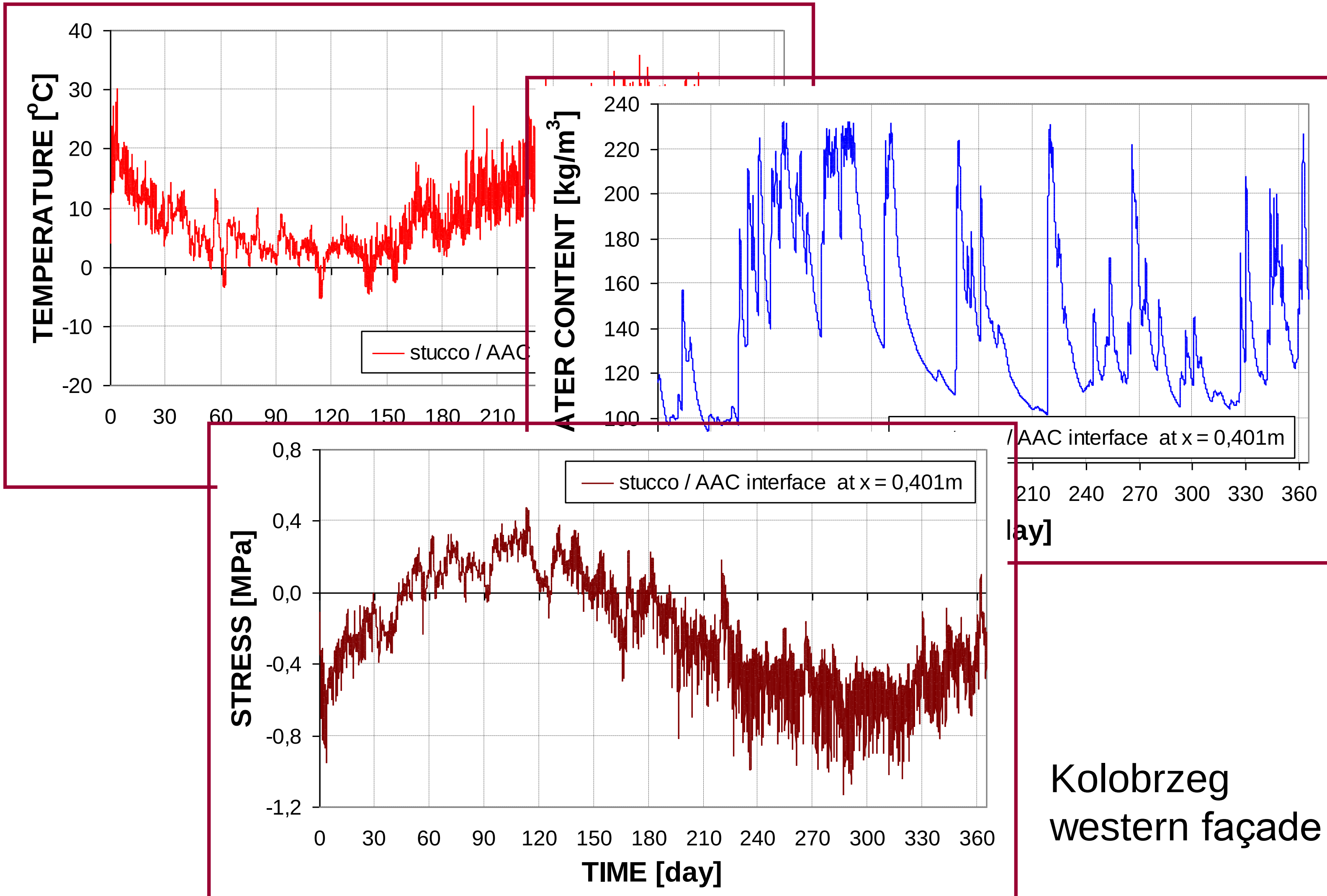
Wall exposed to the climatic conditions of Poland



Cracow
western façade

Material hygro-thermal strains

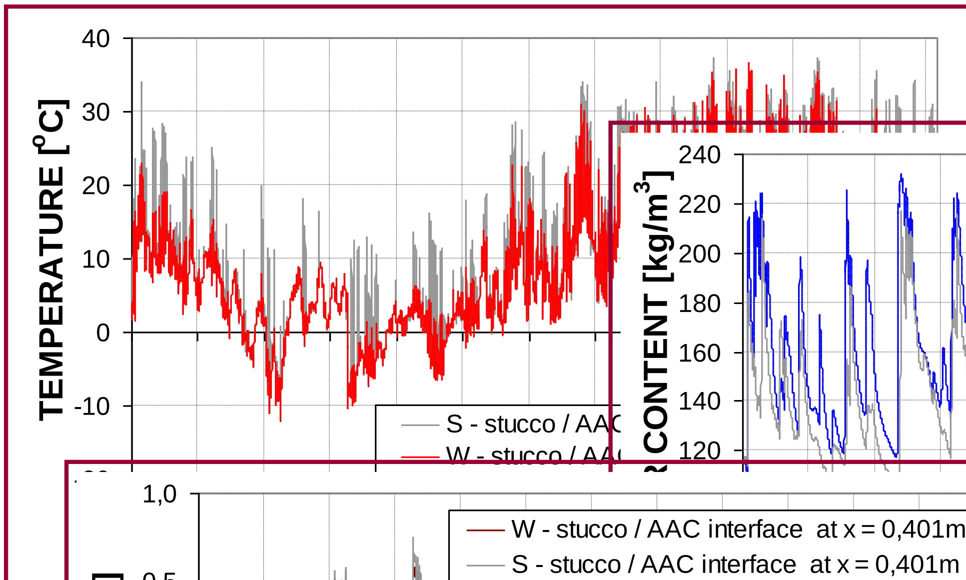
Wall exposed to the climatic conditions of Poland

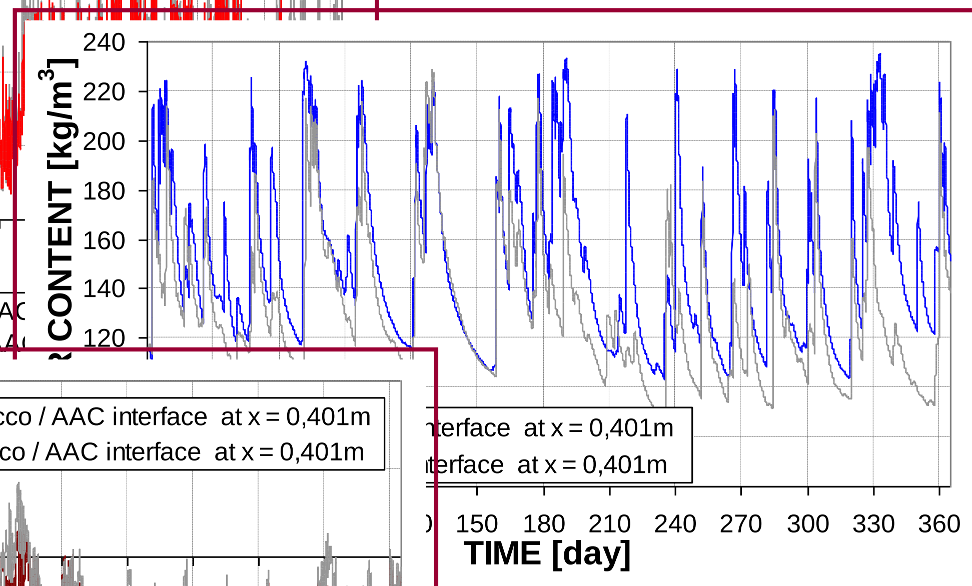


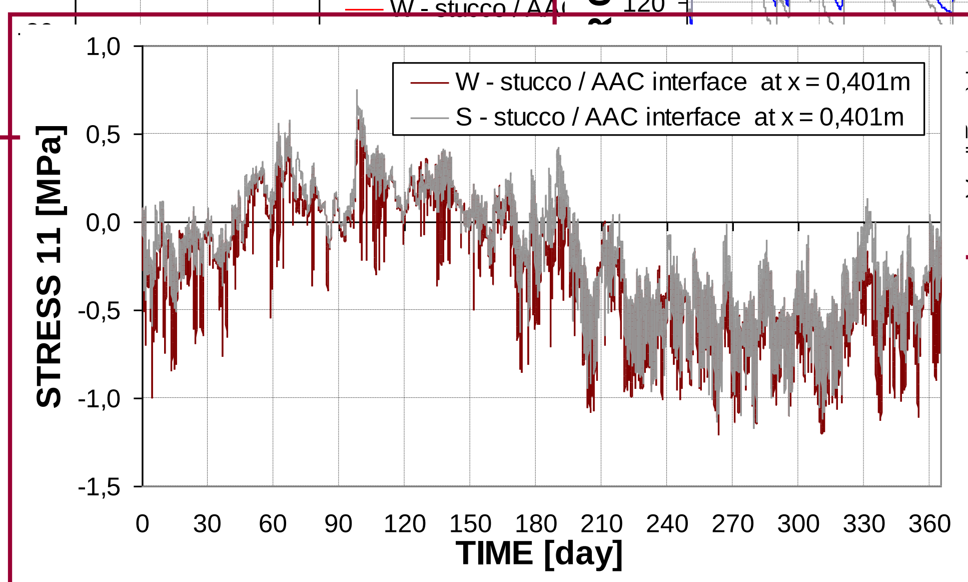
Kolobrzeg
western façade

Material hygro-thermal strains

Wall exposed to the climatic conditions of Poland







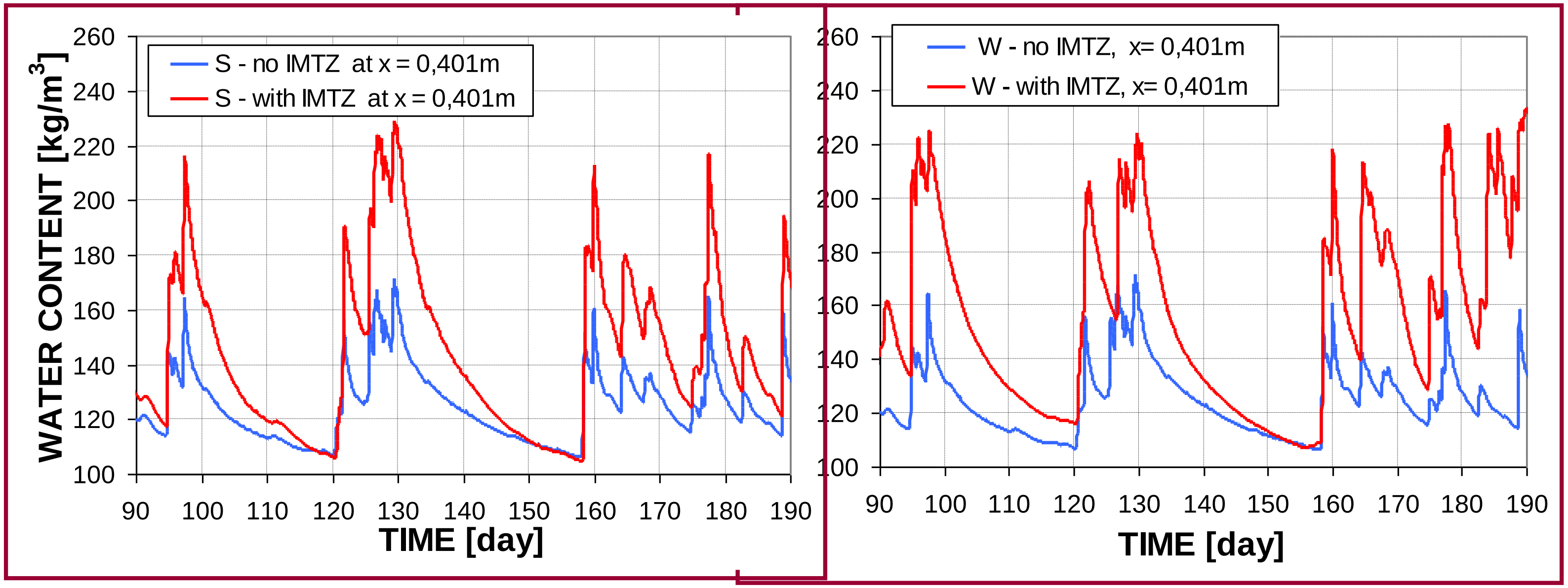
Warsaw
western vs. southern façade

Material hygro-thermal strains

Wall exposed to the climatic conditions of Poland

Warsaw:

- southern vs. western façade of the building
- model considering vs. neglecting IMTZ (on western façade)

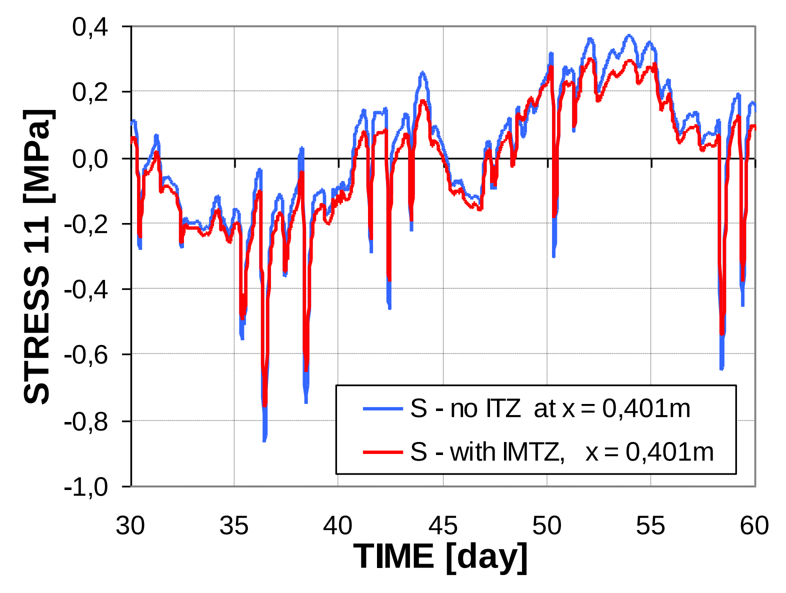


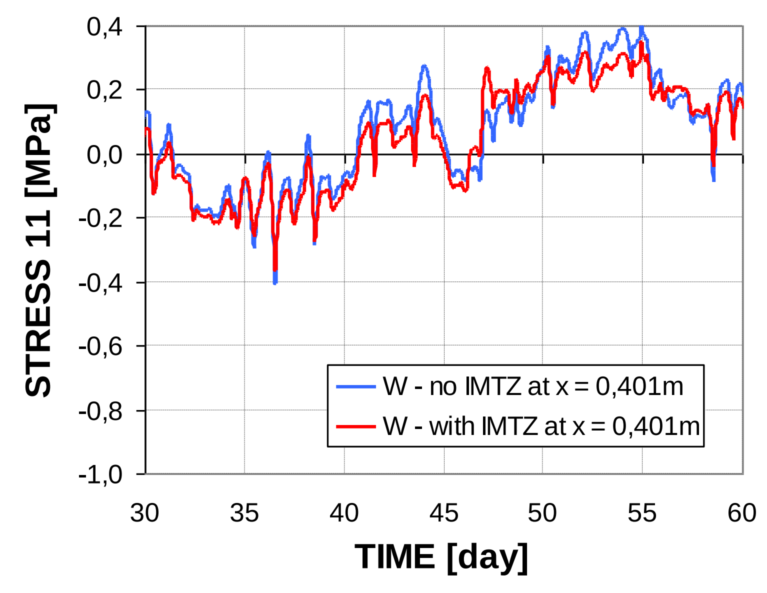
Material hygro-thermal strains

Wall exposed to the climatic conditions of Poland

Warsaw:

- southern vs. western façade of the building
- model considering vs. neglecting IMTZ (on western façade)





Material hygro-thermal strains

Wall exposed to the climatic conditions of Poland

Location	Orientation	σ_{max} [MPa]	σ_{min} [MPa]	N_{fr} [h]
Warsaw	S	0.60	-1.21	0
Warsaw	W	0.76	-1.17	0
Cracow	S	0.65	-1.33	0
Cracow	W	0.70	-1.35	58
Kolobrzeg	S	0,45	-1.18	0
Kolobrzeg	W	0.48	-1.14	0

the highest tensile stresses on the W-façade

the highest tensile stresses on the S-façade

possible frost damage

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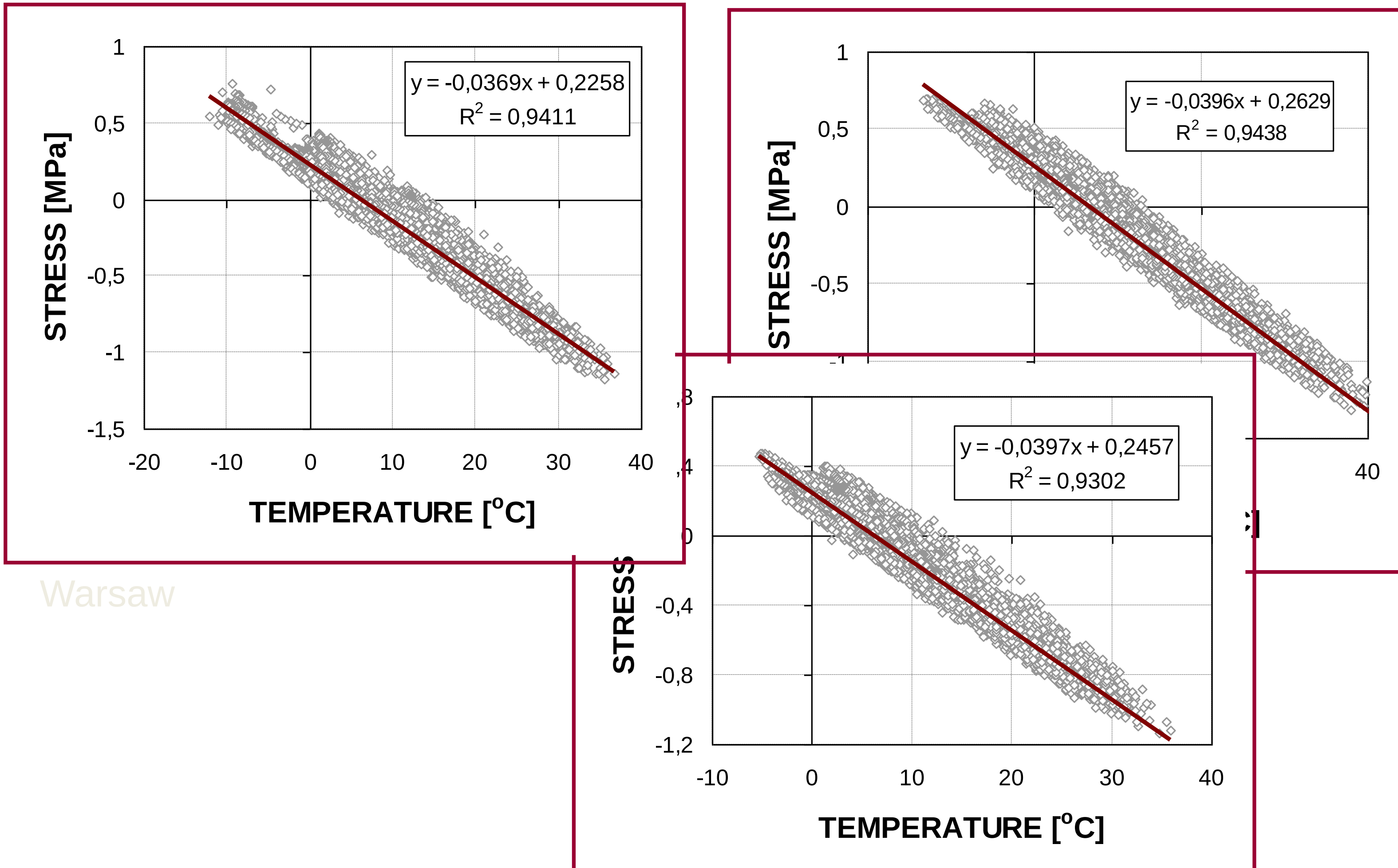
Material hygro-thermal strains

Wall exposed to the climatic conditions of Poland

Correlation of stresses & temperature (western façade):

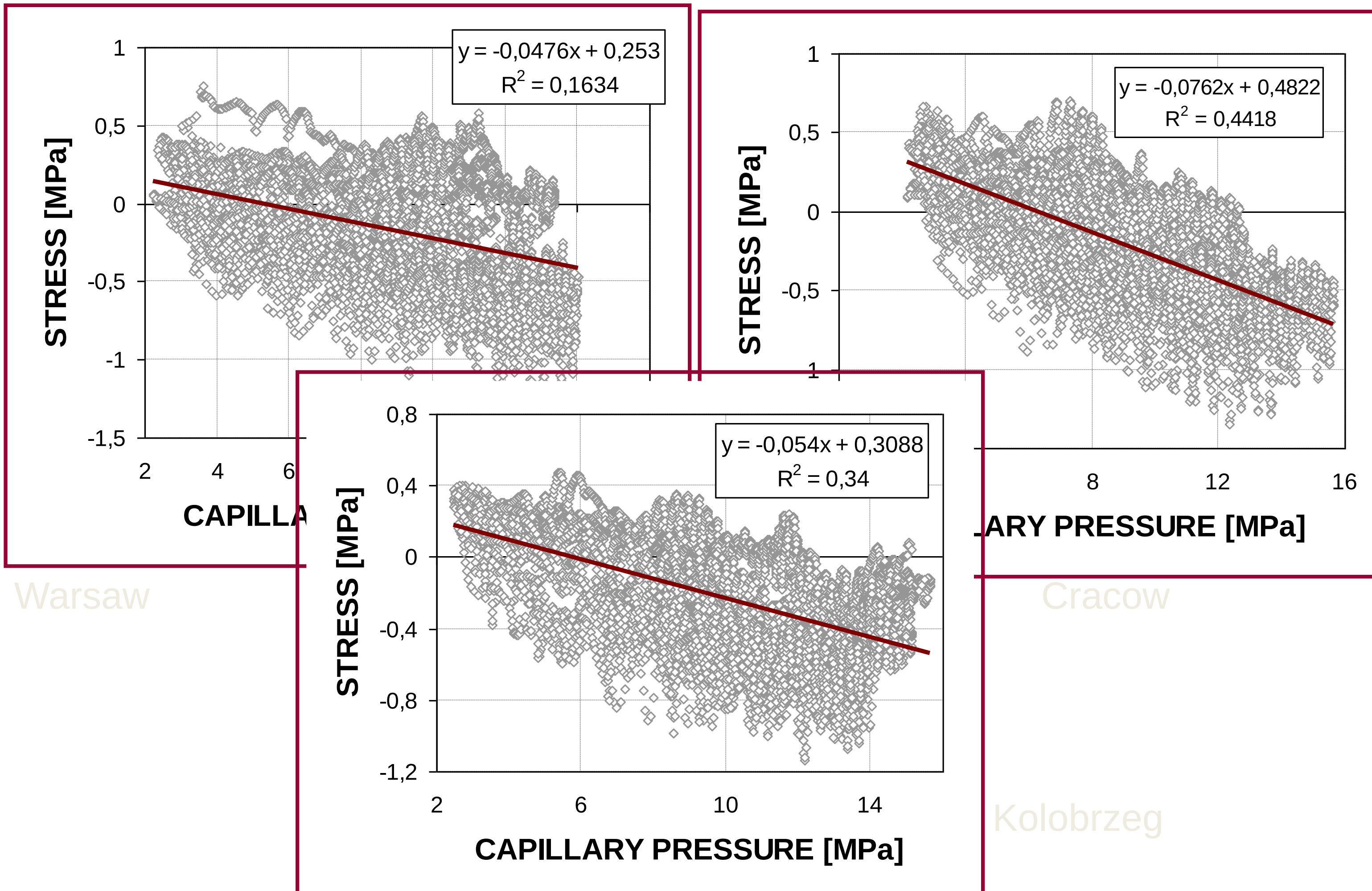


CONTINUING EDUCATION
AIA

Material hygro-thermal strains

Wall exposed to the climatic conditions of Poland

Correlation of stresses & capillary pressures (western façade):



Salt crystallization

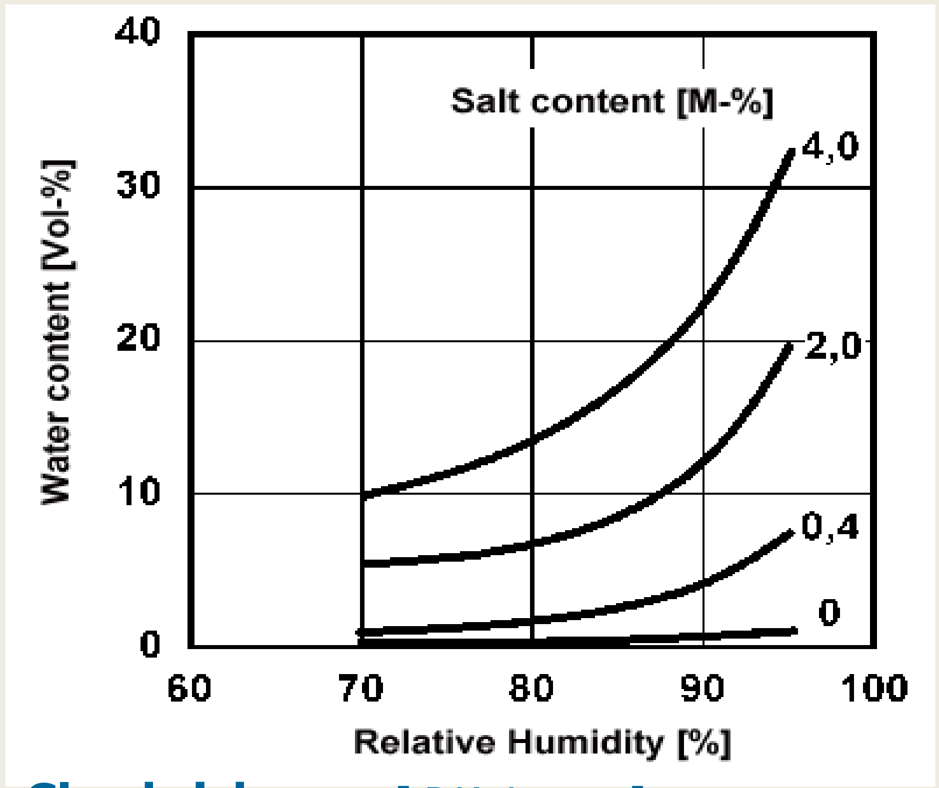
Effect of salt on sorption isotherms

$$r = \frac{2\sigma\cos(\theta)}{p_g - p_{v0} - \frac{RT\rho^w}{M_w}\ln\frac{p_v}{p_{v0}} + \frac{RT\rho^w}{M_w}\ln x_w}$$

Maximum radius
of saturated pores
(Laplace' equation)

alternatively: Raoult's law

$$\varphi = x_w \varphi_K$$

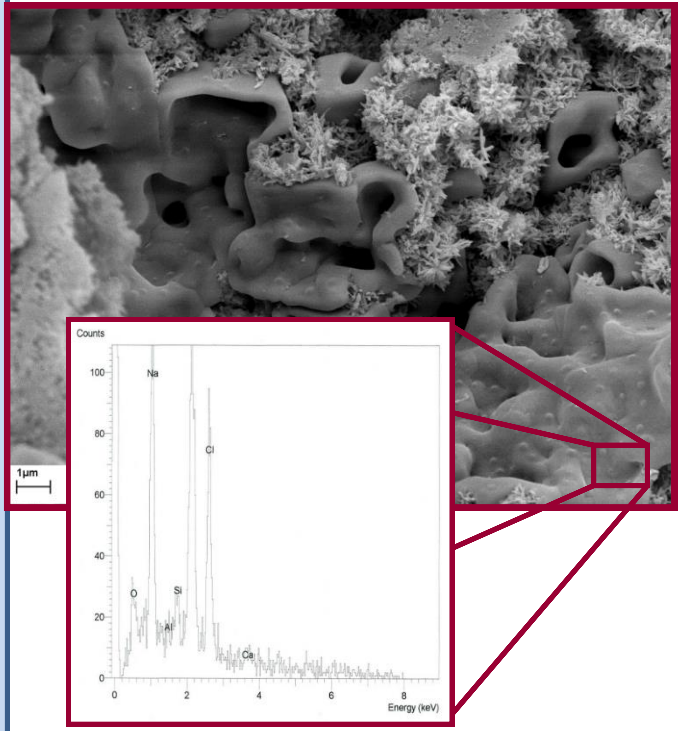


Clay brick [P.K. Larsen]

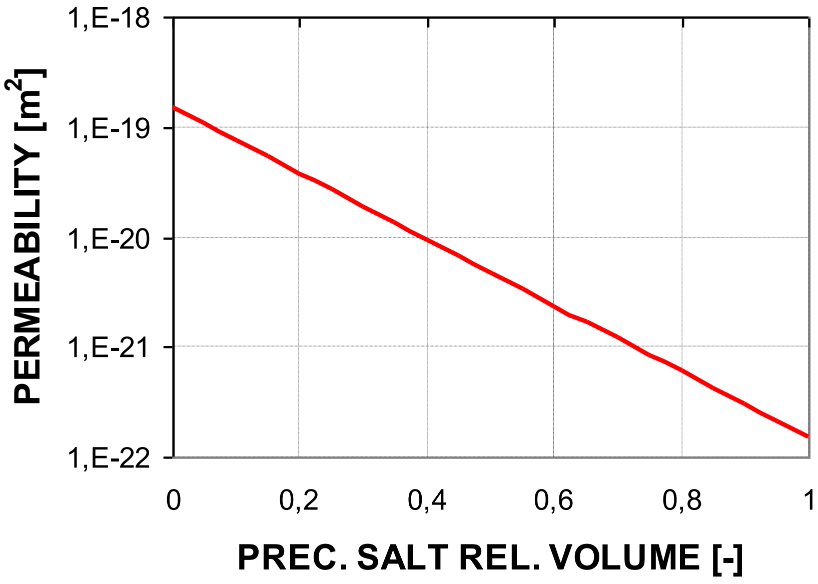
Salt crystallization

Effect of salt on permeability

SEM photographs and EDS analysis



Pore size distribution curves



Salt crystallization

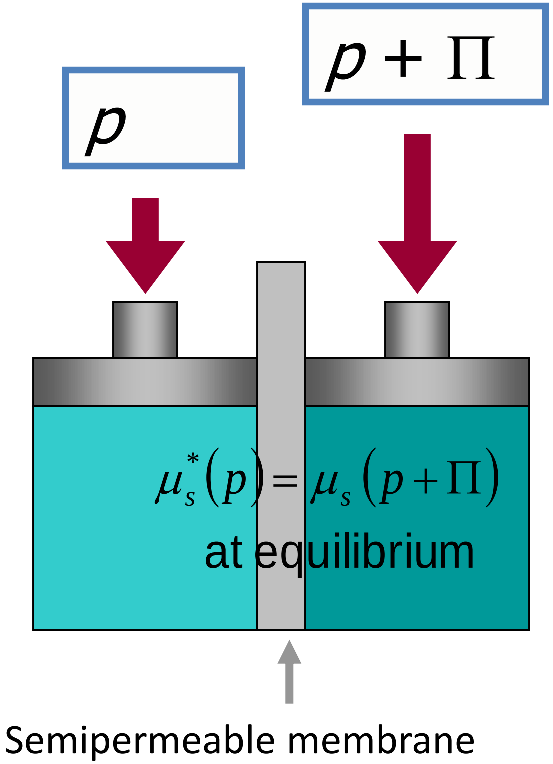
Osmotic pressure & osmotic flow

<u>The Van't Hoff equation:</u>

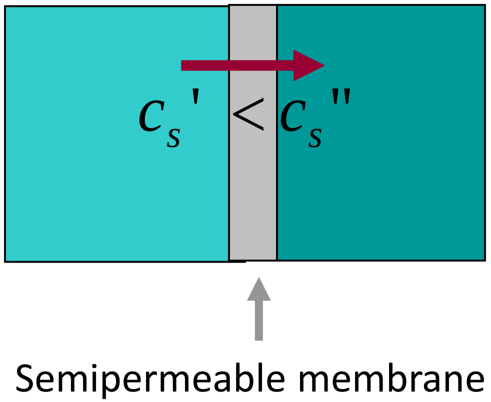
(for dilute solutions)

$$\Pi = c_s RT$$

Π – osmotic pressure
c_s - salt molar concentration



Osmotic flow of solvent



Salt crystallization

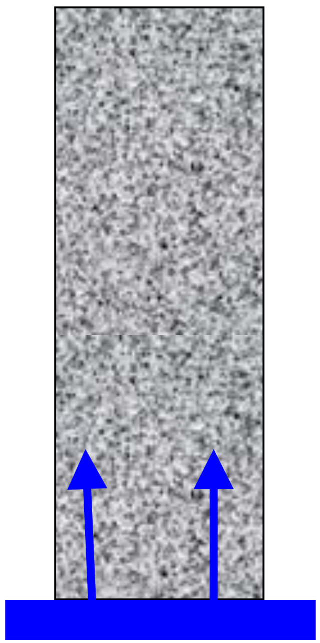
Effect of material microstructure

(wide pores = no osmosis)

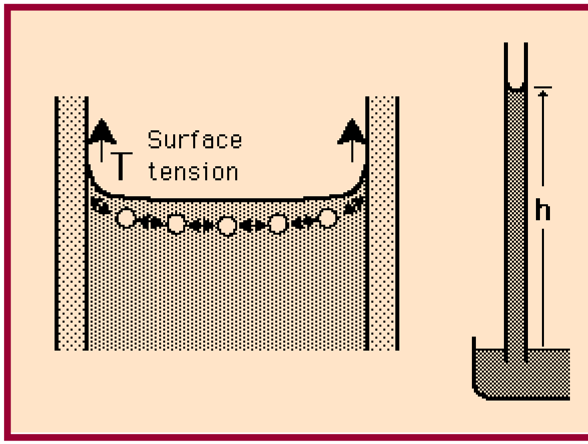
Capillary suction experiment:

[Rucker, Krus, Holm - 2003]

Sandstone sample



Capillary forces



Initial conditions:

- $S_w = 0{,}068$;
- $T = 23\ ^{o}C$;

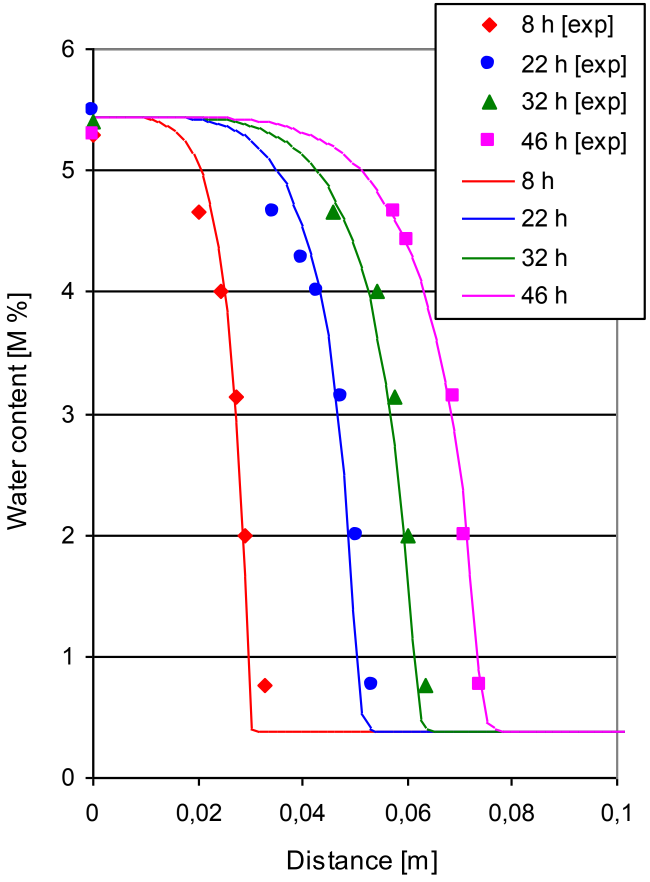
ω = 0,26 [kg/kg].

Salt crystallization

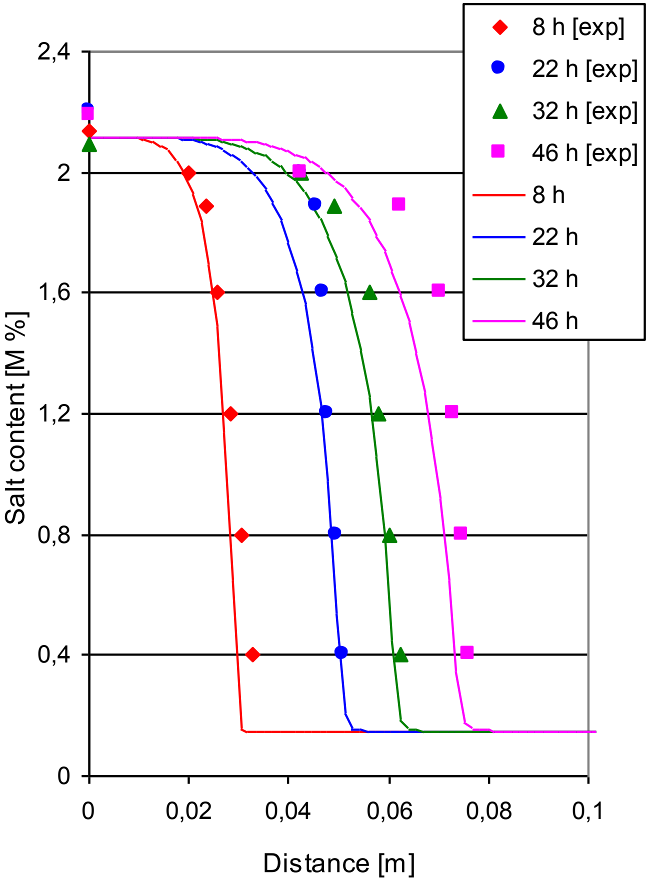
Effect of material microstructure

(wide pores = no osmosis)

Water content



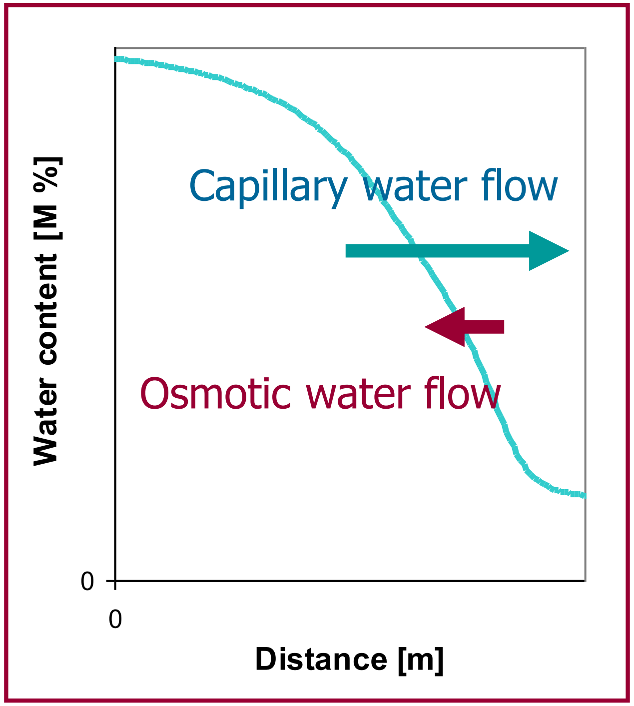
Salt content

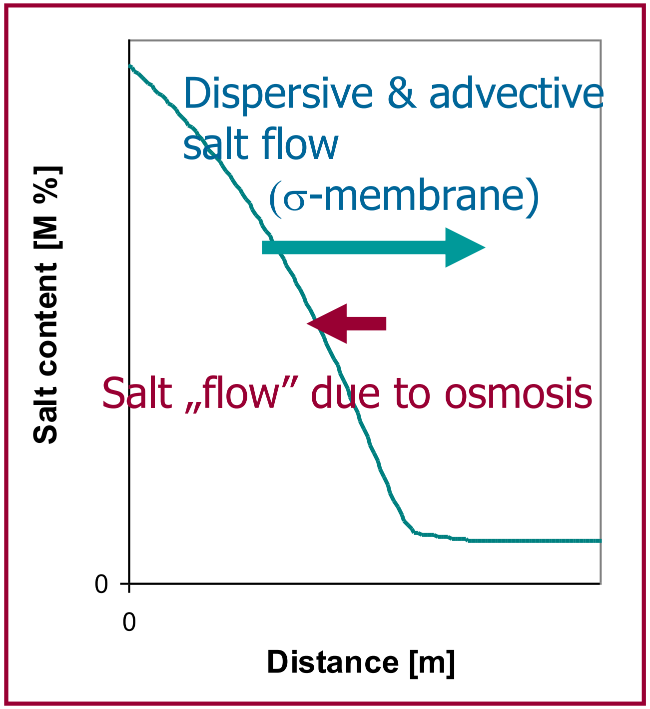


Salt crystallization

Effect of material microstructure

(narrow pores = osmosis)





material with very fine pores (e.g. gel pores) = <u>semipermeable membrane</u>

(lower permeability for the solvated ion groups than for water due to the „double layer" effect)

Salt crystallization

Effect of material microstructure

(narrow pores = osmosis)

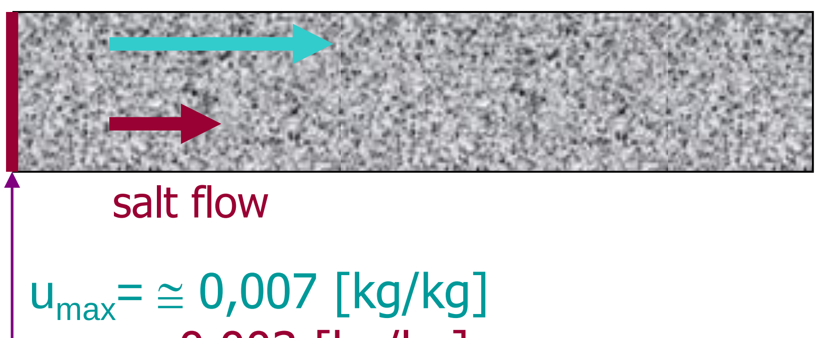
<u>Capillary suction experiment:</u>

[Cerny, Pavlik, Rovniakova - 2004]

<u>Cement mortar sample</u>

(CEM I 42.5 R Lafarge)

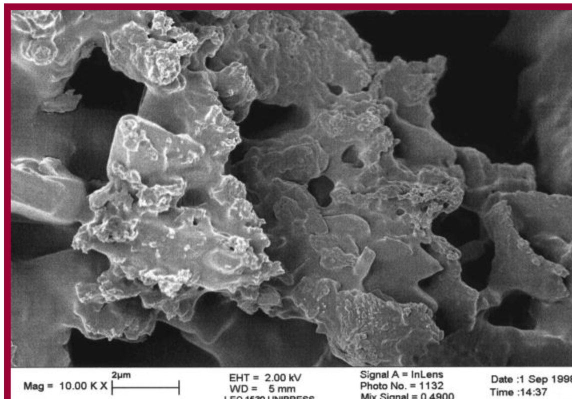
water flow

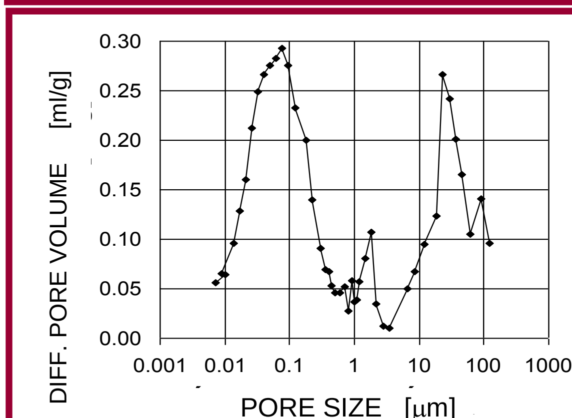


salt flow

$u_{max} = \cong 0{,}007$ [kg/kg]

$\omega_{max} \cong 0{,}003$ [kg/kg]





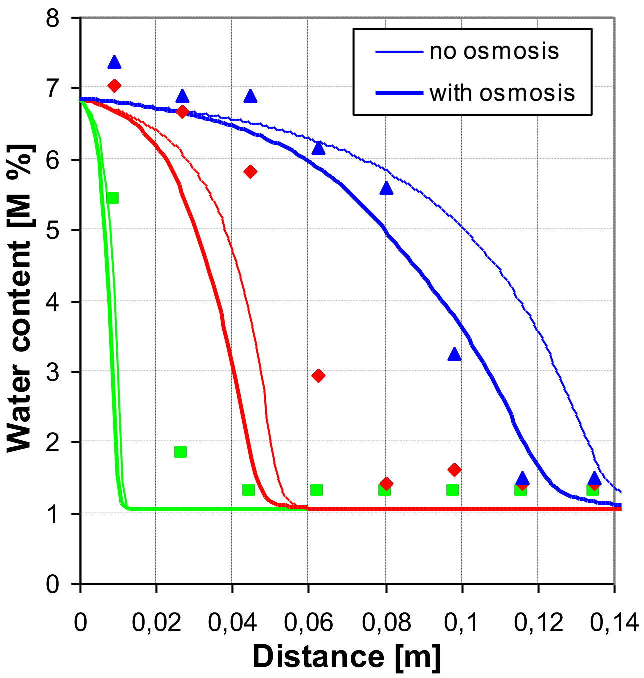
Salt crystallization

Effect of material microstructure

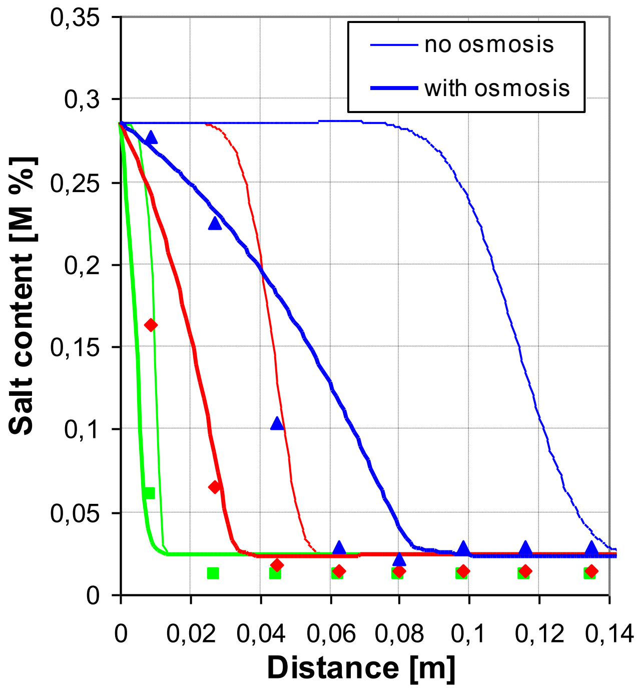
(narrow pores = osmosis)

The results with and without osmosis

Water content



Salt content

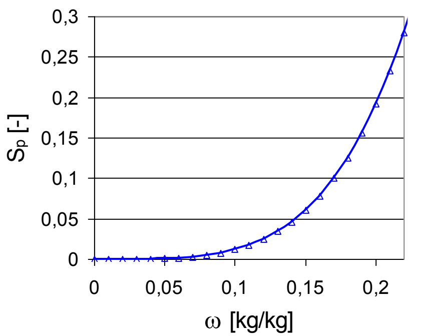


Reflection coefficients σ=0.4 (osmosis) and σ=0.0 (no osmosis.

Salt crystallization

Effect of salt presence on wall drying

Initial conditions:



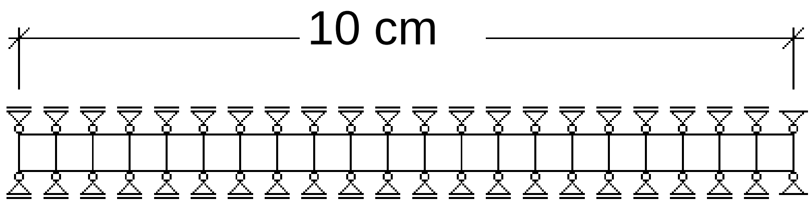
Considered cases:

- no salt effects (pure water);
- effect of prec. salt on permeability (Sp);
- effect of prec. salt on permeability and sorption isotherms (Sp + Sw)

2 cases of the salt (NaCl) binding isotherms of the Freundlich type: $S_p = A_4\, \omega^4$ and $S_p = A_8\, \omega^8$

Boundary conditions:

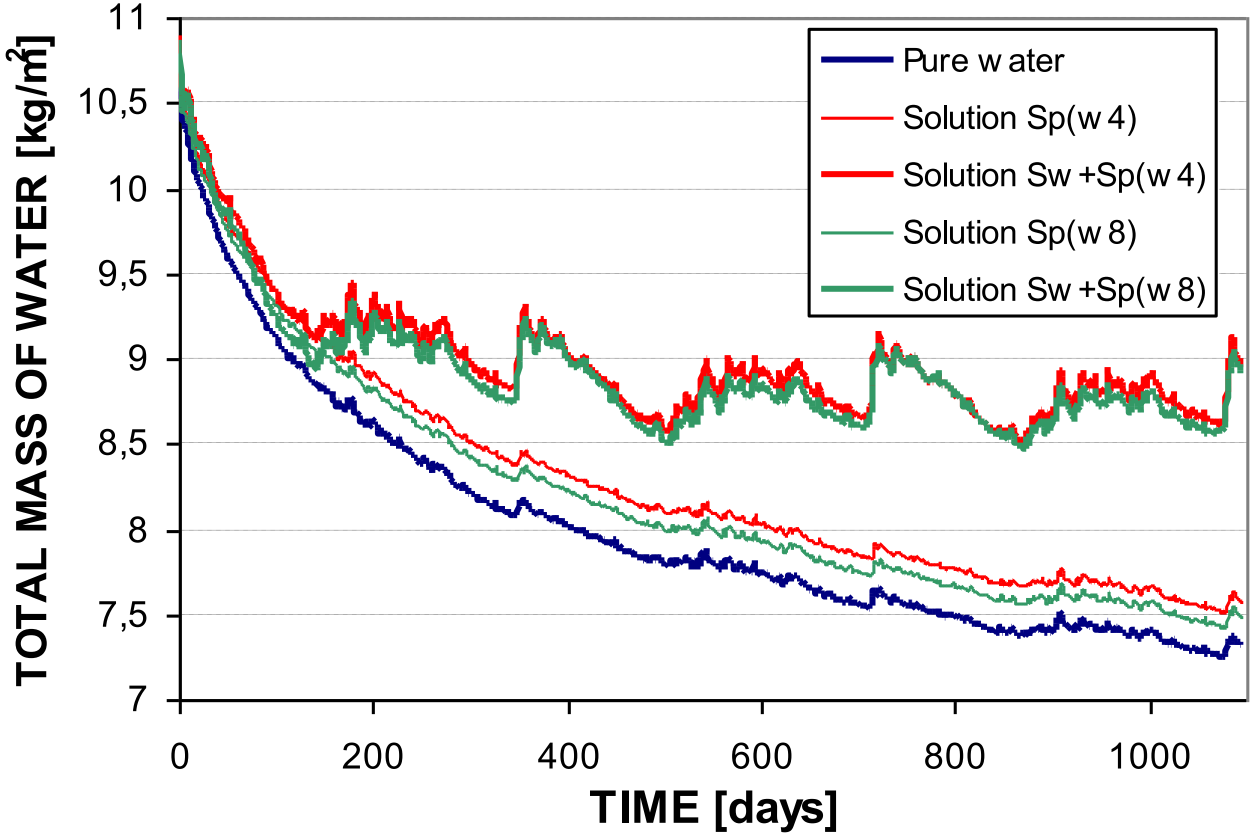
β_i= 0,008 m/s
h_i= 8 W/(m²K)
T_i= 20°C
RH_i= 50%



β_e= 0,023 m/s
h_e= 23 W/(m²K)
T_e= TMY (Warsaw)
RH_e= TMY (Warsaw)

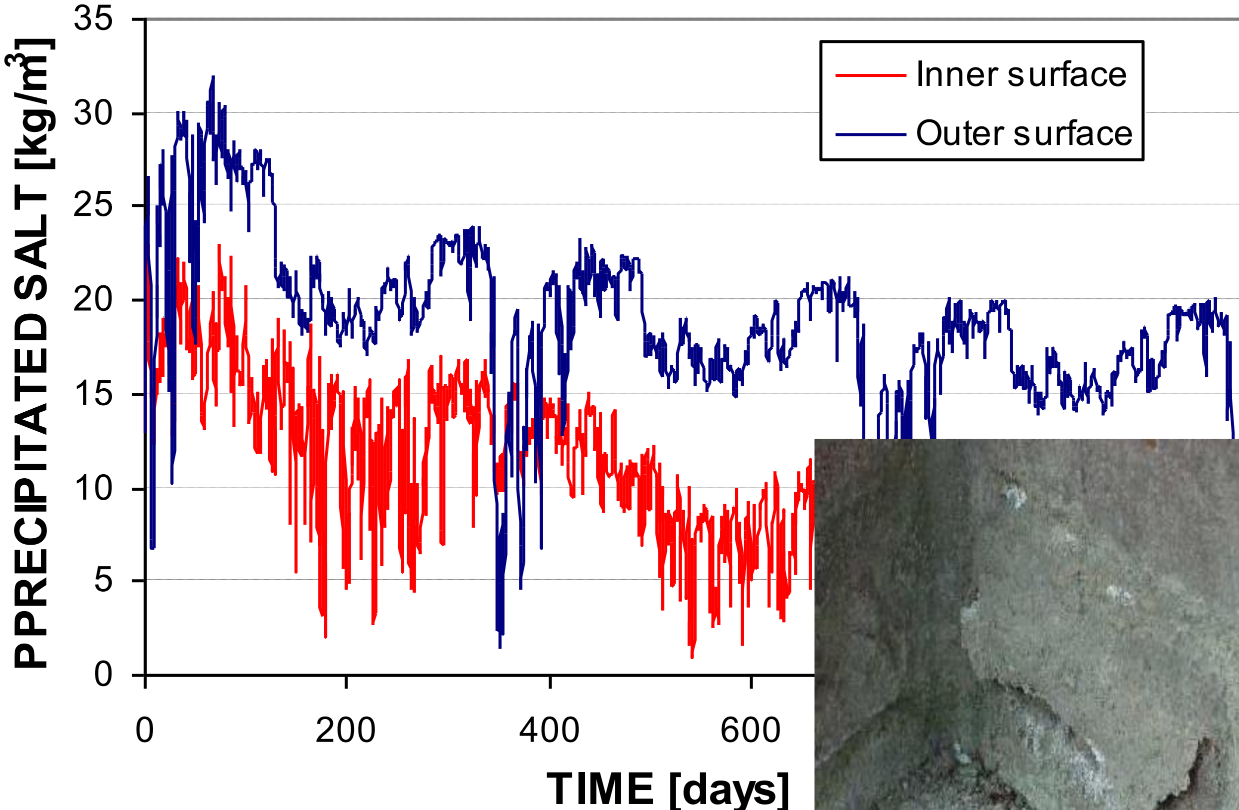
Salt crystallization

Effect of salt presence on wall drying



Salt crystallization

Effect of salt presence on wall drying



Salt crystallization

Kinetics & crystallization pressure

Rate type model

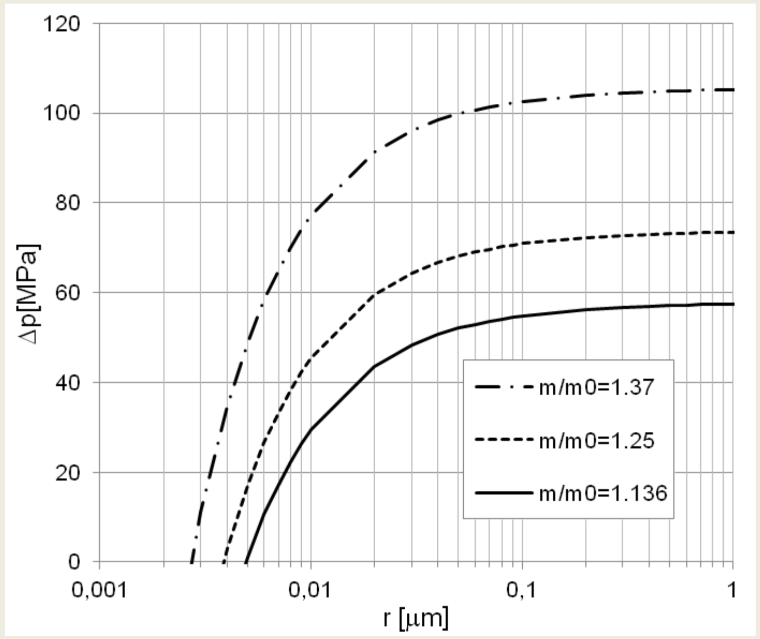
$$\frac{dS_p}{dt} = \begin{cases} S_w K(\omega - A'\omega_{\max})^p, & \omega \geq \omega_{\max} \\ -S_w K\,|\,\omega - A'\omega_{\max}\,|^p, & \omega < \omega_{\max} \wedge S_p > 0 \end{cases}$$

-Primary crystallization $A' \geq 1$
- Further crystallization $A' = 1$
  (salt present in the pores)

where
A' – the supersaturation parameter;
ω_{max} – maximum salt concentr. at temp. T;
p – process order ;
a - equilibrium activity of a salt crystal;
γ_{cl} - mean surface free energy of the crystal-liquid interface;
m/m_0 - relative molality

Crystalization pressure

$$\Delta p = \frac{RT}{V_m} \ln\left(\frac{a}{a_\infty}\right) - \bar{\gamma}_{cl} \frac{dA}{dV}$$



Salt crystallization

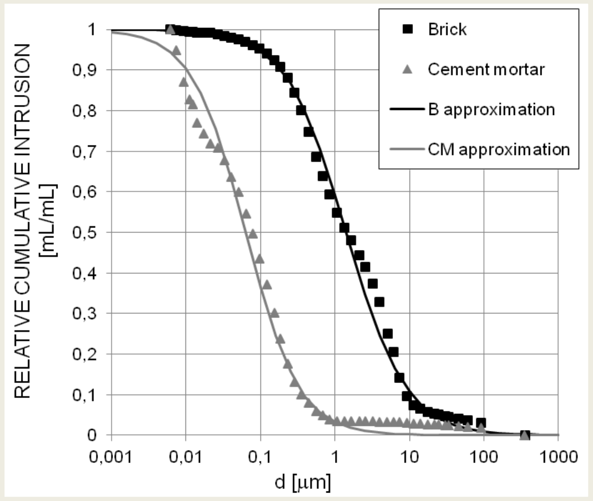
Effect of material microstructure

Initial conditions:

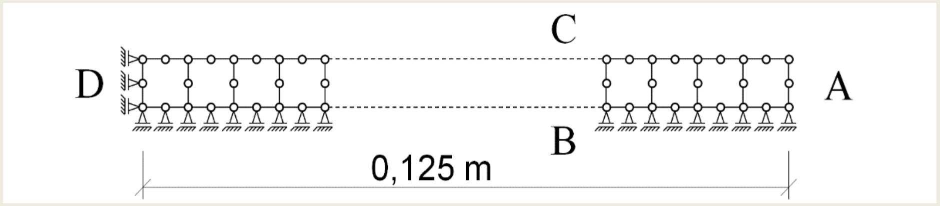
- RH = 0,99;
- T = 20 °C;
- w = 0,15 [kg/kg].

Considered cases:

- brick wall
- concrete wall



Boundary conditions:



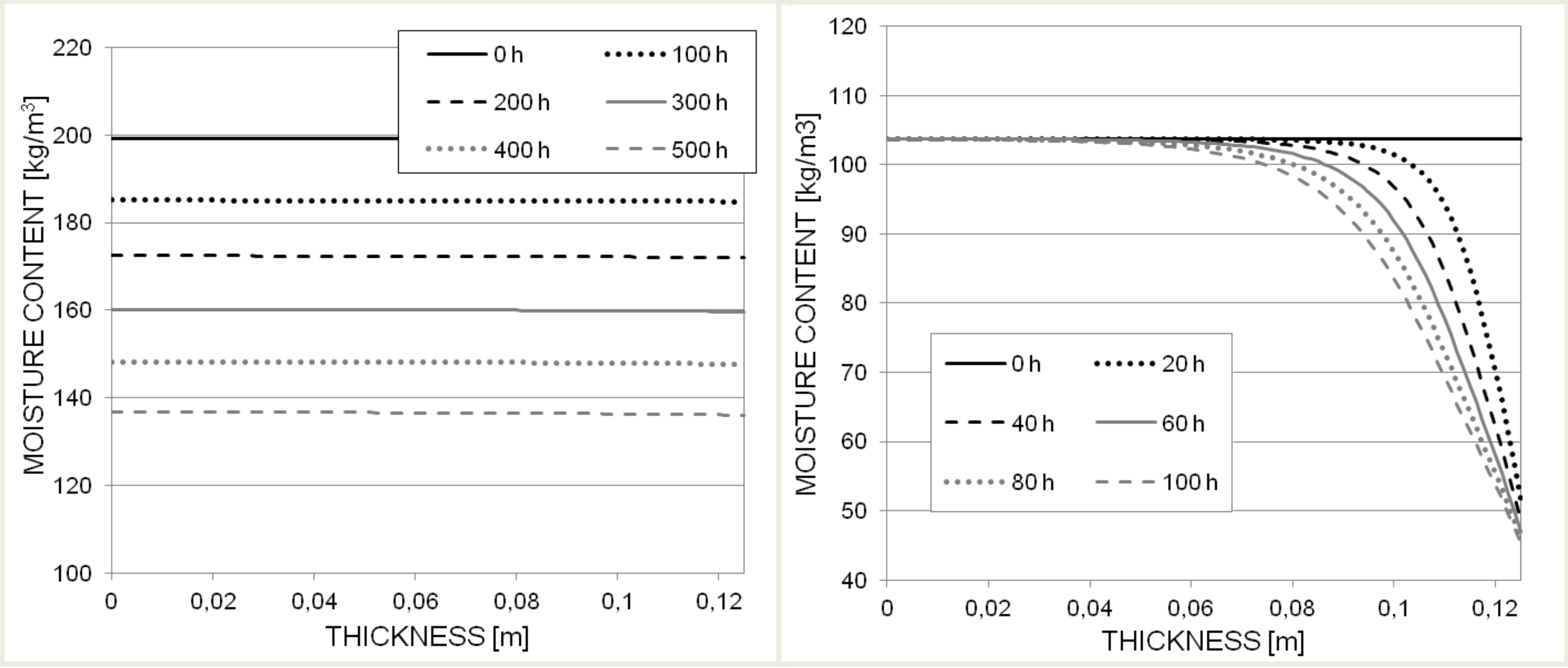
½ of the wall = symmetry

β_c= 0,008 m/s
h_c= 8 W/(m^2K)
T= 20°C
RH= 60% for concrete wall
RH= 85% for brick wall

Salt crystallization

Effect of material microstructure

<u>Moisture content</u>

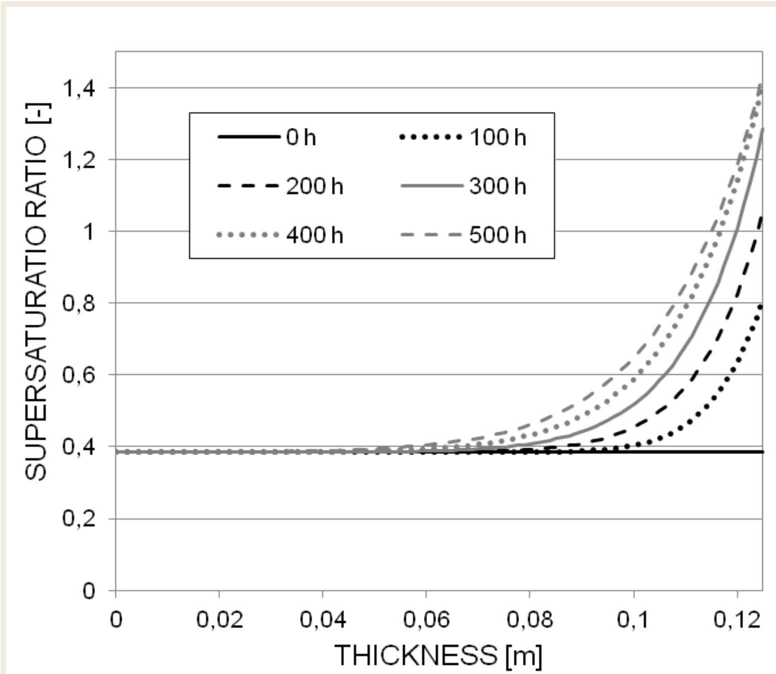


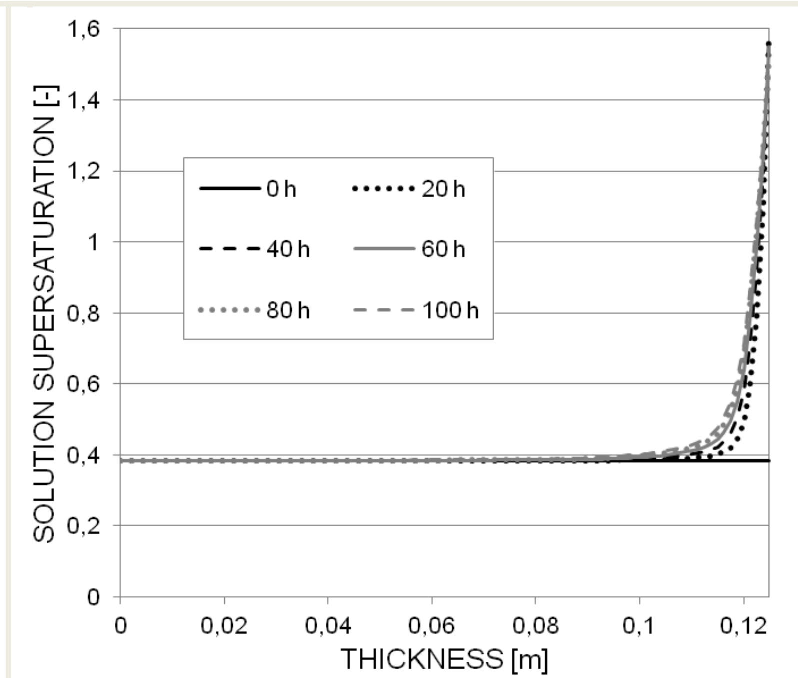
Brick wall vs. Concrete wall

Salt crystallization

Effect of material microstructure

Salt supersaturation degree



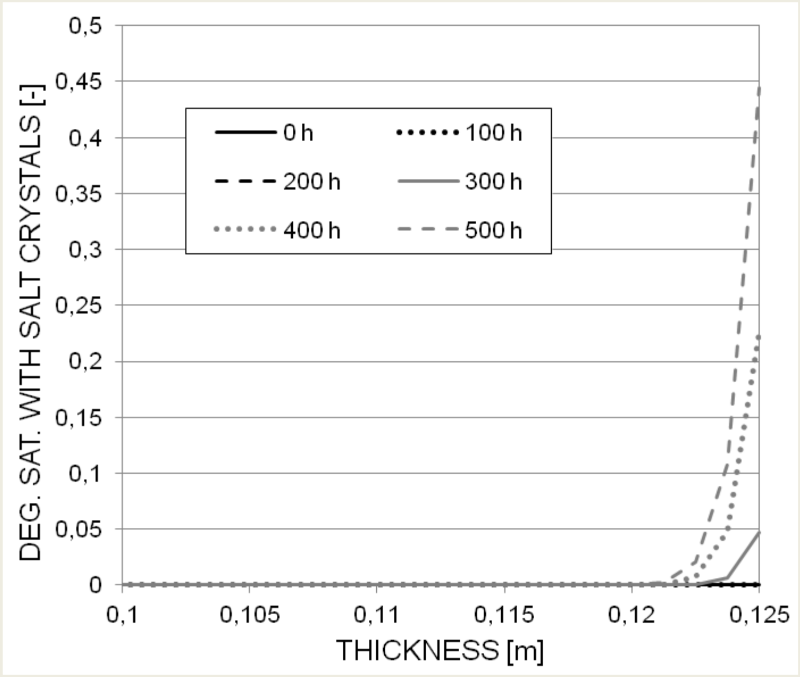


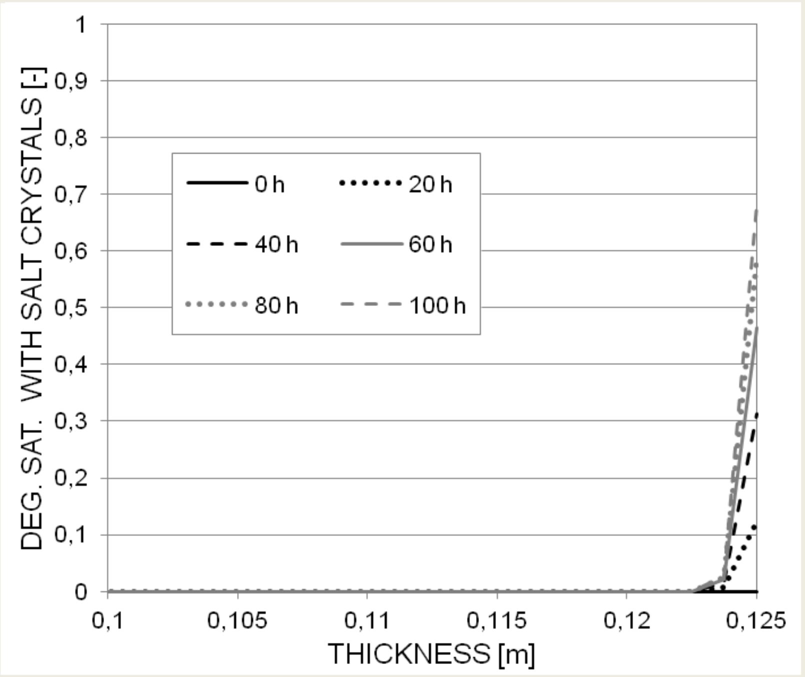
Brick wall vs. Concrete wall

Salt crystallization

Effect of material microstructure

Salt content (degree of saturation with salt)



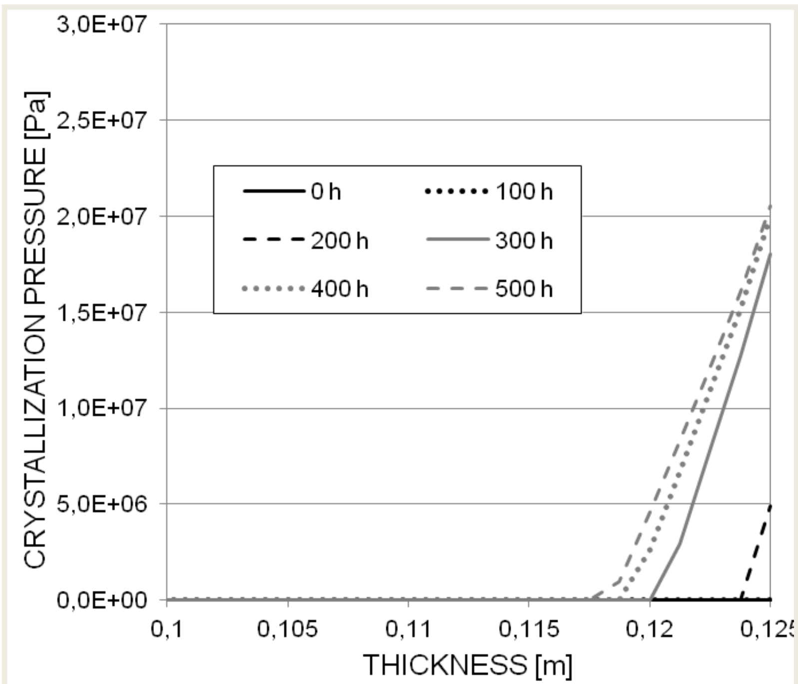


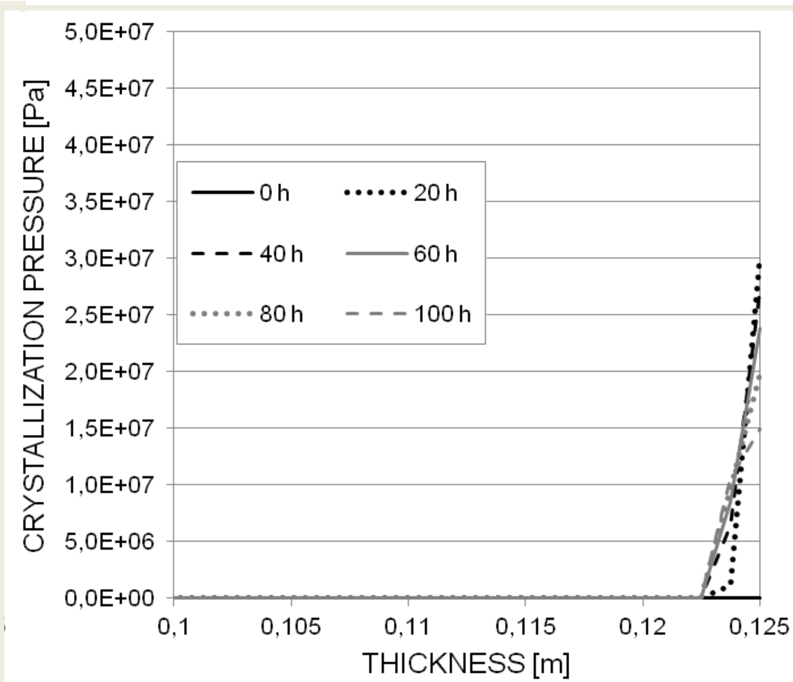
Brick wall vs. Concrete wall

Salt crystallization

Effect of material microstructure

<u>Salt crystallization pressure)</u>

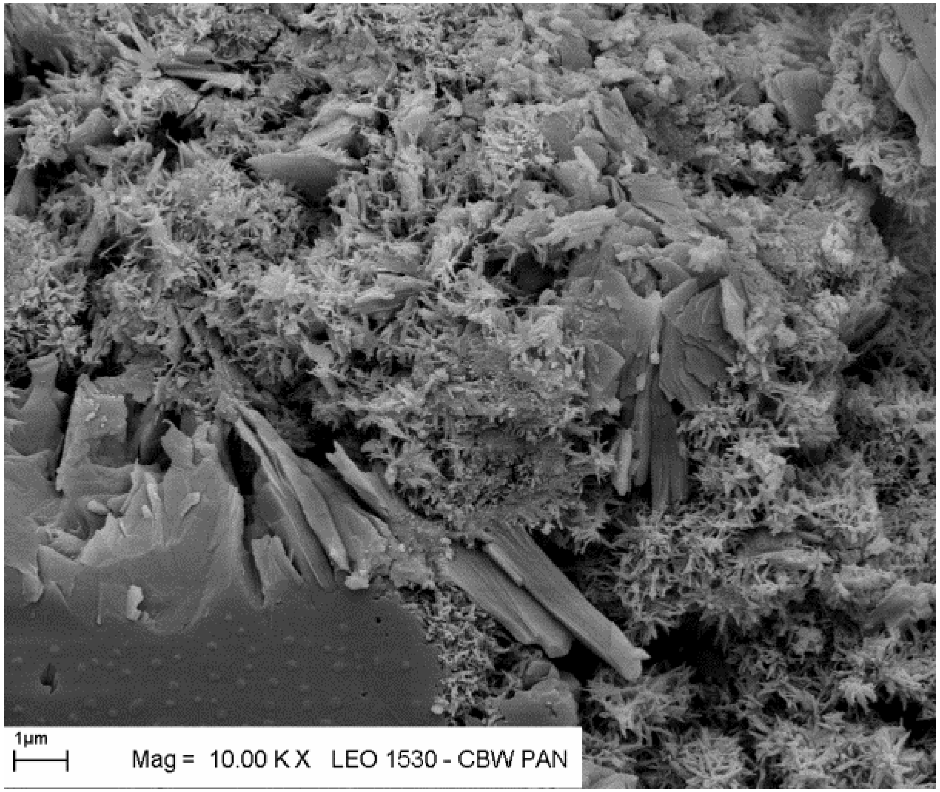


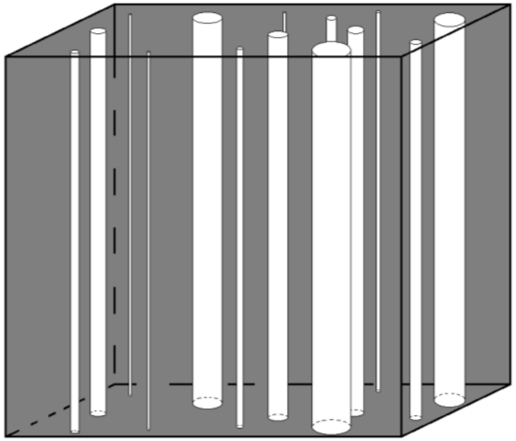


Brick wall vs. Concrete wall

Material deterioration

Mercury Intrusion Porosimetry tests



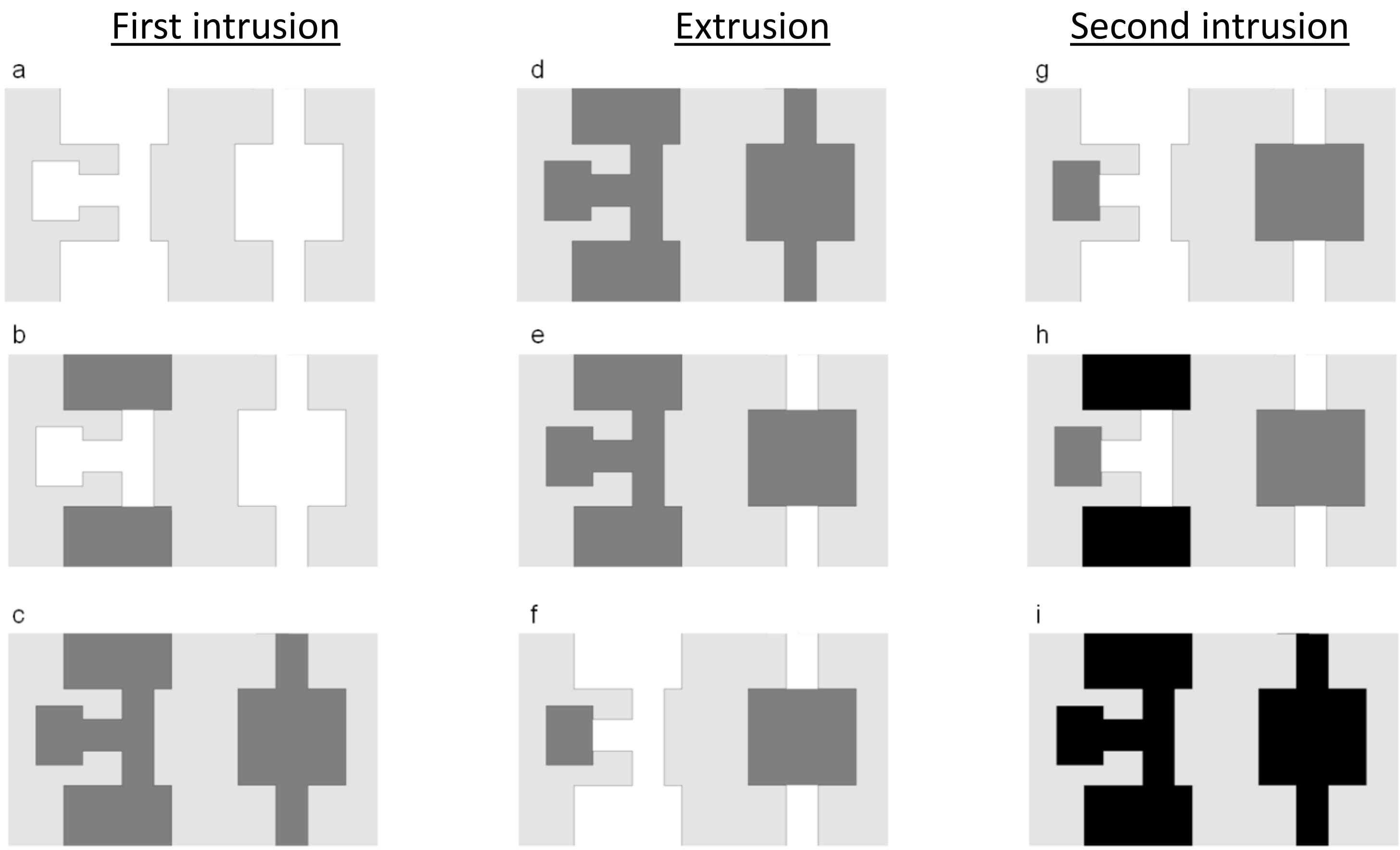


Washburn equation:

$$d = -\frac{4\gamma \cos\theta}{P}$$

Material deterioration

Two-cycle MIP tests

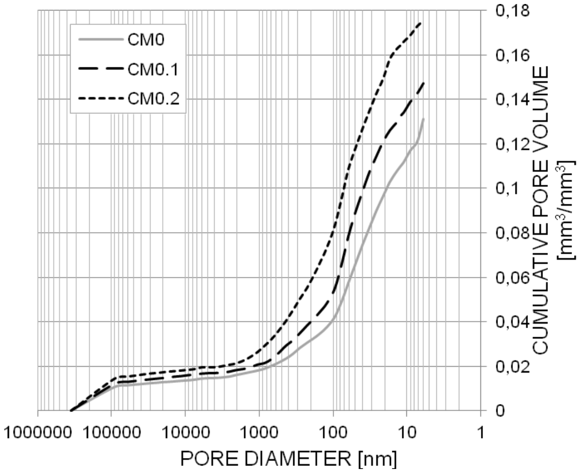


Material deterioration

Two-cycle MIP tests

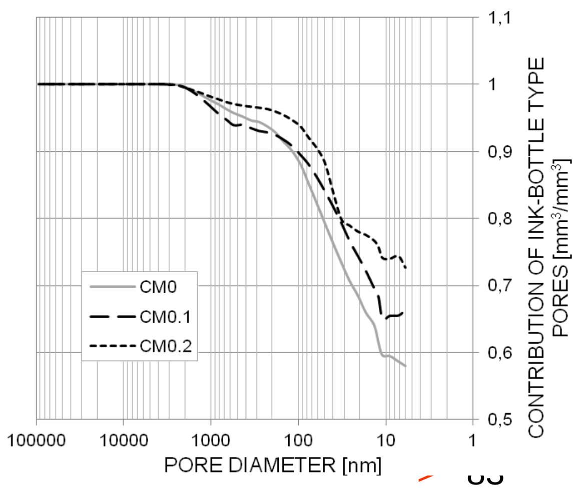
Cement mortar composition

Symbol	CM0	CM0.1	CM0.2
CEM I 32.5 [g]	450	450	450
Sand [g]	1350	1350	1350
Water [g]	203	203	203
AEA [g]	0	0,45	0,9



Contribution of ink-bottle type pores

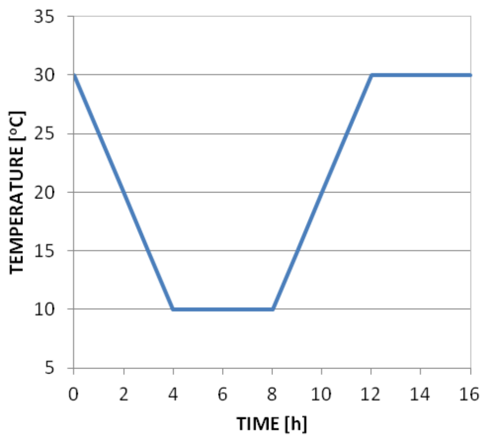
$$C_{ink-bottle}(r \geq r_0) = 1 - \frac{V_{por}^{2.int}(r_0)}{V_{por}^{1.int}(r_0)}$$



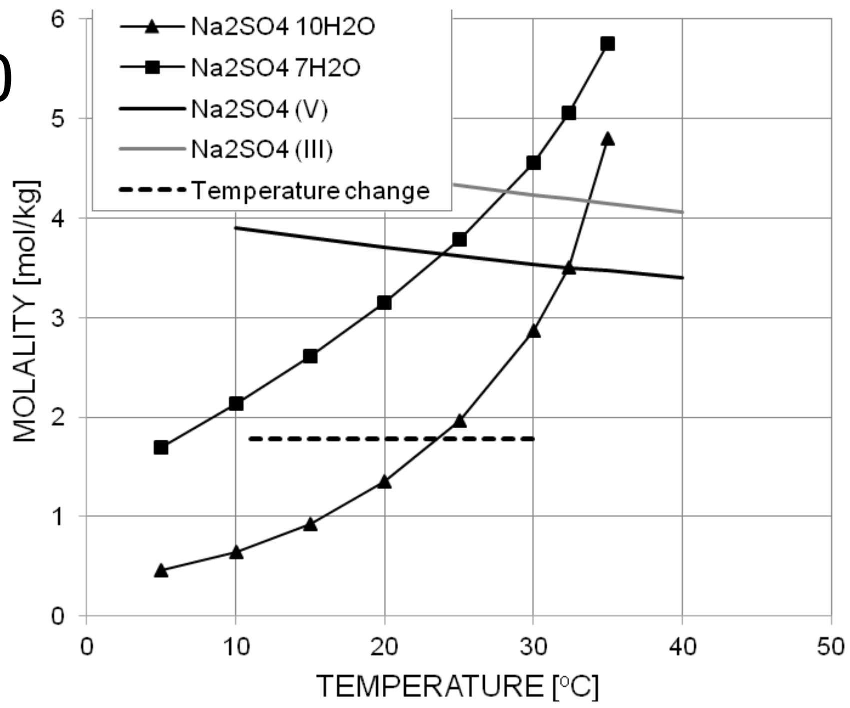
Material deterioration

Sodium Sulphate crystallization

Temperature cycles



x10



Samples initially saturated with 25% Na_2SO_4 water solution

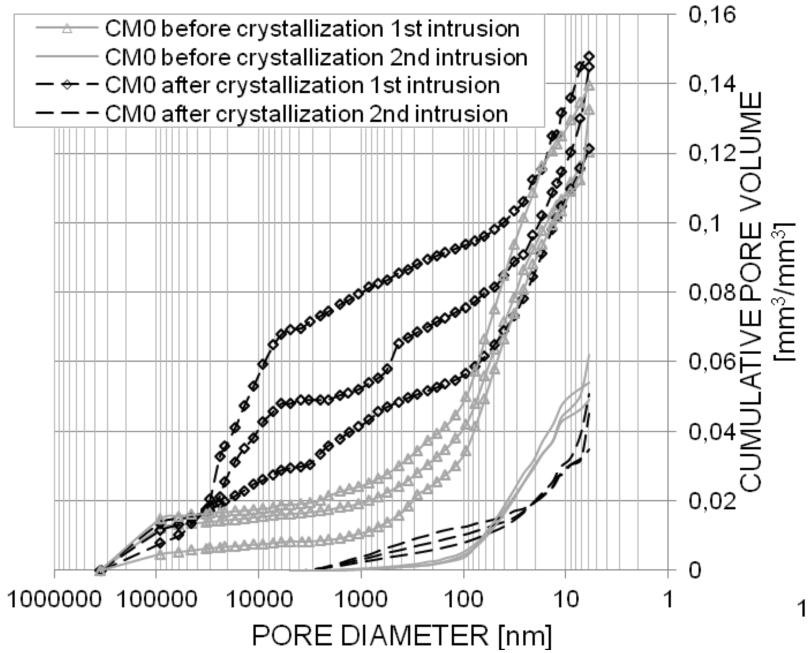
Crystallization pressure

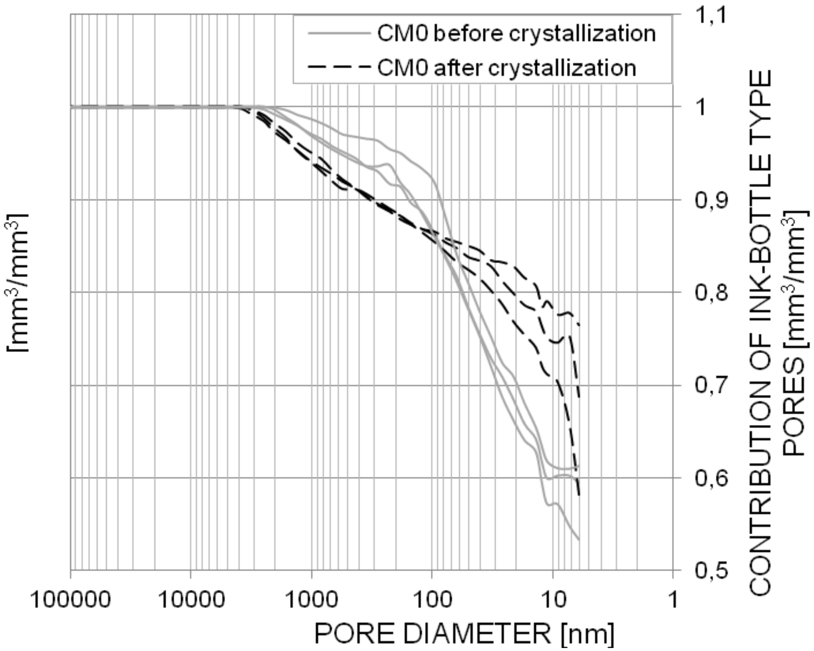
$$\Delta p = \frac{RT}{V_m} \ln\left(\frac{a}{a_\infty}\right) - \bar{\gamma}_{cl} \frac{dA}{dV}$$

Material deterioration

Sodium Sulphate crystallization

Microstructure change due to salt crystallization of **CM0**

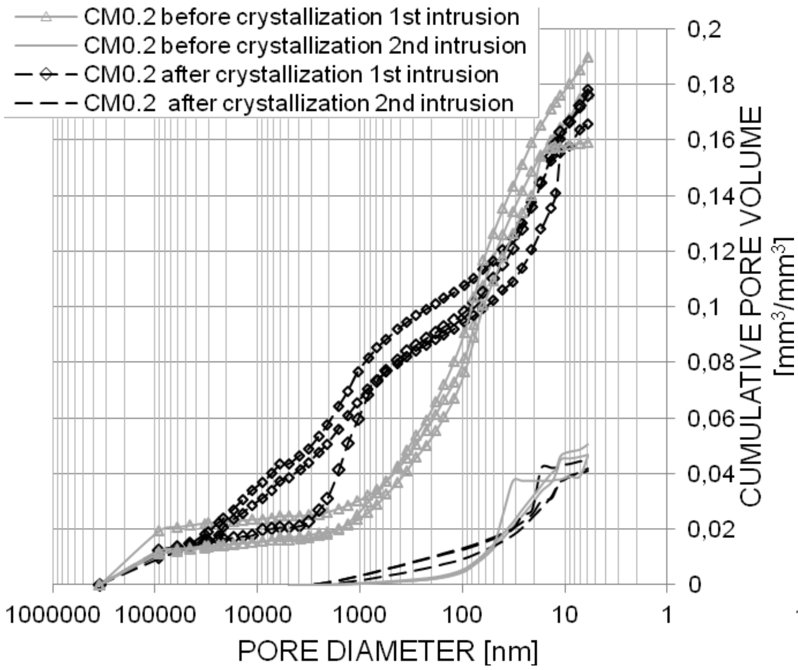


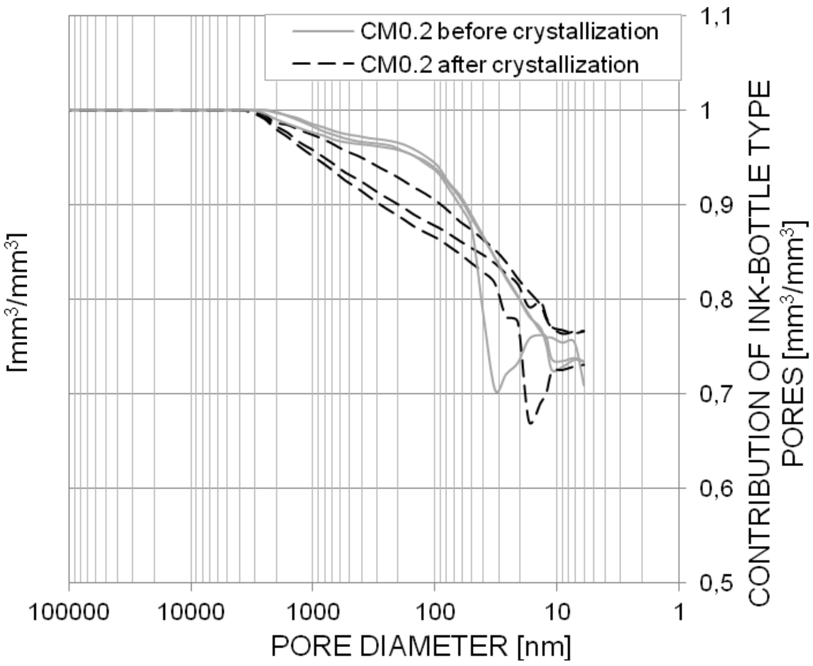


Material deterioration

Sodium Sulphate crystallization

Microstructure change due to salt crystallization of **CM0.2**

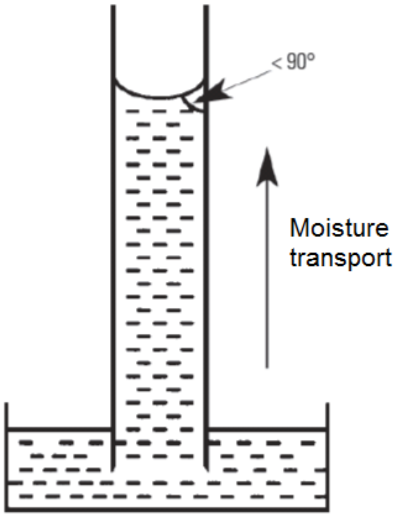




Material deterioration

Sodium Sulphate crystallization

Experimental setup for capillary suction test



$$\frac{\Delta m}{A} = C_{cap}\sqrt{t}$$

Δm - mass change of sample sample

A - area of the cross-section of the sample

C_{cap} - capillary suction coefficient

t - time

Material deterioration

Sodium Sulphate crystallization

Capillary suction coefficient

$$\frac{\Delta m}{A} = C_{cap}\sqrt{t}$$

The coefficient of capillary suction C_{cap}	**CM0 AEA=0.0% [kg/(h$^{0.5}$m^2)]**	**CM0.1 AEA=0.1% [kg/(h$^{0.5}$m^2)]**	**CM0.2 AEA=0.2% [kg/(h$^{0.5}$m^2)]**
Before crystallization test	0.484	0.463	0.424
After 10 crystallization cycles	0.570	0.514	0.465
Increase	18%	10%	9%

Material deterioration

Sodium Sulphate crystallization

Pore microstructure

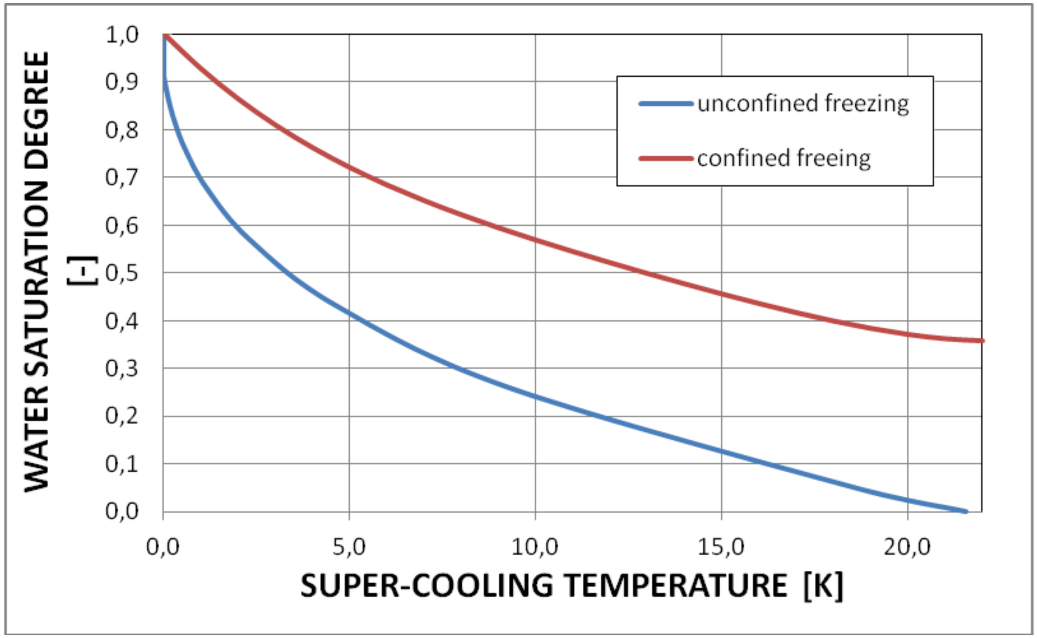
Material parameter	CM0 AEA=0.0%		CM0.1 AEA=0.1%		CM0.2 AEA=0.2%	
	Before	After	Before	After	Before	After
Total pore area [m2/g]	8.98	8.93	7.43	6.99	7.03	8.59
Bulk density [g/ml]	2.20	2.10	2.22	2.25	2.21	2.18
Apparent density [g/ml]	2.53	2.43	2.61	2.61	2.68	2.63
Porosity [%]	13.10	13.80	14.74	13.99	17.52	17.35

Freezing of water in porous materials

Equilibrium during freezing/thawing

$$S_w^{eq}(T) = S_w\left(\frac{2\gamma_{w/gw}}{r_{fr}^{eq}(T)}\right)$$

$$r_{fr}^{eq}(T) = \frac{2\gamma_{w/ice}}{\Sigma_{fr}\left(T_m^* - T\right)}$$



S_w^{eq} - equilibrium water saturation

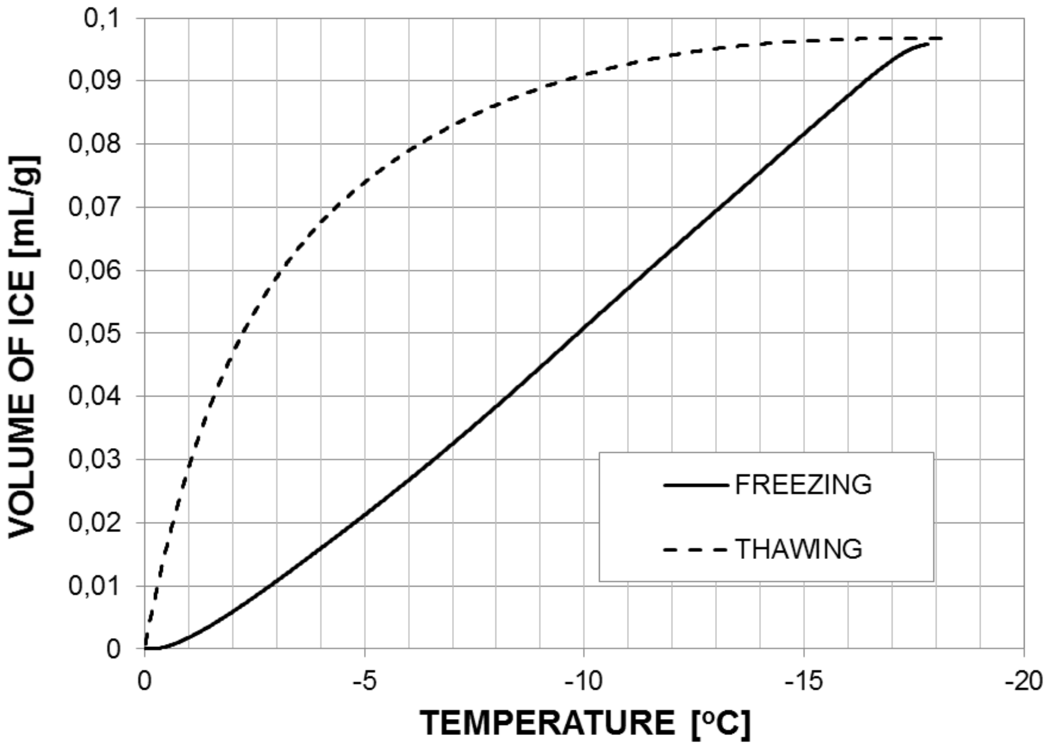
r_{fr}^{eq} - pore radius where water is in equilibrium with ice

$\gamma_{w/ice}$ - surface tension at water-ice interface

Σ_{fr} - entropy of water freezing

Freezing of water in porous materials

Equilibrium during freezing/thawing



Experimental data from DSC calorimeter

$$S_{ice}^{eq}(T) = S_{ice}\left(\frac{2\gamma_{w/gw}}{r_{fr}^{eq}(T)}\right)$$

S_w^{eq} - equilibrium ice saturation

r_{fr}^{eq} - pore radius where water is in equilibrium with ice at temp. T

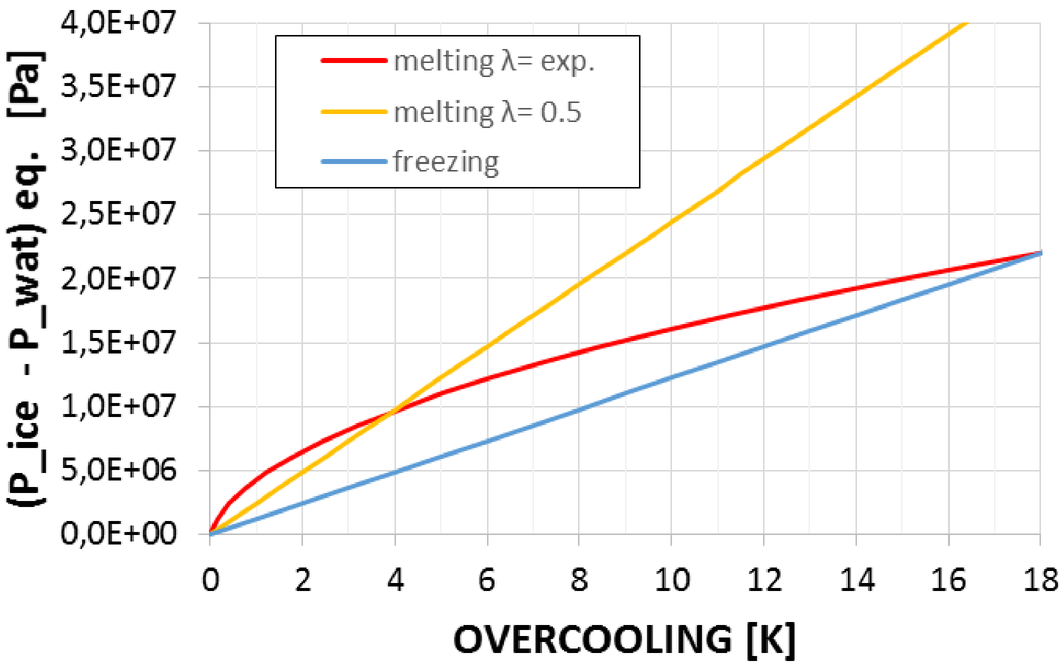
$\gamma_{w/ice}$ - surface tension at water-ice interface

Freezing of water in porous materials

Kinetics of freezing/thawing

$$\dot{\Gamma}_{fr} = \frac{1}{RT\tau_{fr}} A_{fr}$$

$$\dot{\Gamma}_{fr} = -\frac{v_w}{RT} \frac{p^c_{fr} - p^c_{fr,eq}}{\tau_{fr}}$$



$$p^c_{fr} = \frac{\gamma_{ice,w}}{\gamma_{w,g}} p^c \qquad p^c_{fr,eq} = \Sigma_m \left(T^*_m - T \right)$$

τ_{fr} - characteristic time of water freezing

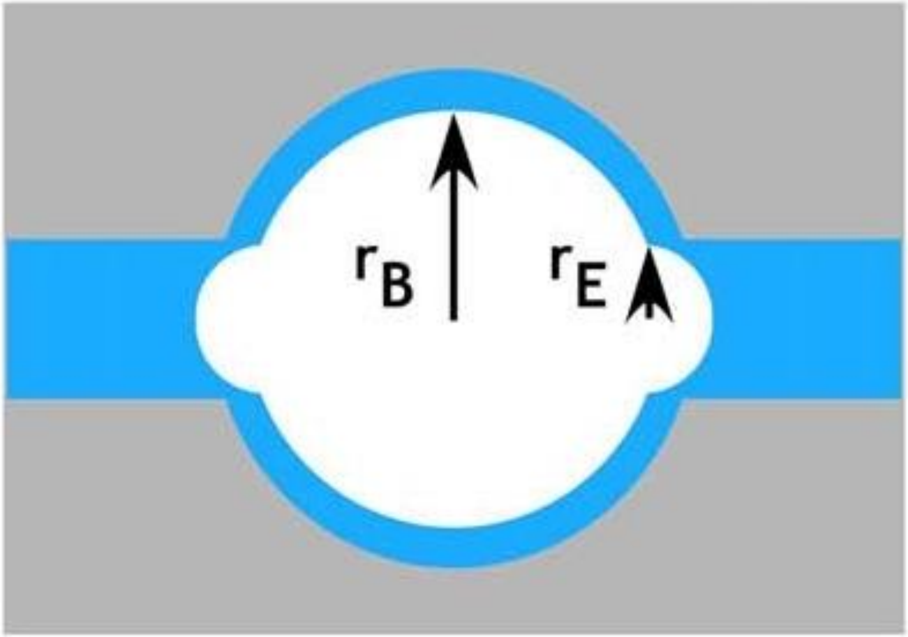
A_{fr} - chem. affinity for water freezing

Σ_{fr} - entropy of water freezing

Freezing of water in porous materials

Equilibrium crystallization pressure

$$p^{cryst} = \gamma_{ice/w}\left(\frac{2}{r_{pore}} - \kappa_{pore}\right) = \frac{2\gamma_{ice/w}}{r_{pore}}\left(1-\bar{\lambda}\right) = \frac{\gamma_{ice/w}}{\gamma_{vap/w}}\, p^{c}\left(1-\bar{\lambda}\right)$$



$$\bar{\lambda}(S_w) = \frac{\kappa^{m}_{ice,w}}{2/r_{pore}} = \frac{1/r_B}{2/r_E}$$

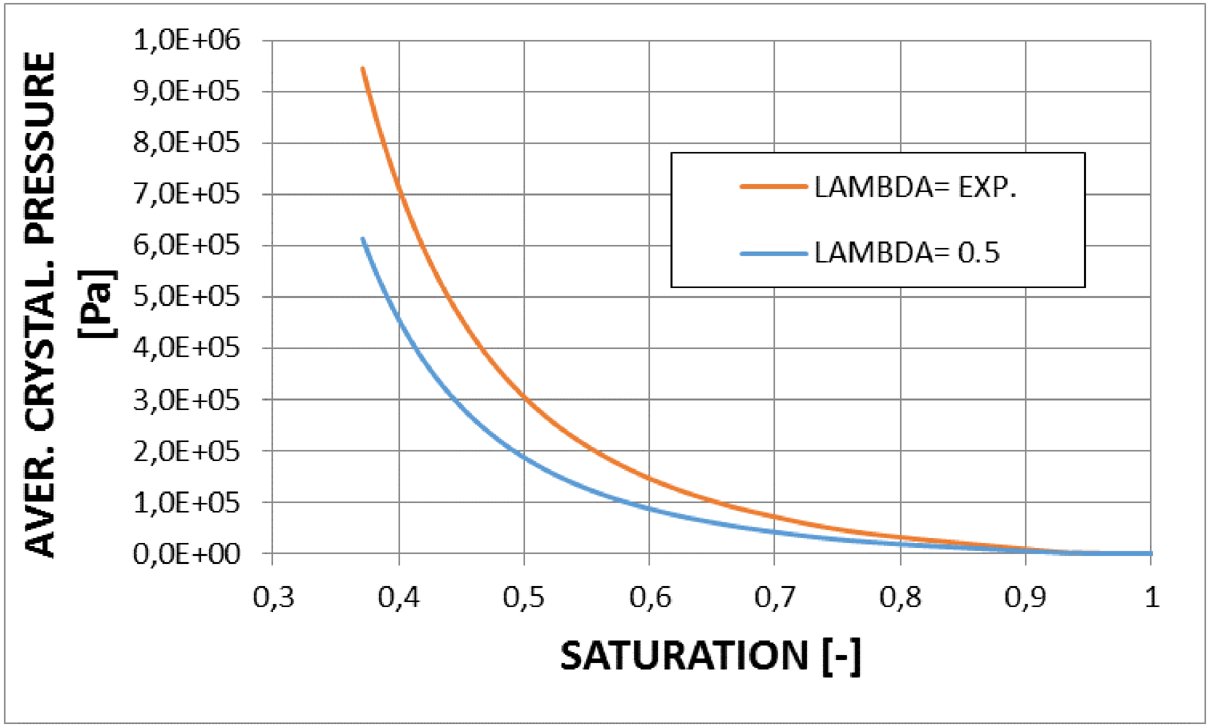
$\kappa^{m}_{ice,w}$ - curvature of pore interior

r_E - pore entrance radius

Freezing of water in porous materials

Average pore crystallization pressure

$$\Pi^{cryst}(S_w) = \langle S_{ice} p^{cryst} \rangle = \int_{1-S_w(p^c)}^{1} \frac{\gamma_{ice/w}}{\gamma_{vap/w}} p^c (1-\bar{\lambda}) \frac{\partial S_w}{\partial p^c} dp^c$$

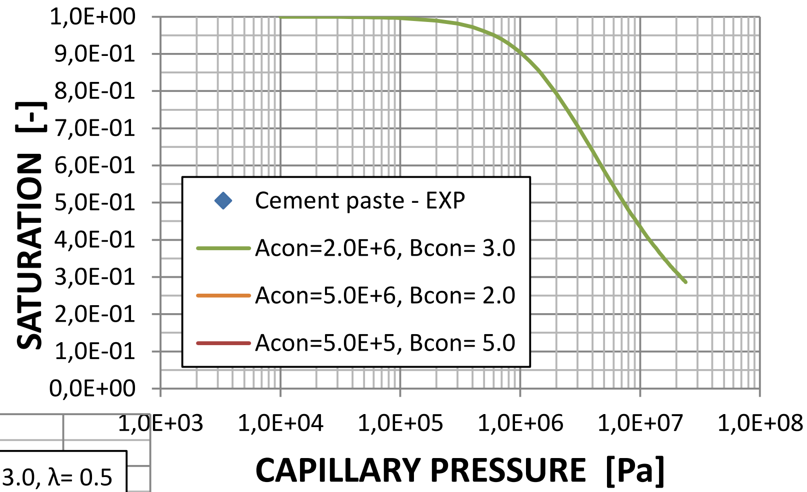


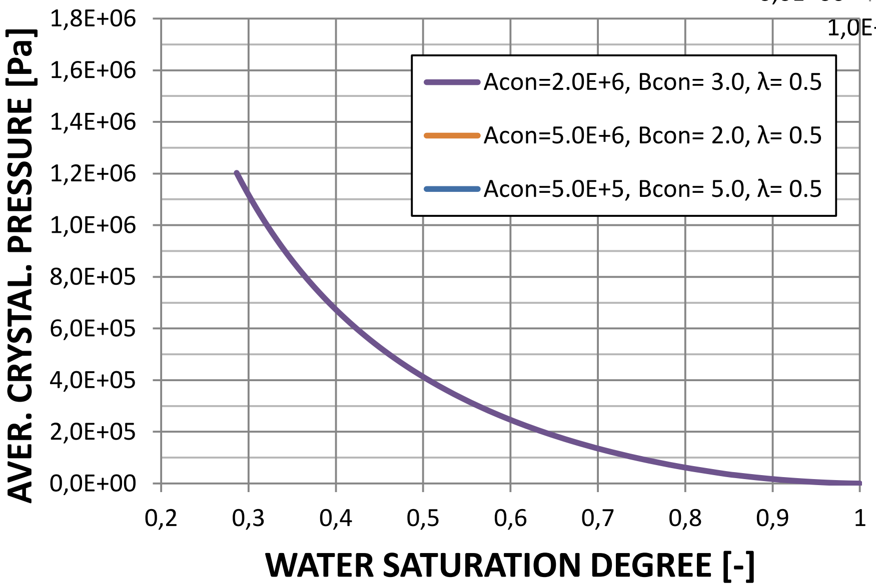
$S_w(p^c)$- water saturation, sorption isotherm of a material

Freezing of water in porous materials

Effect of the pore structure on the crystallization pressure

Sorption isotherm
$S_w(p^c)$

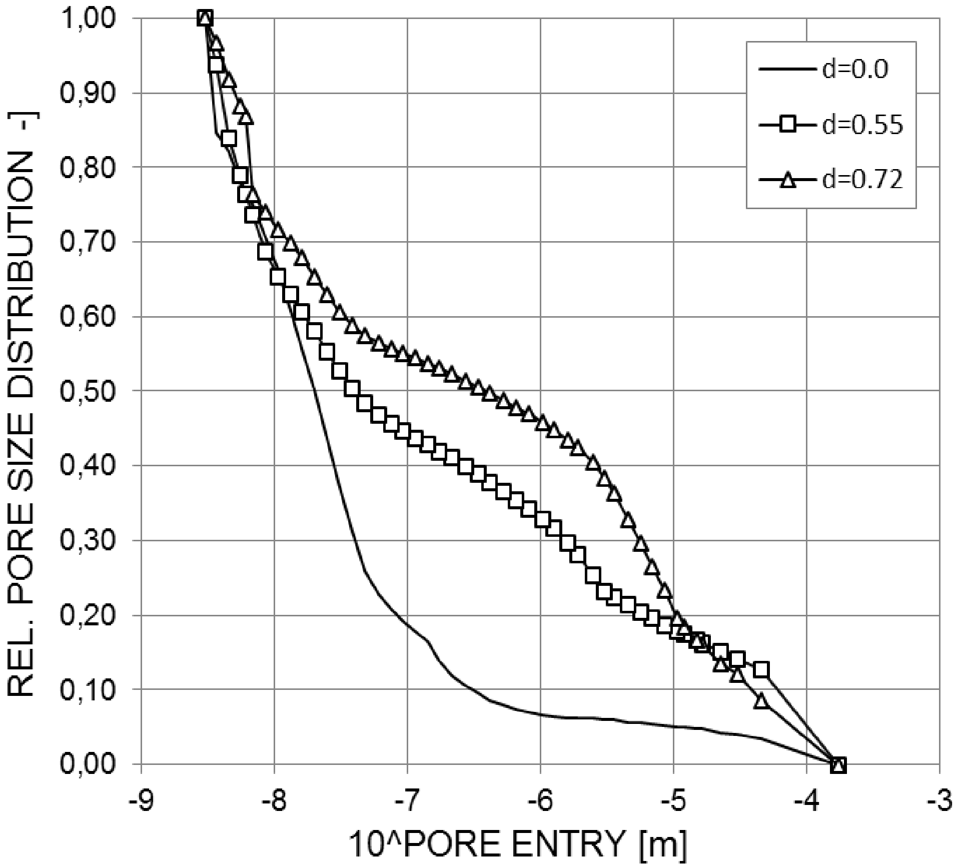




Crystallization pressure
$<p^{cryst}>(S_w)$

Freezing of water in porous materials

Deterioration of pore structure

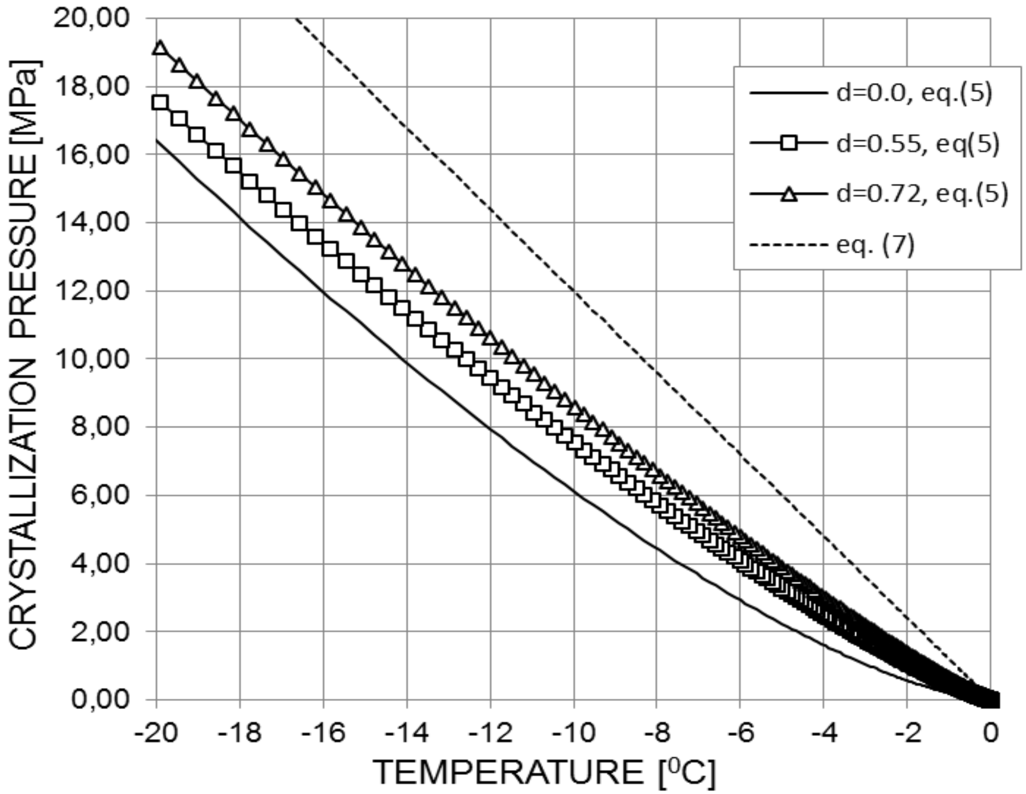


Experimental data from MIP porosimeter

d – damage parameter (= % decrease of compresive strength)

Freezing of water in porous materials

Crystallization pressure in deteriorated material



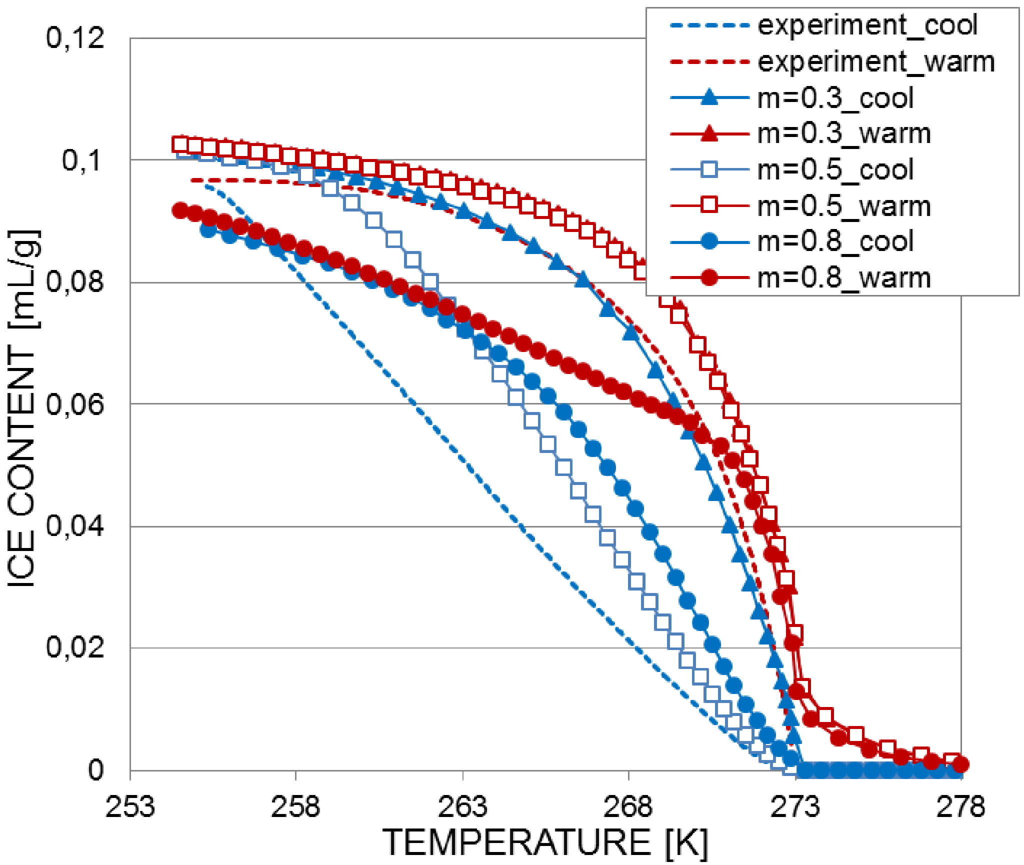
Calculated with using pore size distribution from MIP porosimeter

d=0 – undamaged mat.
d=0.55 – after 25 cycles
d=0.72 – after 50 cycles

d – damage parameter (= % decrease of compresive strength)

Freezing of water in porous materials

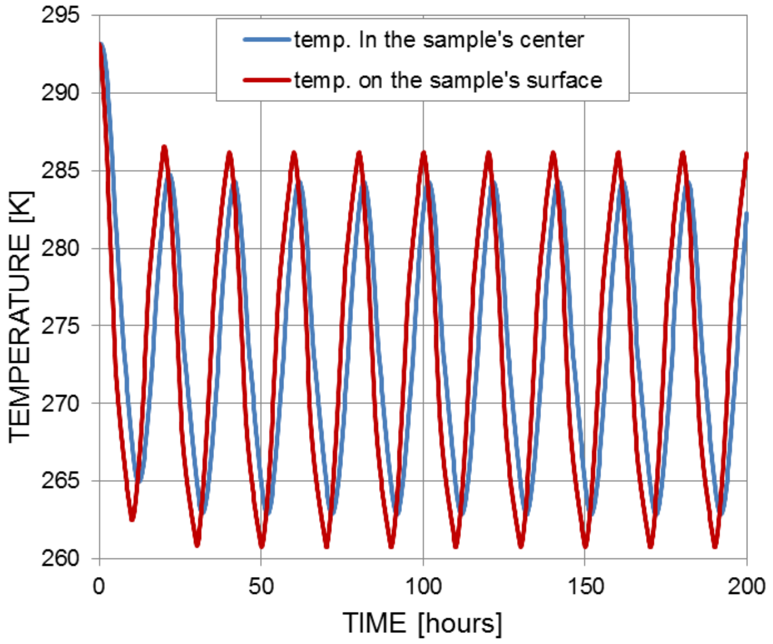
Model validation

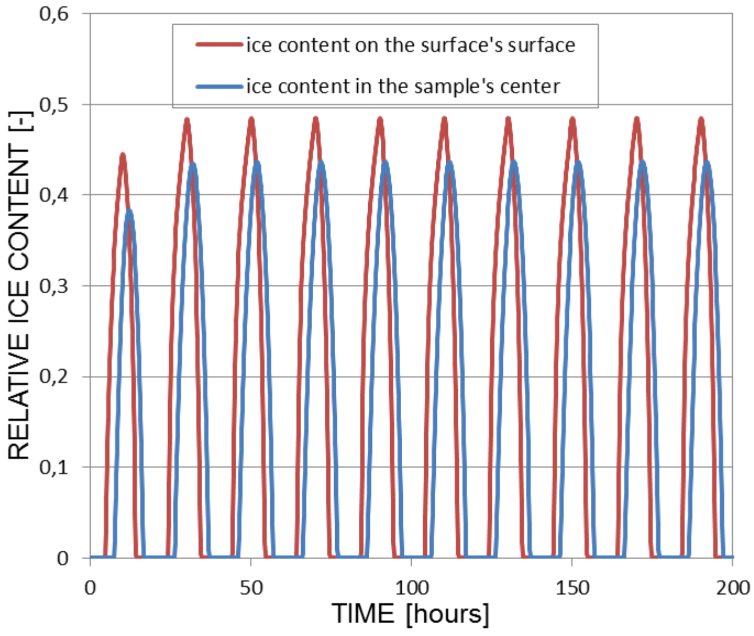


Experimental data from DSC calorimeter

Freezing of water in porous materials

Model application – concrete wall cyclic freezing /thawing

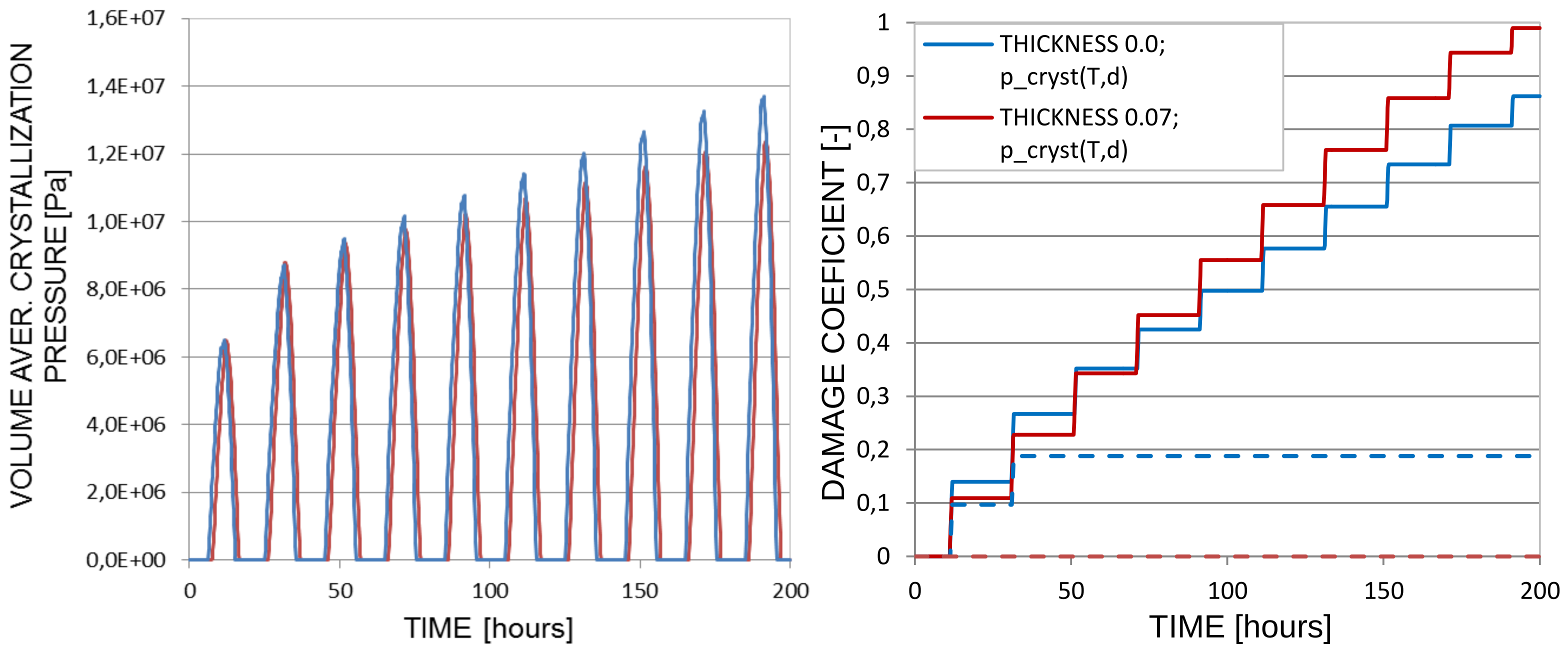




Temperature & Ice content vs. Time
during cyclic freezing / thawing

Freezing of water in porous materials

Model application – concrete wall cyclic freezing /thawing



Crystallization pressure & Frsot damage vs. Time
during cyclic freezing / thawing

Material deterioration

Cyclic freezing / thawing tests

Casting

↓

Water storage (28 days)

↓

Drying until constant mass → MIP

↓

Freeze/thaw cycles

↓

Drying until constant mass → MIP

The samples of series F-01,F-02,F-05 and F-06 after 100 freeze-thawing cycles

Material deterioration

Cyclic freezing / thawing tests

Material parameter	F-01 (w/c=0.5)			F-05 (AEA=0.1%)			
	0c.	25c.	50c.	0c.	25c.	50c.	100c.
Total pore area [m^2/g]	5.94	8.75	8.44	5.93	7.91	6.93	8.04
Bulk density [g/ml]	2.03	2.04	1.88	2.10	2.04	2.05	1.87
Apparent density [g/ml]	2.51	2.57	2.49	2.53	2.58	2.52	2.52
Porosity [%]	19.04	20.70	24.51	16.93	21.02	18.90	25.95

Material parameter	F-02 (AEA=0.0%)			F-06 (AEA=0.2%)			
	0c.	25c.	50c.	0c.	25c.	50c.	100c.
Total pore area [m^2/g]	5.67	6.01	7.21	5.78	7.87	8.26	8.02
Bulk density [g/ml]	2.10	2.20	2.04	1.81	1.79	1.84	1.80
Apparent density [g/ml]	2.51	2.56	2.52	2.60	2.57	2.51	2.56
Porosity [%]	16.44	14.11	18.93	27.49	30.38	26.68	29.36

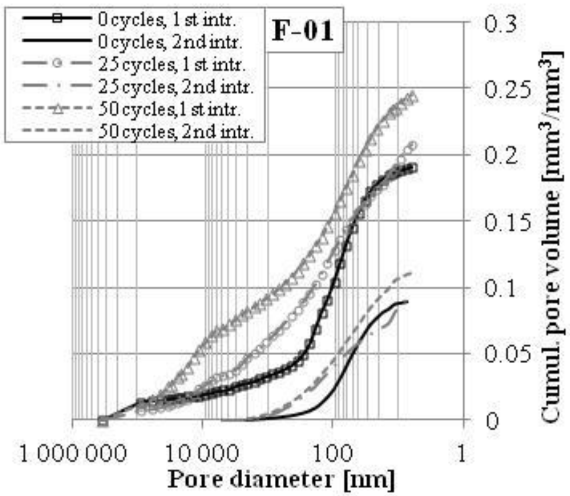
Material deterioration

Cyclic freezing / thawing tests

Material parameter	F-01 (w/c=0.5)			F-05 (AEA=0.1%)			
	0c.	25c.	50c.	0c.	25c.	50c.	100c.
Total pore area [m^2/g]	5.94	8.75	8.44	5.93	7.91	6.93	8.04
Bulk density [g/ml]	2.03	2.04	1.88	2.10	2.04	2.05	1.87
Apparent density [g/ml]	2.51	2.57	2.49	2.53	2.58	2.52	2.52
Porosity [%]	19.04	20.70	24.51	16.93	21.02	18.90	25.95
Material parameter	F-02 (AEA=0.0%)			F-06 (AEA=0.2%)			
	0c.	25c.	50c.	0c.	25c.	50c.	100c.
Total pore area [m^2/g]	5.67	6.01	7.21	5.78	7.87	8.26	8.02
Bulk density [g/ml]	2.10	2.20	2.04	1.81	1.79	1.84	1.80
Apparent density [g/ml]	2.51	2.56	2.52	2.60	2.57	2.51	2.56
Porosity [%]	16.44	14.11	18.93	27.49	30.38	26.68	29.36

Material deterioration

Cyclic freezing / thawing tests

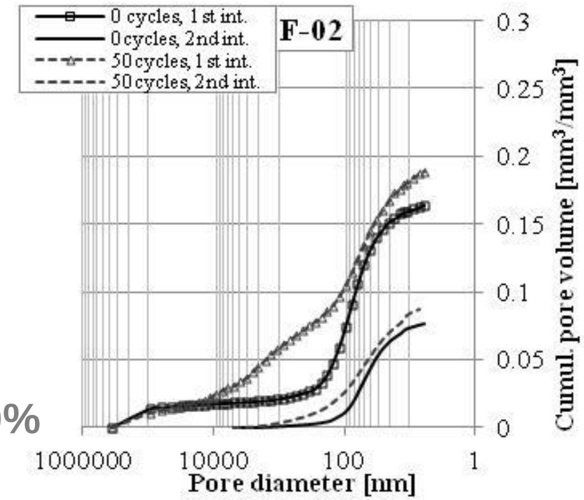


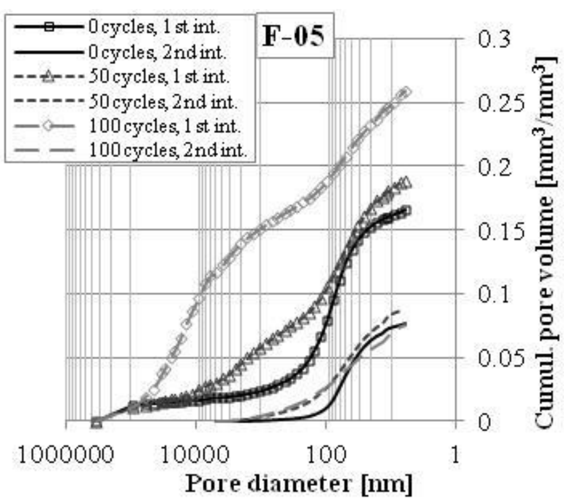
w/c=0.5

AEA=0.0%

w/c=0.4

AEA=0.0%



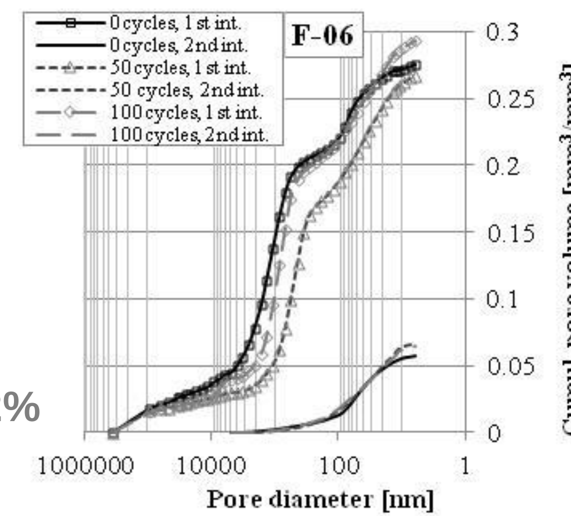


w/c=0.4

AEA=0.1%

w/c=0.4

AEA=0.2%



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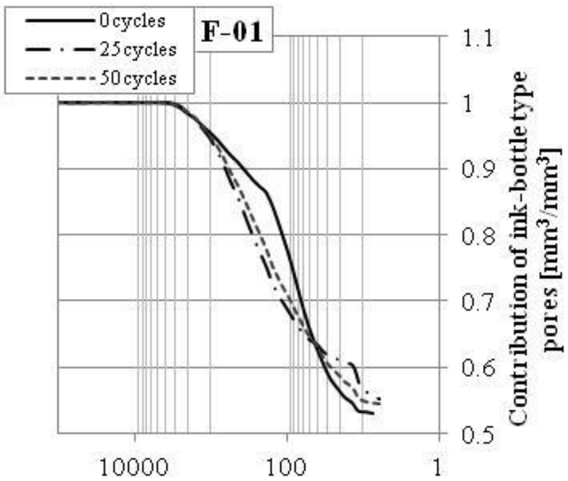
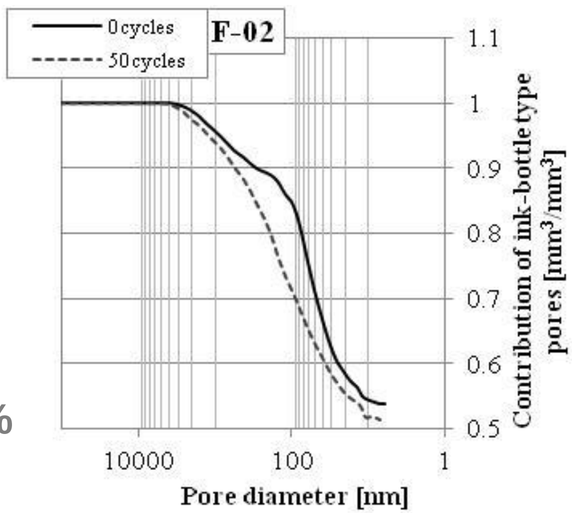
Material deterioration

Cyclic freezing / thawing tests



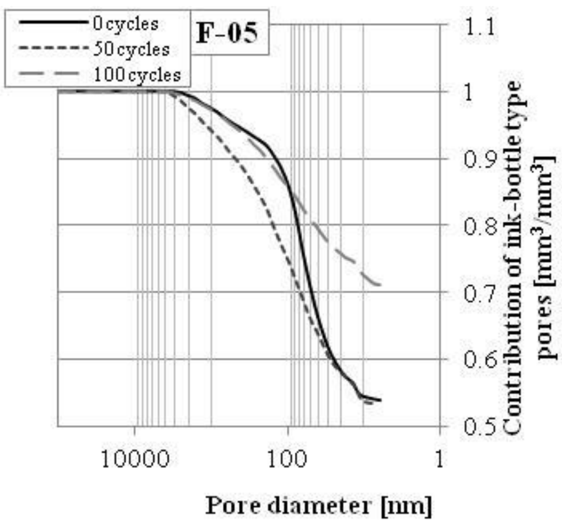
w/c=0.5

AEA=0.0%



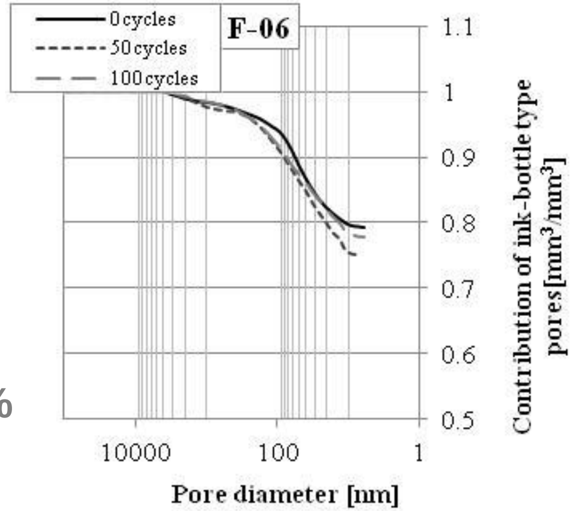
w/c=0.4

AEA=0.0%



w/c=0.4

AEA=0.1%



w/c=0.4

AEA=0.2%

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Material deterioration

Cyclic freezing / thawing tests

Capillary suction coefficient

$$\frac{\Delta m}{A} = C_{cap}\sqrt{t}$$

Material parameter	Unit	F-01 (w/c=0.5)			F-05 (AEA=0.1%)			
		0c.	25c.	50c.	0c.	25c.	50c.	100c.
C_{cap}	[kg/(h^0.5 m^2)]	1.983	2.723	8.254	1.01	1.176	1.879	4.847
Material parameter	**Unit**	**F-02 (AEA=0.0%)**			**F-06(AEA=0.2%)**			
		0c.	**25c.**	**50c.**	**0c.**	**25c.**	**50c.**	**100c.**
C_{cap}	[kg/(h^0.5 m^2)]	1.119	1.543	1.699	0.55	0.730	0.747	0.767

CONTINUING EDUCATION AIA

Material deterioration

Cyclic freezing / thawing tests

Capillary suction coefficient

$$\frac{\Delta m}{A} = C_{cap}\sqrt{t}$$

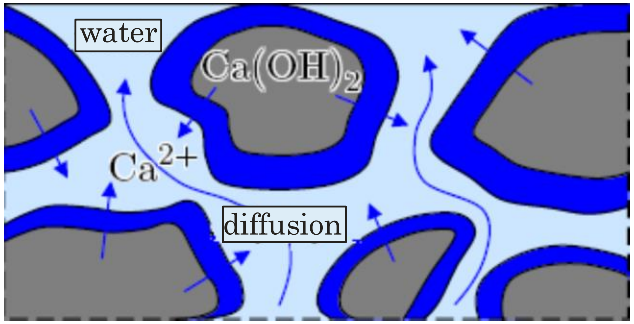
Material parameter	Unit	F-01 (w/c=0.5)			F-05 (AEA=0.1%)			
		0c.	25c.	50c.	0c.	25c.	50c.	100c.
C_{cap}	[kg/(h^0.5 m^2)]	1.983	2.723	8.254	1.01	1.176	1.879	4.847
Material parameter	**Unit**	**F-02 (AEA=0.0%)**			**F-06(AEA=0.2%)**			
		0c.	**25c.**	**50c.**	**0c.**	**25c.**	**50c.**	**100c.**
C_{cap}	[kg/(h^0.5 m^2)]	1.119	1.543	1.699	0.55	0.730	0.747	0.767

Calcium leaching in cement paste

Chemical reactions leading to calcium leaching process

- **Portlandite** dissolution (calcium hydroxide)

$$Ca(OH)_2 \Leftrightarrow Ca^{2+} + 2OH^-$$



- **Ettringite** dissolution

$$Ca_6Al_2O_6(SO_4)_3 \cdot 32H_2O \Leftrightarrow 6Ca^{2+} + 2Al(OH)_4^- + 3SO_4^{2-} + 4OH^- + 26H_2O$$

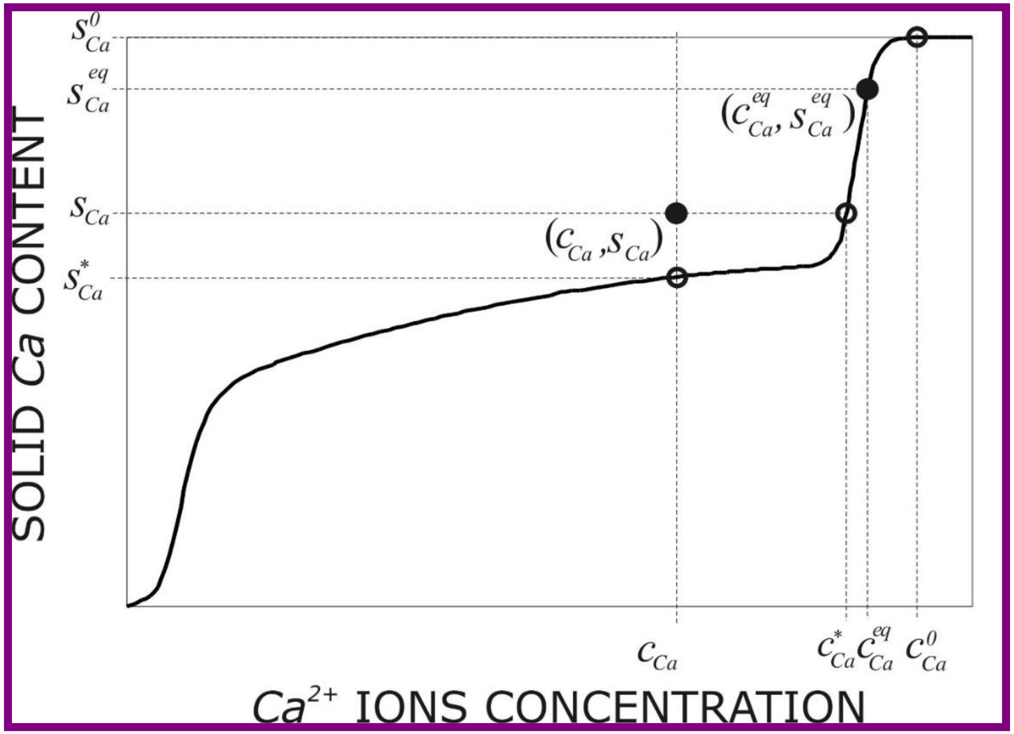
- dissolution of different phases of **CSH gel**

$$nCaO \cdot SiO_2 \cdot nH_2O \Leftrightarrow nCa^{2+} + H_3SiO_4^- + [2n-1]H_2O$$

Calcium leaching in cement paste

Kinetics of calcium leaching process

$$\frac{ds}{dt} = \frac{1}{\eta}\left[RT \ln\left(c / c_0\right) - \int_{s_0}^{s} \kappa(\bar{s}) d\bar{s} \right]$$



R – universal constant of gas,

κ – process equilibrium const.,

η - parameter dependent on micro-diffusion of, Ca^{2+}

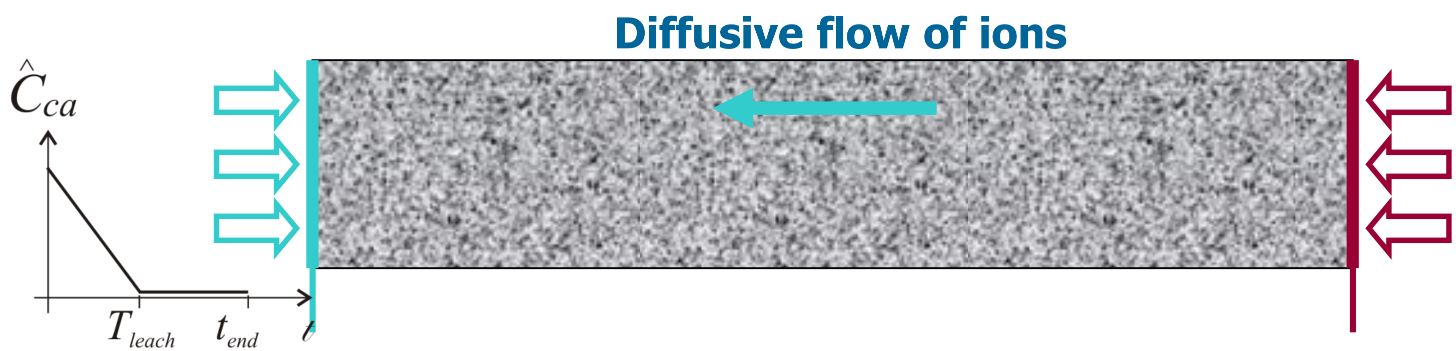
$\tau_s = \frac{\eta}{RT}$ - characteristic time

[Gawin, Pesavento, Schrefler – J. Solids Struct. 2008]

Calcium leaching in cement paste

Effect of temperature

Specimen (bar, 16 cm) – uniform temperature



Convective ions exchange with the environment:
$c_{\infty} = c_{equil} \rightarrow 1$ [mol/m^3] in T_{leach} =1000 days;
$\delta_c = 10^{-5}$ kg/m^{2}s, t_{end} =10000 days
Temperature fixed on the surface:
T_{sup}=25°C = const OR T_{sup}= 60°C= const

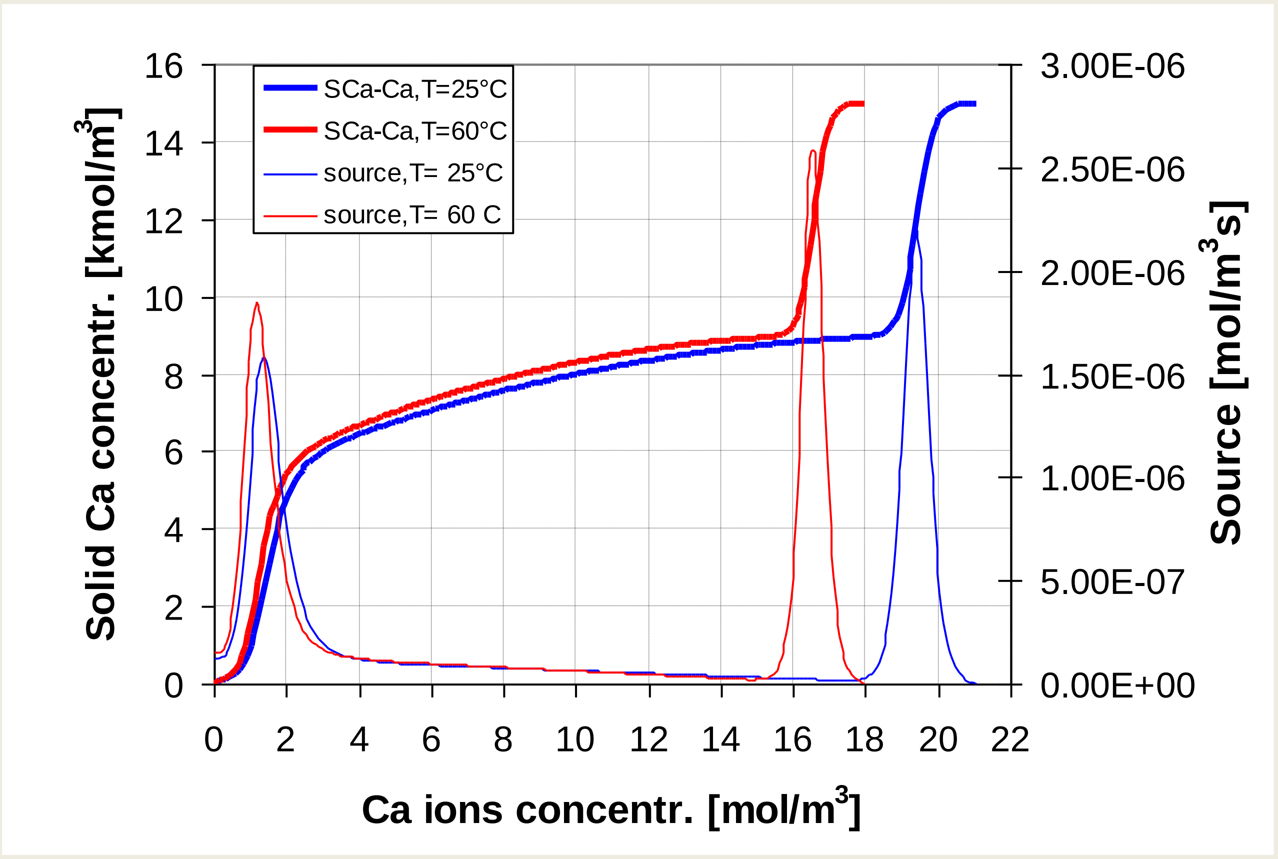
$c_{ini} = c_{equil}$ [mol/m^3]
Temperature fixed on the surface:
T_{sup} =25°C=const
OR
T_{sup}=60°C= const

- Initial porosity = 12.2%
- Material properties according to [Kuhl, Bangert, Meschke, 2004]
- Characteristic time of the process: t_s= 2 hours

Calcium leaching in cement paste

Effect of temperature

Equilibrium curves at different temperatures

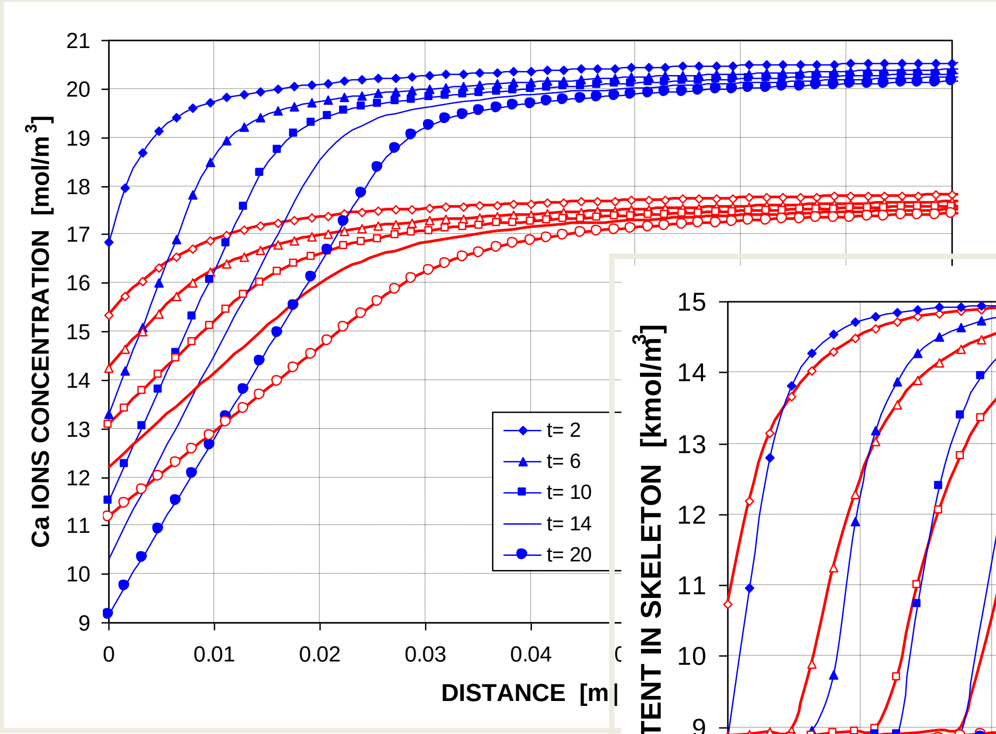


[Gawin, Pesavento, Schrefler – J. Solids Struct. 2008]

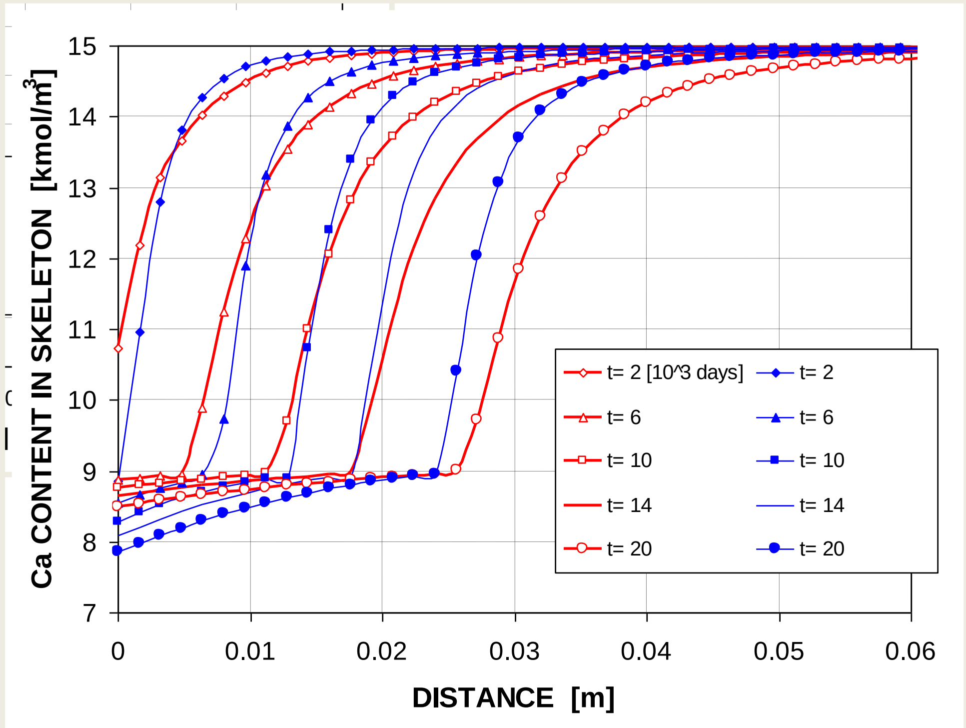
Calcium leaching in cement paste

Effect of temperature

Liquid calcium concentr.



Solid calcium content



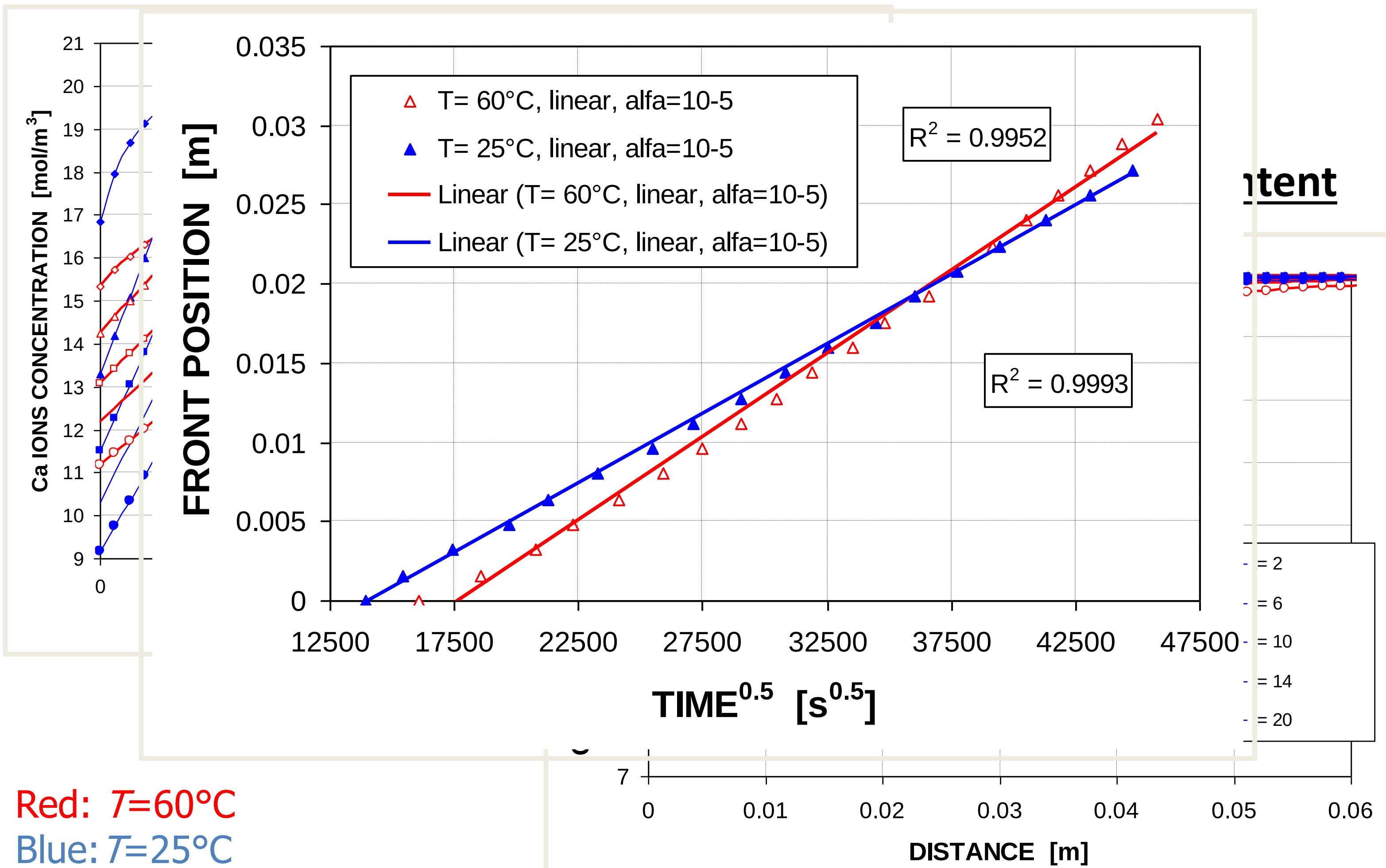
Red: T=60°C

Blue: T=25°C

Calcium leaching in cement paste

Effect of temperature

Liquid calcium concentr.



Red: *T*=60°C
Blue: *T*=25°C