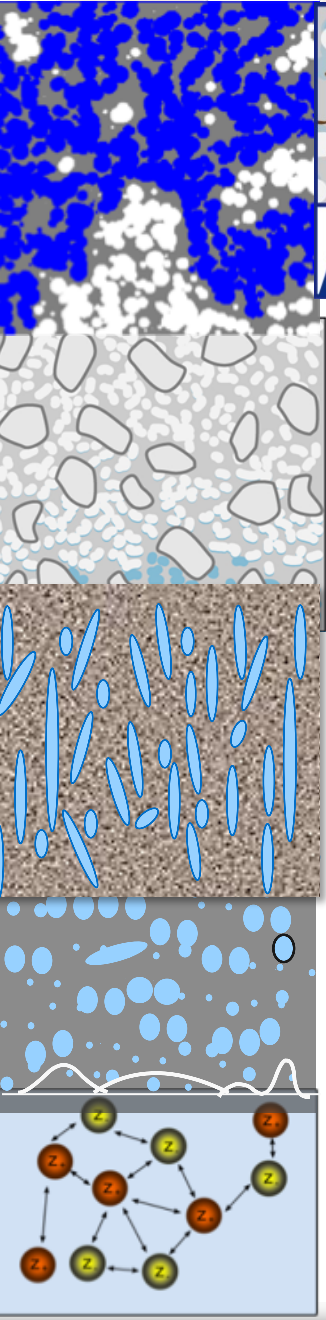
RUHR-UNIVERSITÄT BOCHUM



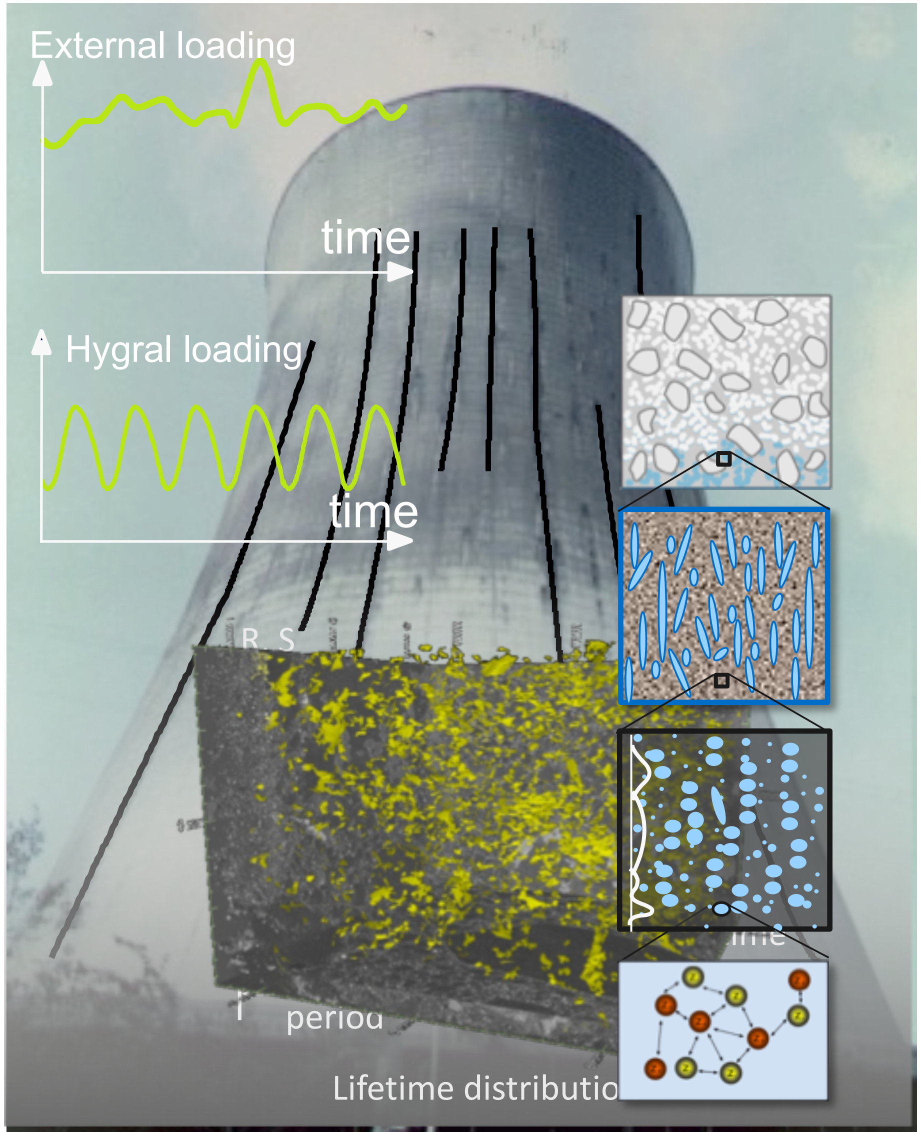
Scale traversing models for durability oriented computational analyses of concrete and concrete structures

Günther Meschke

J. J. Timothy, T. Iskhakov, M. Hofmann

Institute for Structural Mechanics
Ruhr University Bochum

Durabilty of concrete infrastructure: Phenomenological modeling



Long-term structural degradation:

- Coupled processes
- load carrying capacity (ULS) , serviceabilty of structures affected

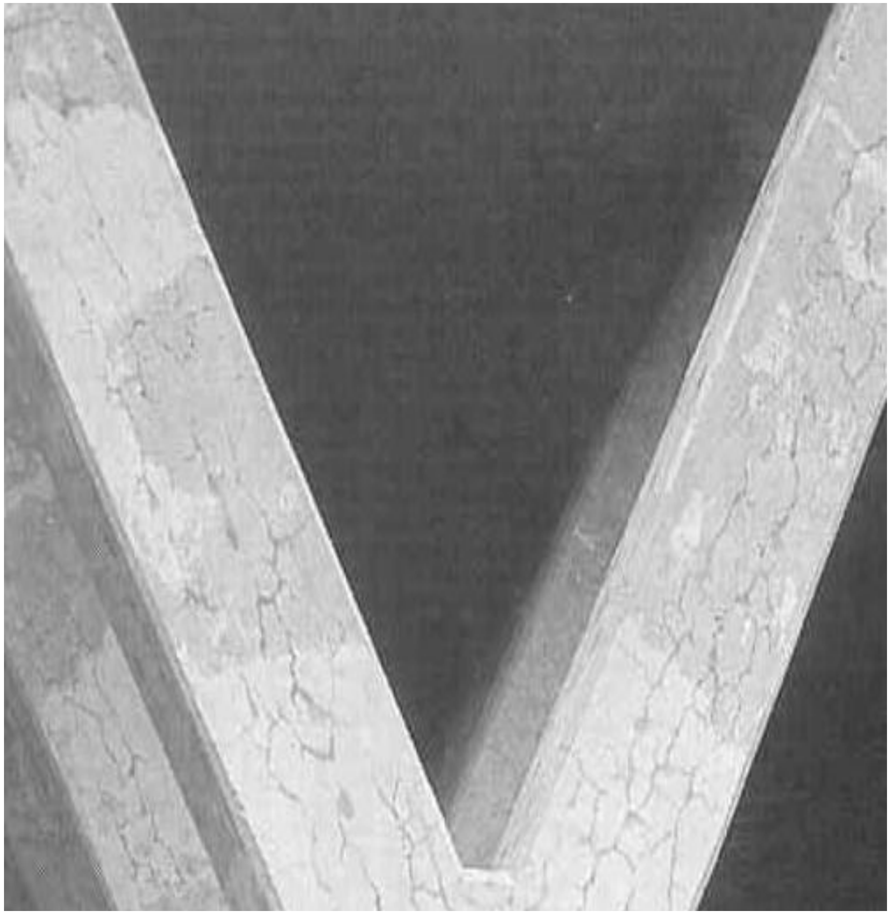
Durability analysis:

- multiphase & multifield models

- Phenomenological vs. multiscale modeling
- Multiphysics models: macroscopic stiffness, diffusivity and permeability depending on microstructure and state of damage
- Example: Moisture transport in pre-damaged concrete road pavements
- Alkali-Silica reaction: phenomenological vs. multiscale model

Durabilty of concrete infrastructure

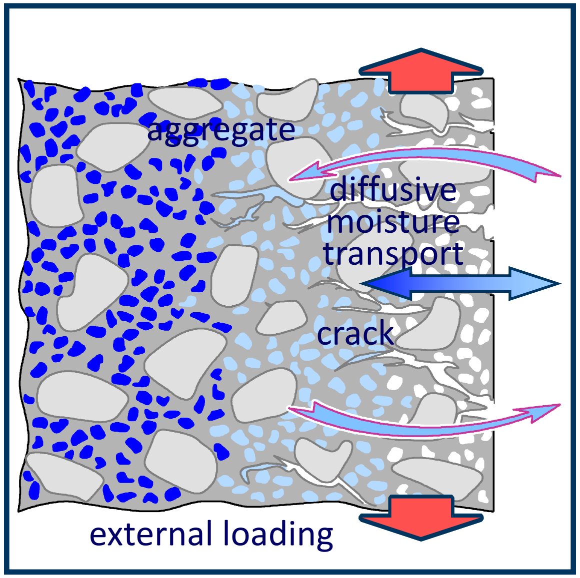
RUB

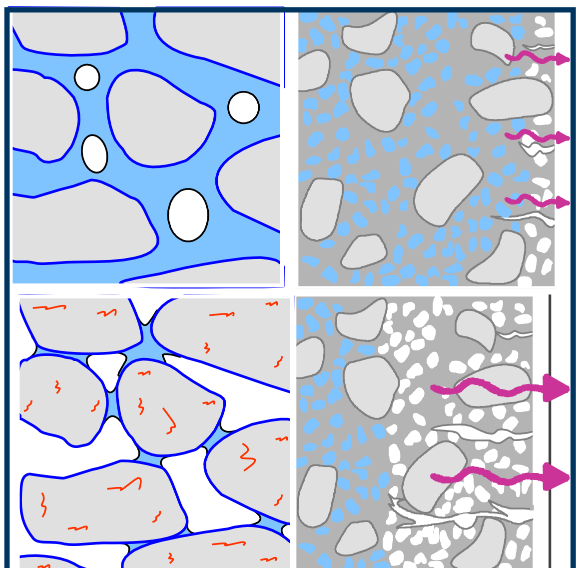


STARK & WICHT 2001

Germany: ~ 8 % of Highways affected

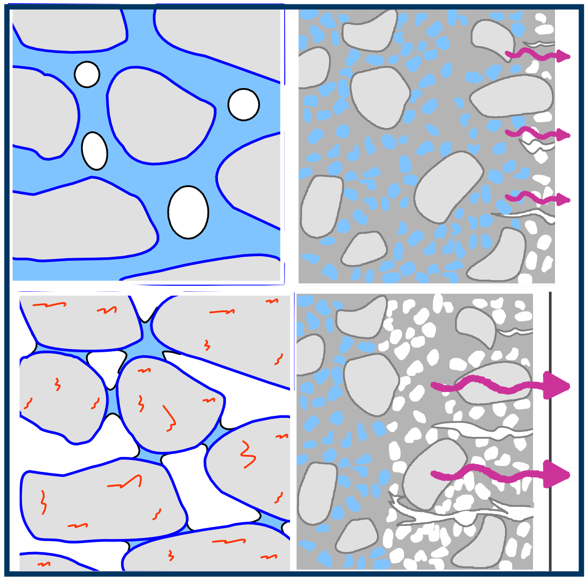
Phenomenological model: Drying shrinkage, damage and creep

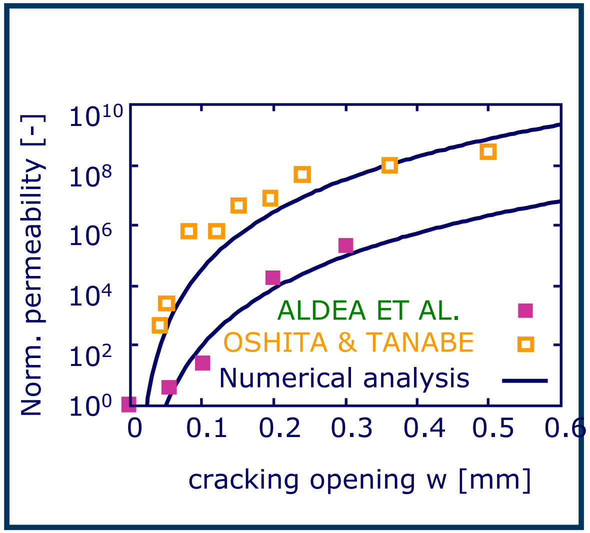




- Diffusive moisture transport
- Capillary stresses increase with drying
- Shrinkage deformations
- Cracking due to restrained shrinkage deformations
- Cracks promote moisture transport
- Moisture changes microprestress in gelpores
- Drying promotes creep deformations (Pickett-Effect)

- Three-field (u, p_g, p_l) and two-field formulations (u, p_c) in the framework of the Biot-Coussy Theory of porous media
- Hygro-mechanical couplings considered – damage - drying shrinkage, drying creep





Porosity: $\phi = \phi_l + \phi_g,$

Balance of momentum: $\operatorname{div} \boldsymbol{\sigma} + \mathbf{b} = 0$

Balance of mass of pore fluid: $\operatorname{div} q_l + \dot{m} = 0$

Moisture transport: $q_l = \dfrac{\rho_l}{\eta_l} k_r(S_l)[k_\phi(\phi)\mathbf{k}_0 + \mathbf{k}_d(d)]$

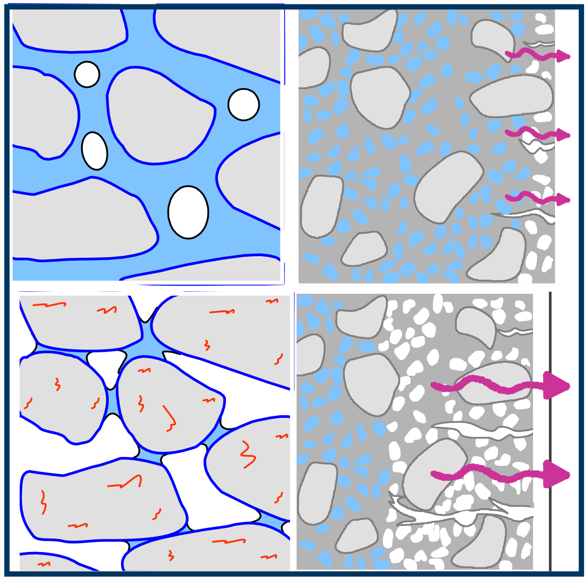
Constitutive relations:

$$\boldsymbol{\sigma} = \nabla_{\boldsymbol{\varepsilon}^e} \psi(\boldsymbol{\varepsilon}, \boldsymbol{\varepsilon}^p, \boldsymbol{\varepsilon}^f, m_l, d, \gamma)$$

$$p_c = \nabla_{\phi_l^e} \psi(\boldsymbol{\varepsilon}^e, m_l, \phi_l^p, d, \gamma)$$

Coussy 2005, GM & Grasberger, S. (2003) ASCE Engineering Mechanics

Phenomenological model: Drying shrinkage, damage and creep



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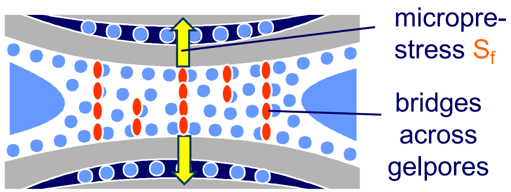
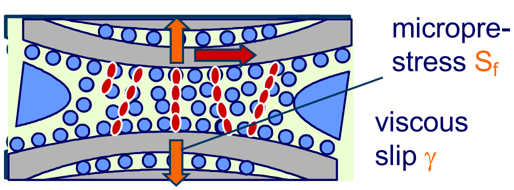


Prestressed bonds across gel pores [Bazant et al. 1997]



Bazant, Hauggaard , Baweja & Ulm (1997) ASCE Engineering Mechanics
GM & Grasberger, S. (2003) ASCE Engineering Mechanics

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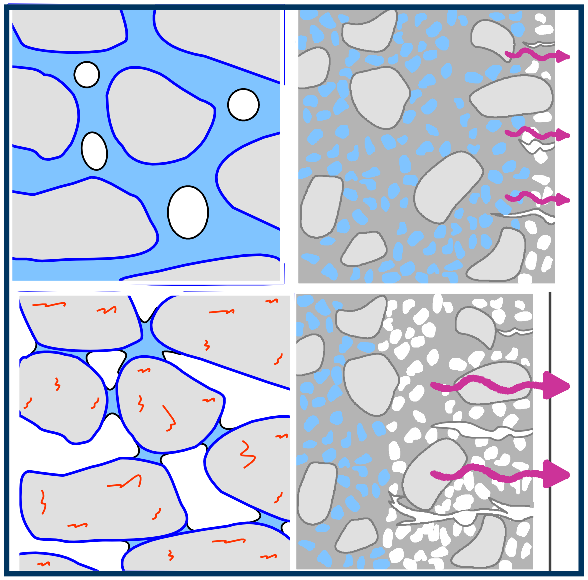

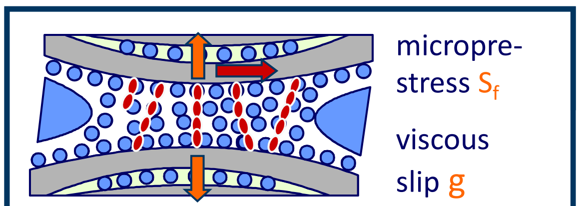

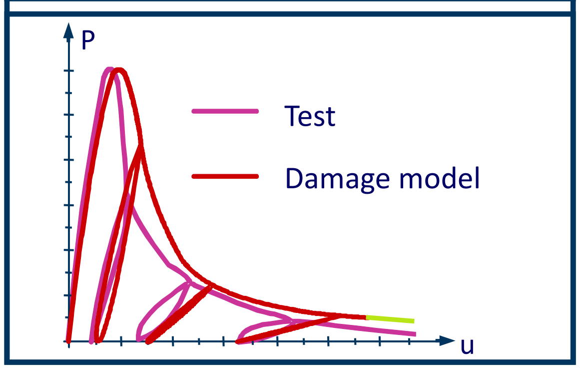

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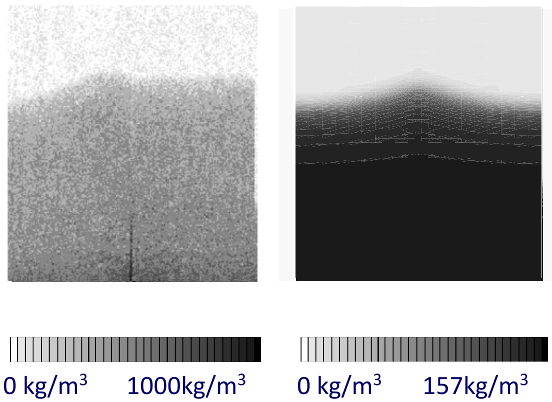
Grasberger, S. & GM (2004), Materials and Structures,

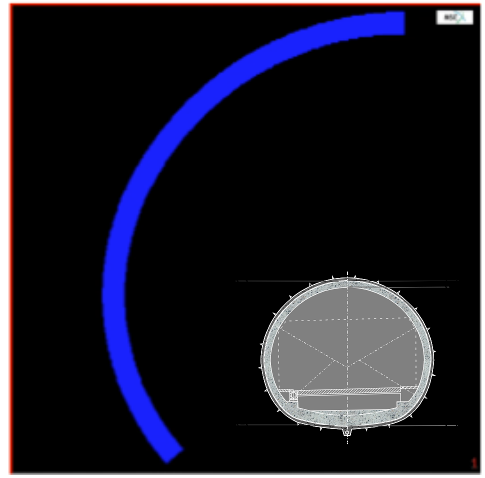
Phenomenological model: Drying shrinkage, damage and creep

Moisture flow through cracks

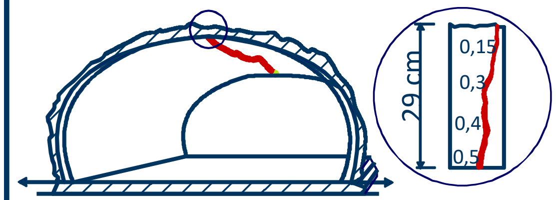
t = 40 Min.

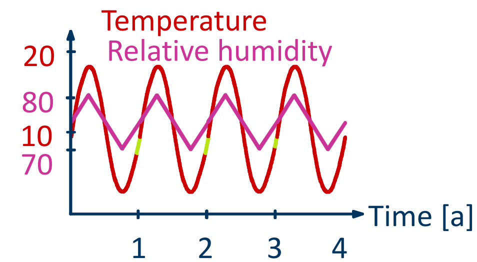


Crack penetration within 5 years



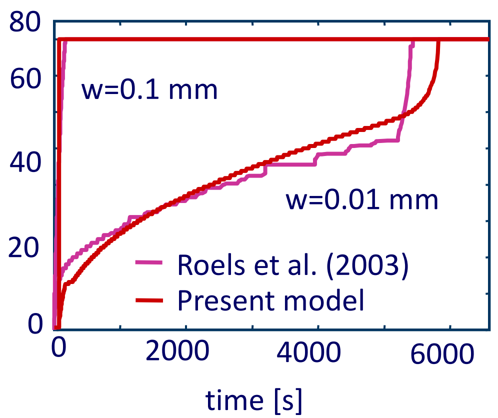
Drying of tunnel linings



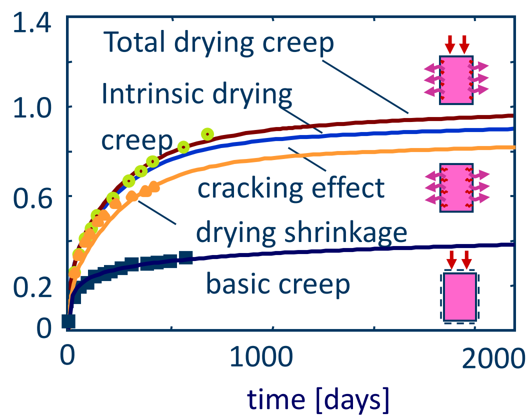


German Science Foundation

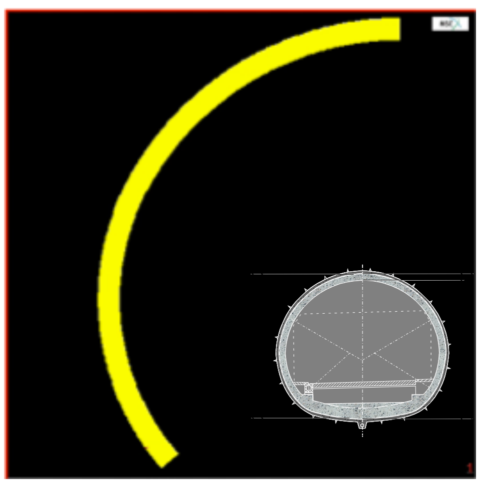
Height of the waterfront [mm]



Creep, shrinkage and drying creep strains e [10^{-3}]



Drying evolution within 5 years



Phenomenological model: Drying shrinkage, damage and creep

RUB

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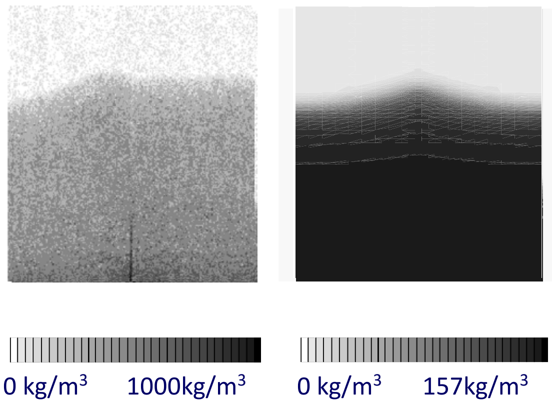
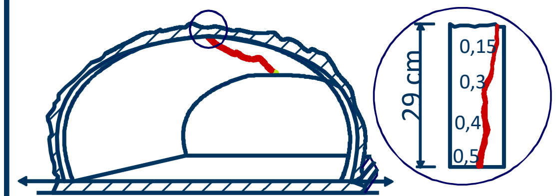
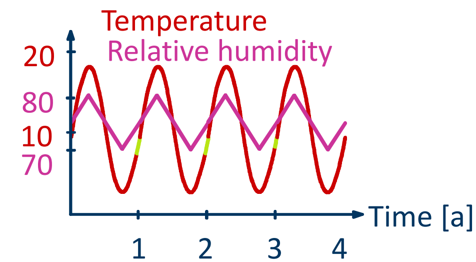


Drying of a concrete wall

Drying of tunnel linings





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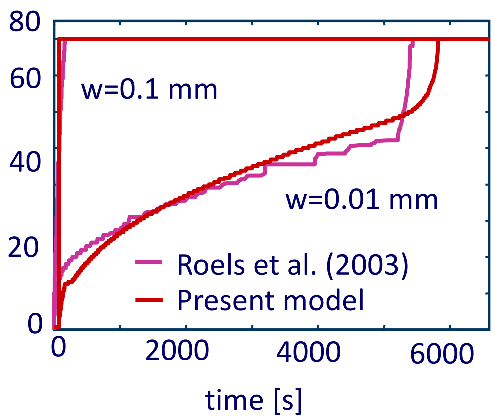

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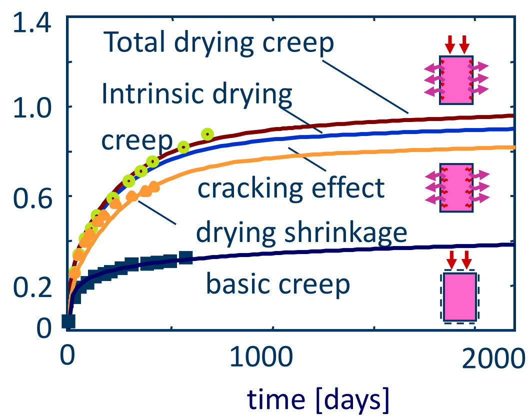

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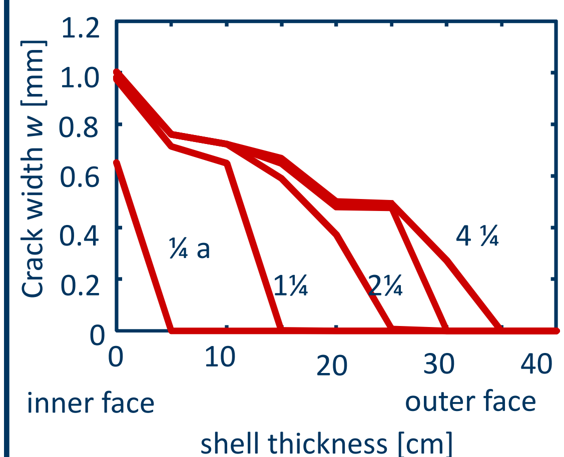

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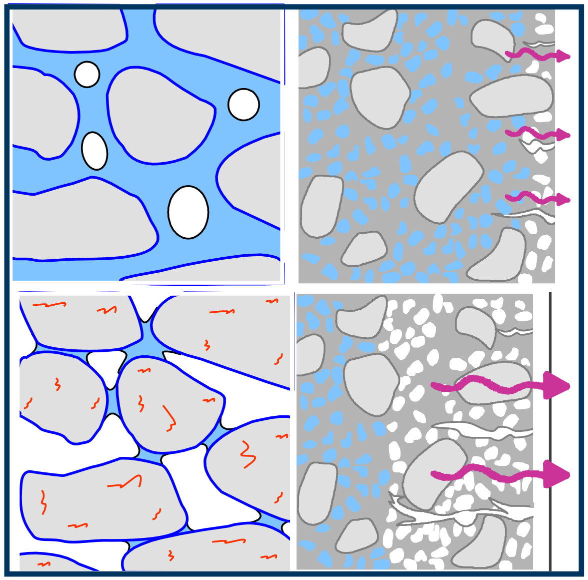

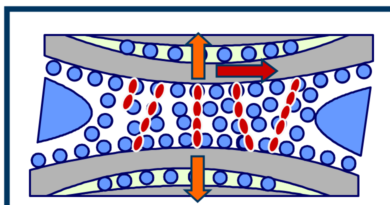

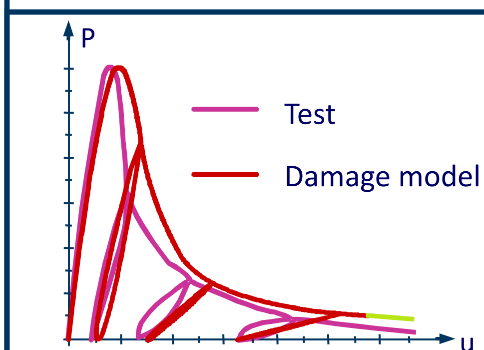

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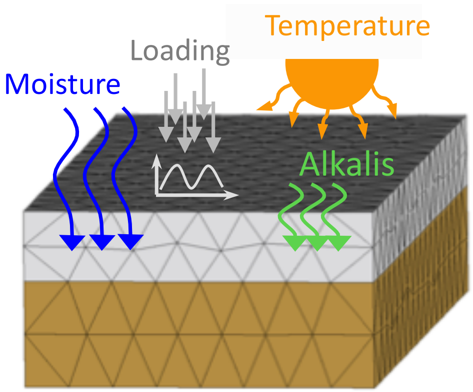
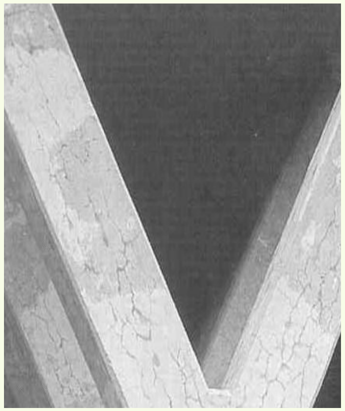
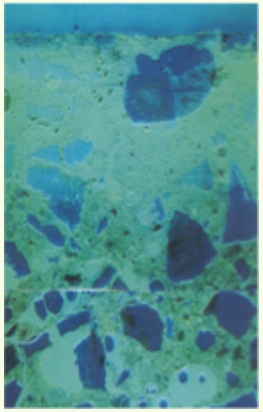


ASR damage in Road surfaces



ASR damage in concrete structures

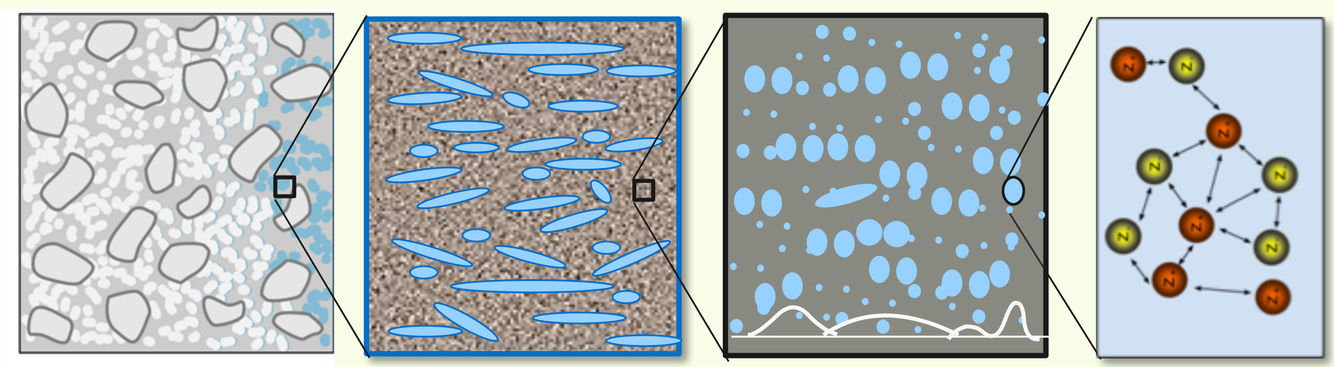


Calcium Leaching in concrete

Reinforcement Corrosion

Lifetime prognosis

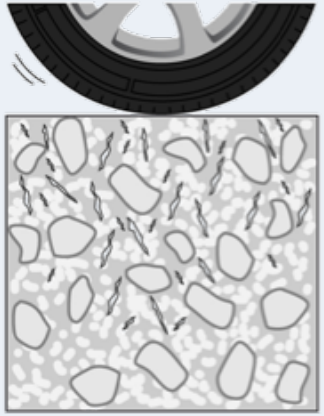
Scale-bridging Modeling



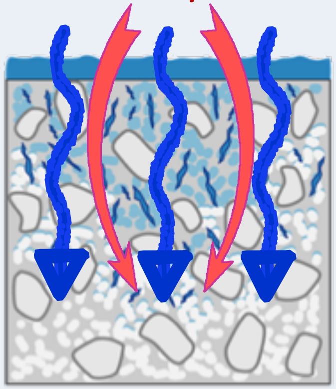
Meter | Millimeter | Micrometer | Nanometer

Durabilty of concrete infrastructure: A multiscale perspective

RUB

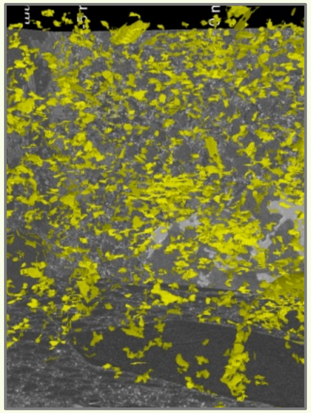


Diffuse fatigue damage in road pavements caused by traffic

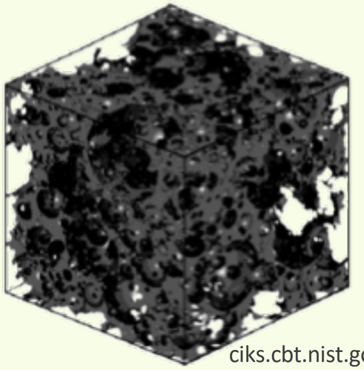


Water and Alkali transport in damaged concrete

ASR damage in road surfaces



Microcracks in concrete

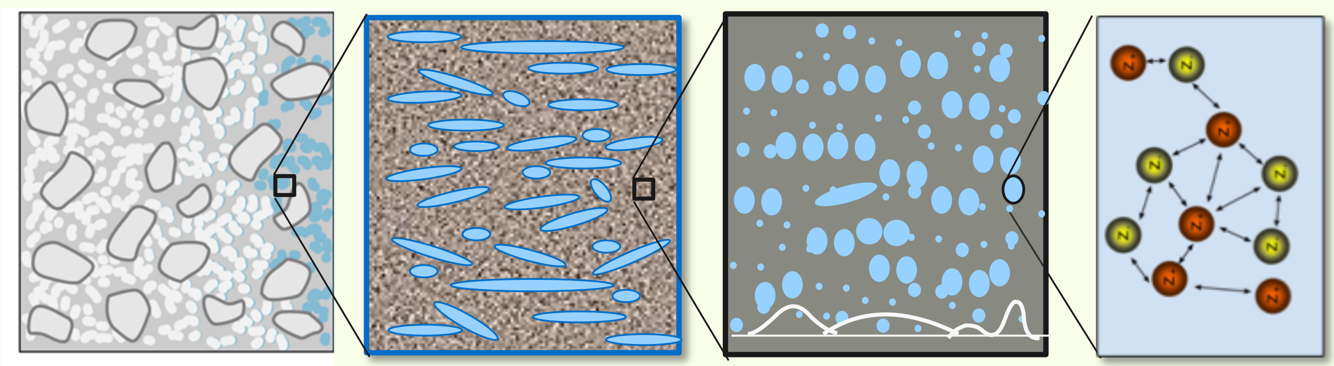


ciks.cbt.nist.gov

Pore space

CSH phases

Scale-bridging Modeling of Transport processes



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Durabilty of concrete infrastructure: A multiscale perspective

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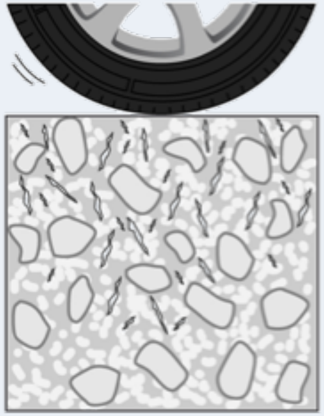

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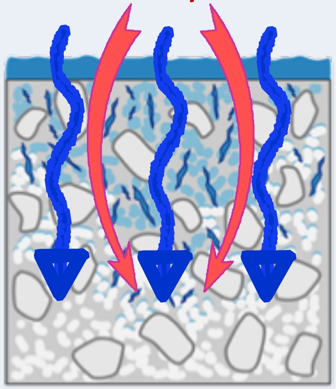

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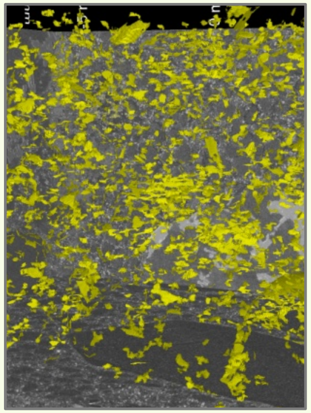
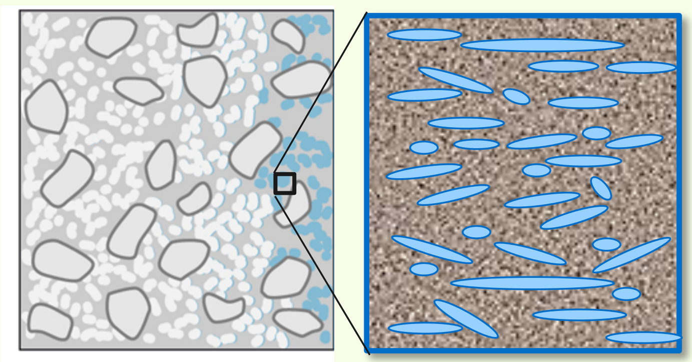


Microcracks in concrete

Influence of microcracks on transport processes ?

Scale-bridging Modeling of Transport processes



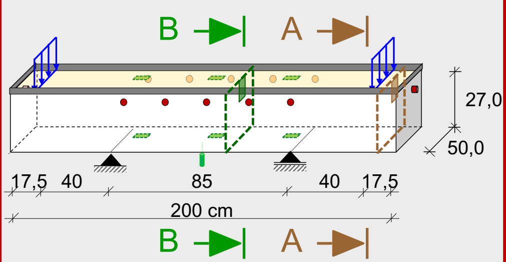
Determination of macroscopic stiffness diffusivity and permeability depending on state of damage

Experimental evidence

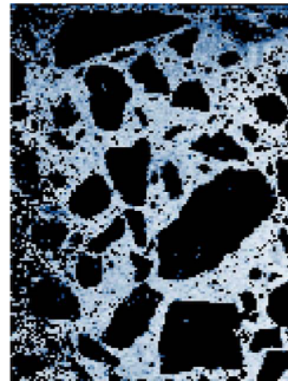
RUB

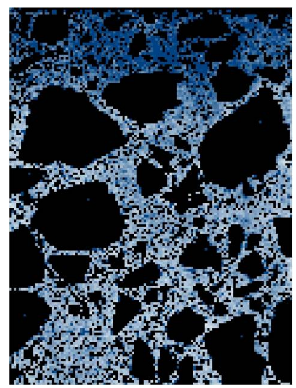
Influence of diffuse load-induced damage on Alkali transport in concrete

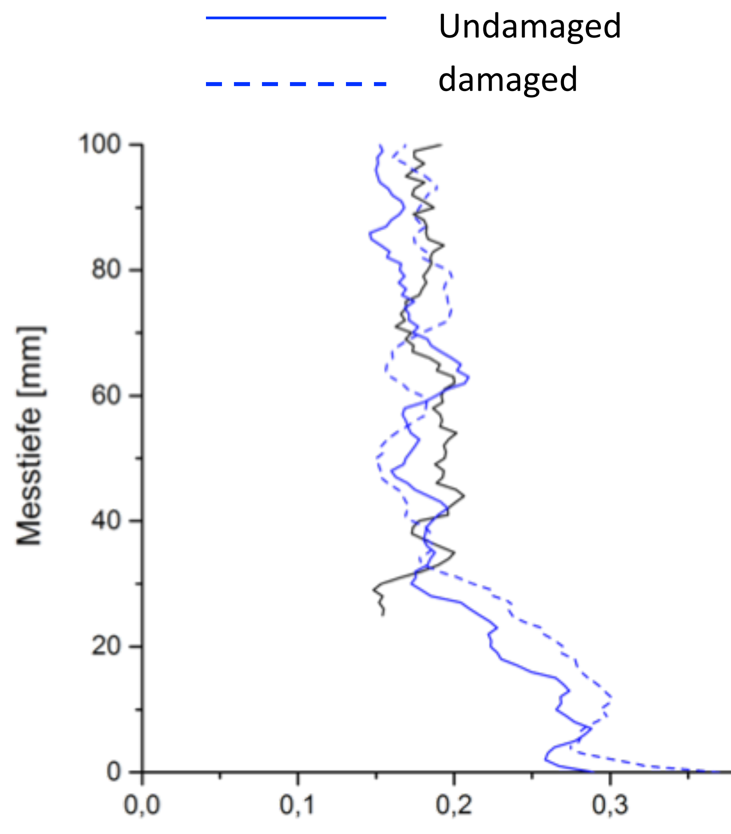
R. Przondiono et al. Beton- und Stahlbeton 2014



5 Mio. load cycles







Load induced damage

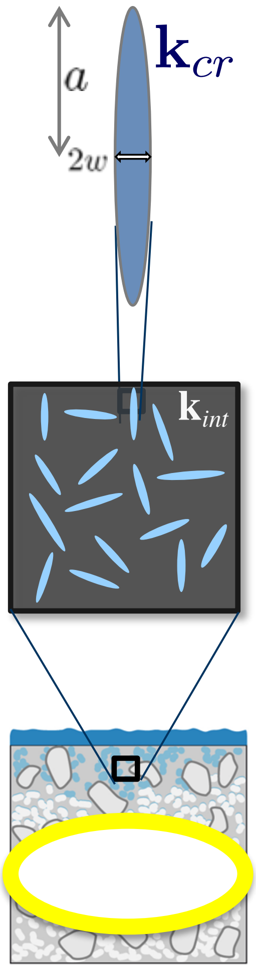
Vertical section

CT scan

Na-profiles

F. Weise & B. Meng IBAUSIL, Weimar, 2015

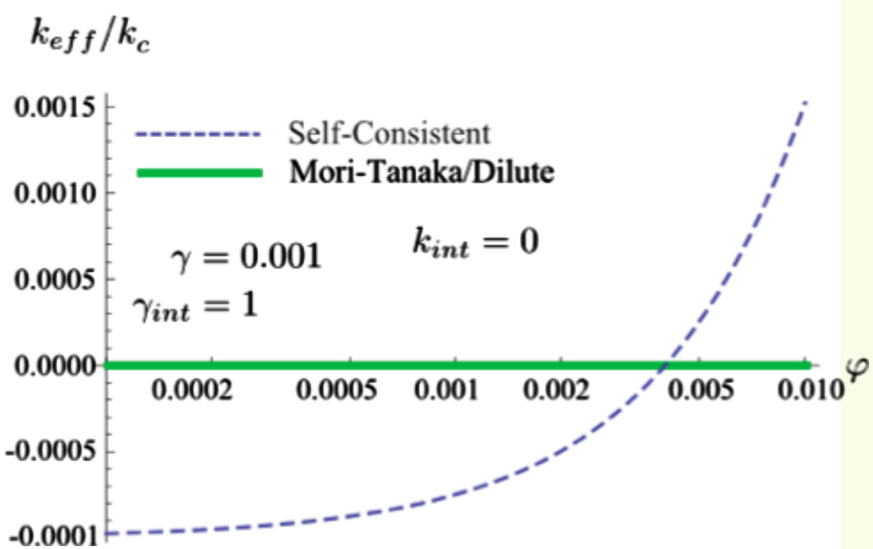
Effective Permeability of Cracked Porous Materials

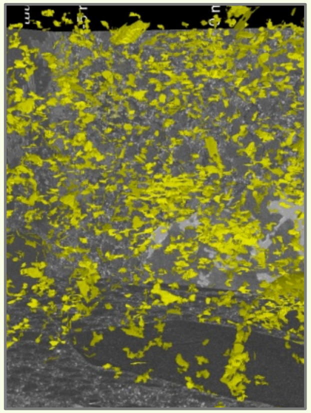


Given the topology of distributed microcracks:

What is the **effective permeability $\mathbf{k}_{eff}$** ?

Does Continuum Micromechanics Homogenization methods work?

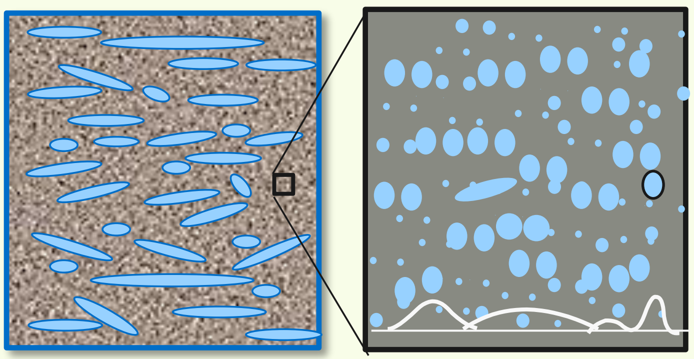




Microcracks in concrete

Pore space

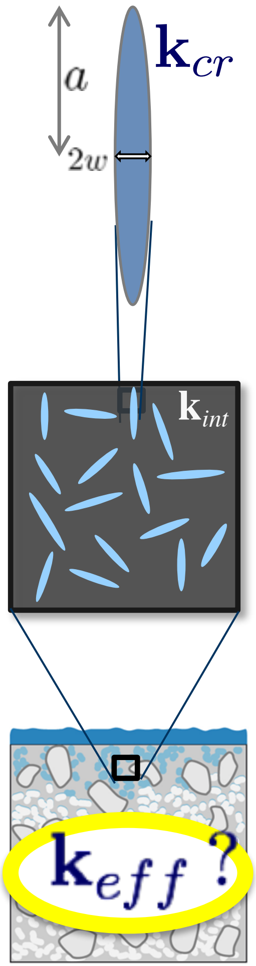
Scale bridging Modeling



Millimeter

Micrometer

Effective Permeability of Cracked Porous Materials



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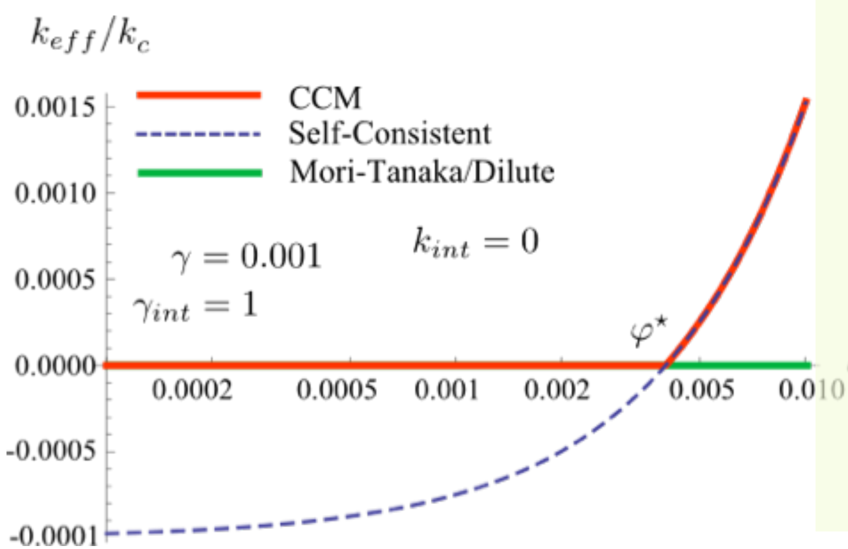
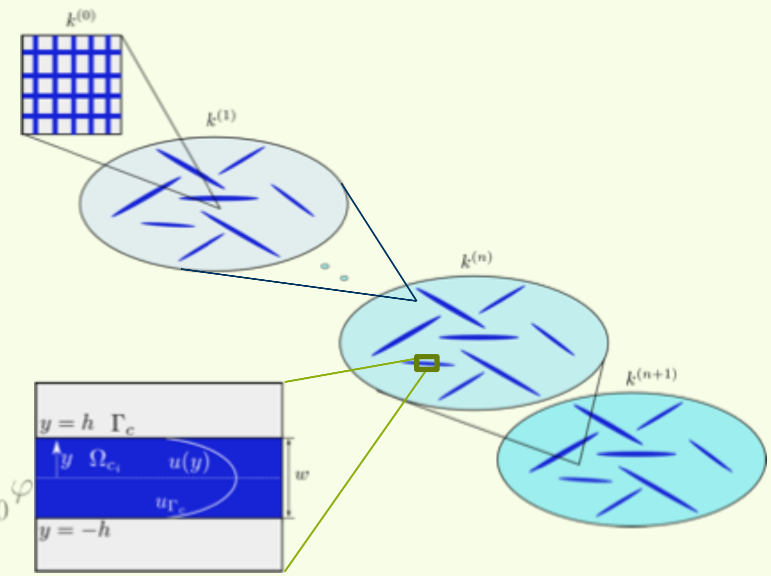
New recursive Micromechanics Model (CCM) for permeability

$$\mathbf{k}_{eff}^{(n+1)} = \left(k_{int}\,(1-\varphi)\,\mathbf{A}_{int}^{(n+1)} + k_c\varphi\mathbf{A}_c^{(n+1)}\right)\cdot\mathbf{B}^{(n+1)}$$

$$\mathbf{A}_c^{(n)} = \mathbf{K}^{(n)}\cdot\left(\mathbf{K}^{(n)} - \mathbf{P}_c^{(n)}\right)^{-1}$$

contrast shape





J. J. Timothy & GM (2016): Mechanics of Materials

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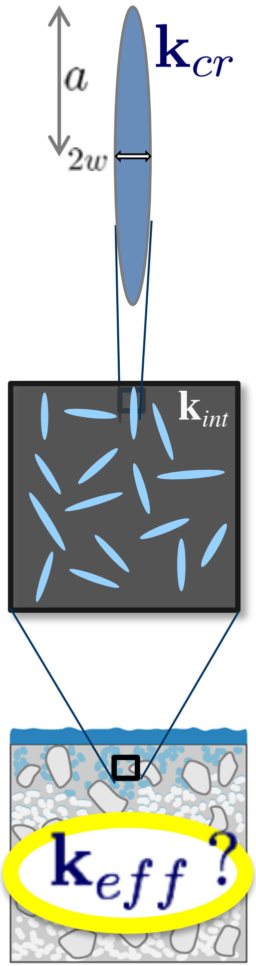

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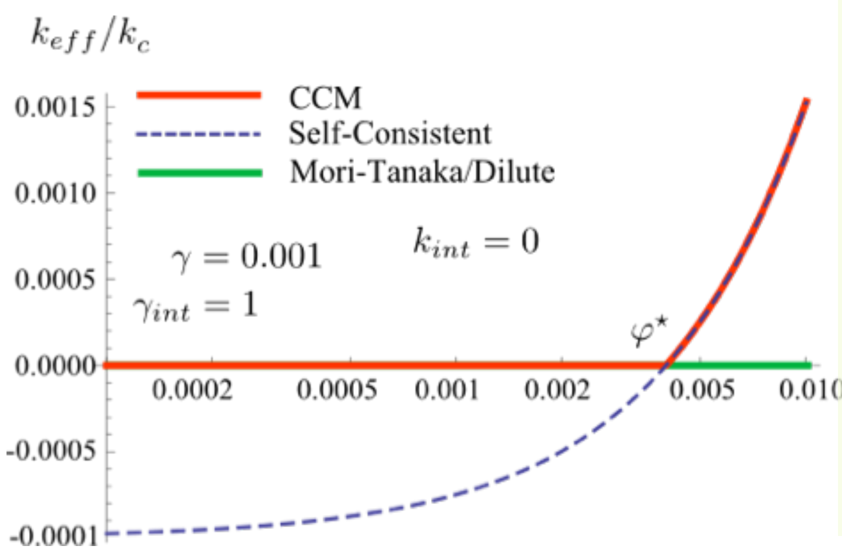
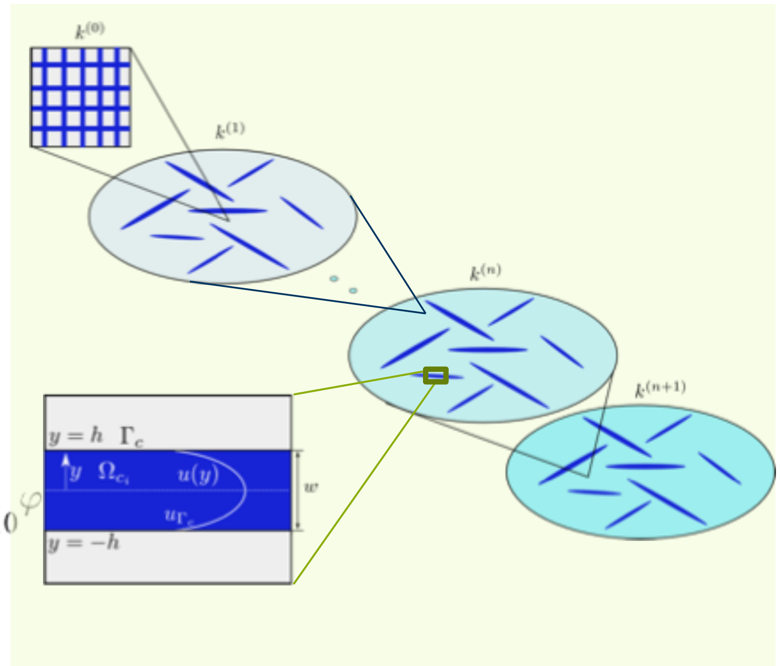
$$k_c = \frac{w^2}{12}$$

not strictly valid for permeable matrix

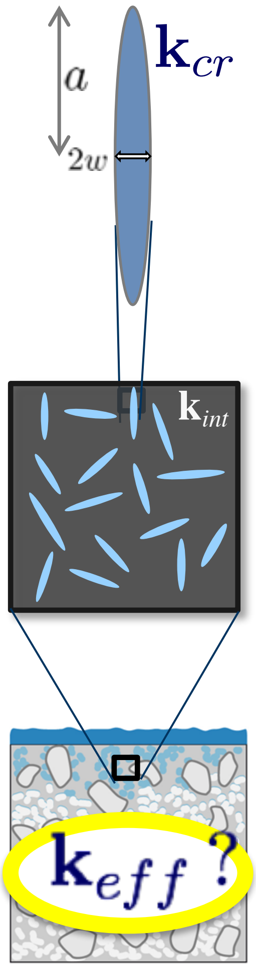




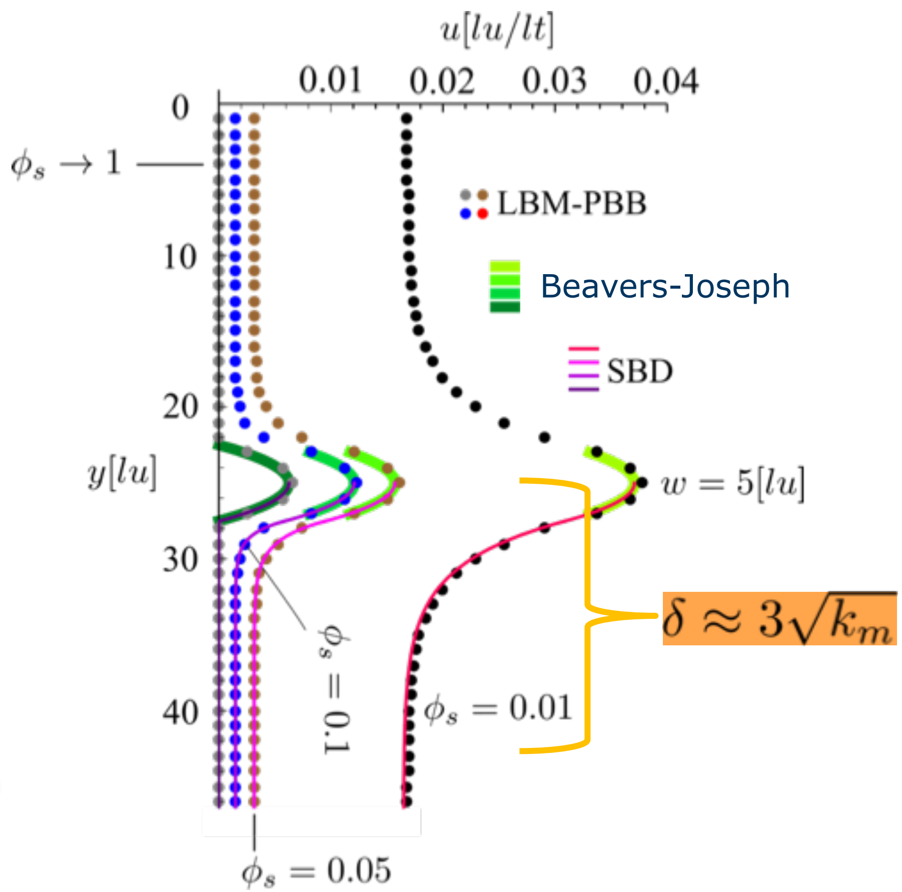
J. J. Timothy, G. Meschke: Mechanics of Materials, 2016

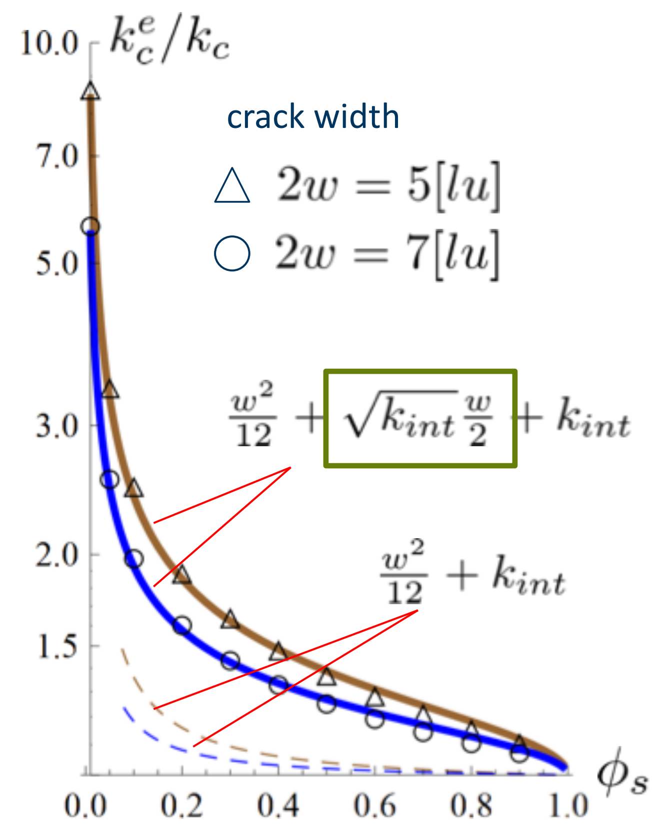
RUB

Analytical models vs. LBM-PBB simulations



Fluid-velocity profile





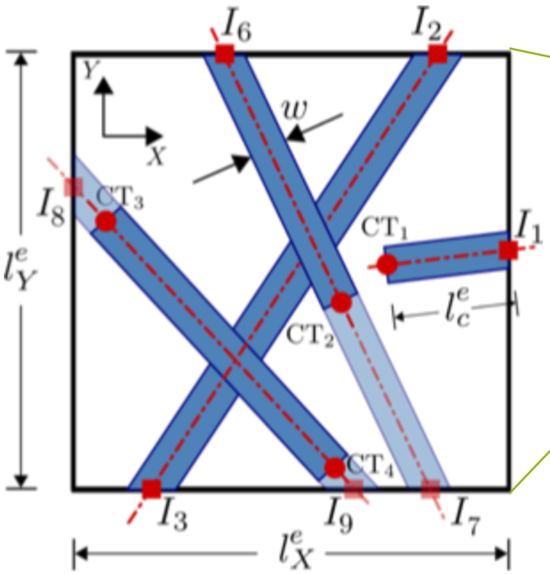
$w \approx 6\sqrt{k_m}$

-> cubic law not valid !

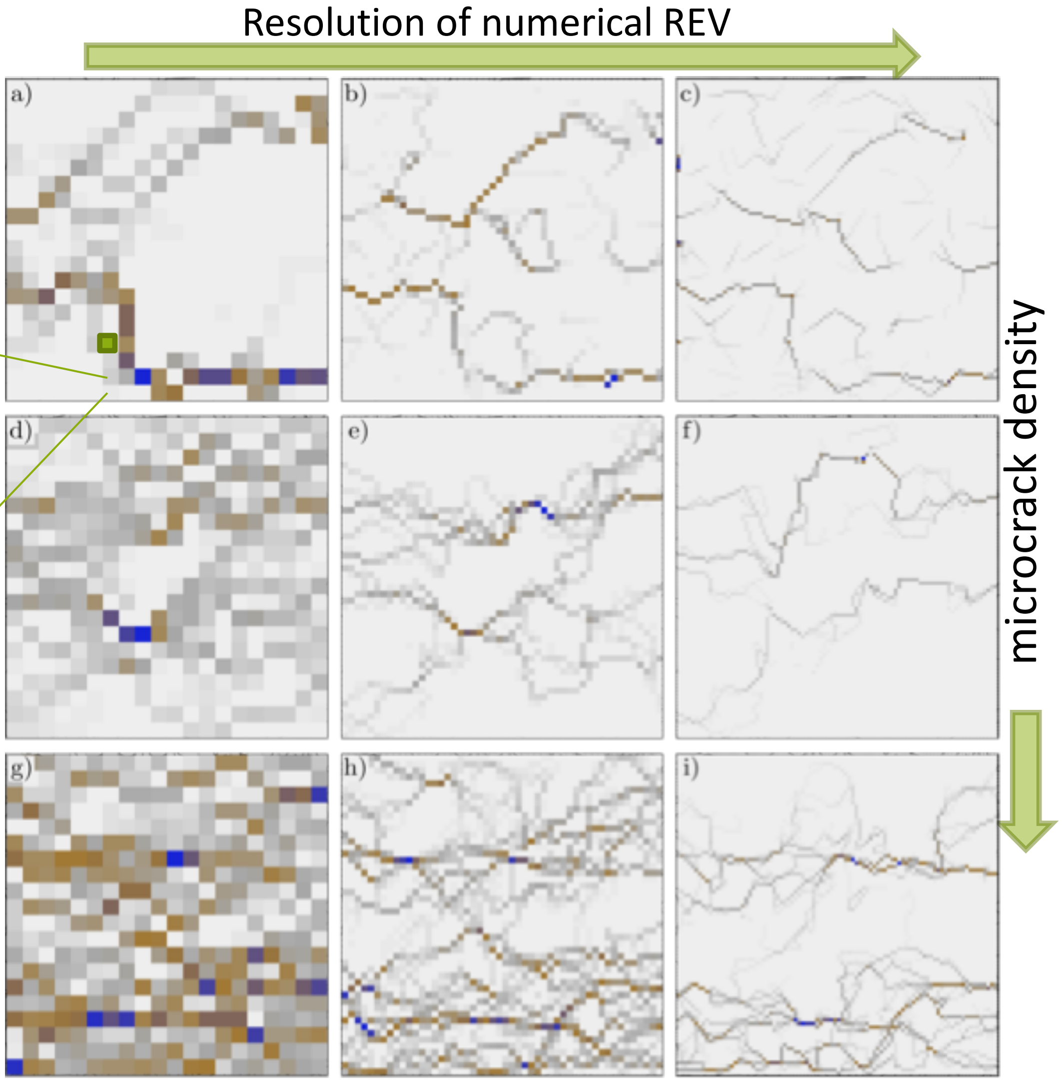
Timothy, J. J. & GM, (2017) *International Journal for Numerical and Analytical Methods in Geomechanics.*

Computational meso-scale analyses vs. Cascade Micromechanics Model

Effective Permeability computed for different microcrack densities and FE meshes



$$\mathbf{k}^e = \mathbf{k}_{int}(1-\varphi^e) + \mathbf{t}_{\Gamma_c}^T\, k_c^t(w)\varphi^e\, \mathbf{t}_{\Gamma_c}$$



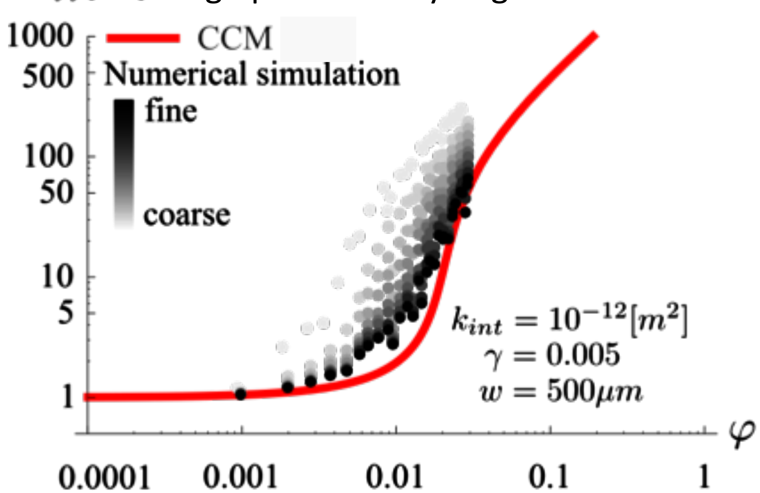
D. Leonhart, J. Timothy & GM (2017) Mechanics of Materials

Effective permeability of cracked porous materials

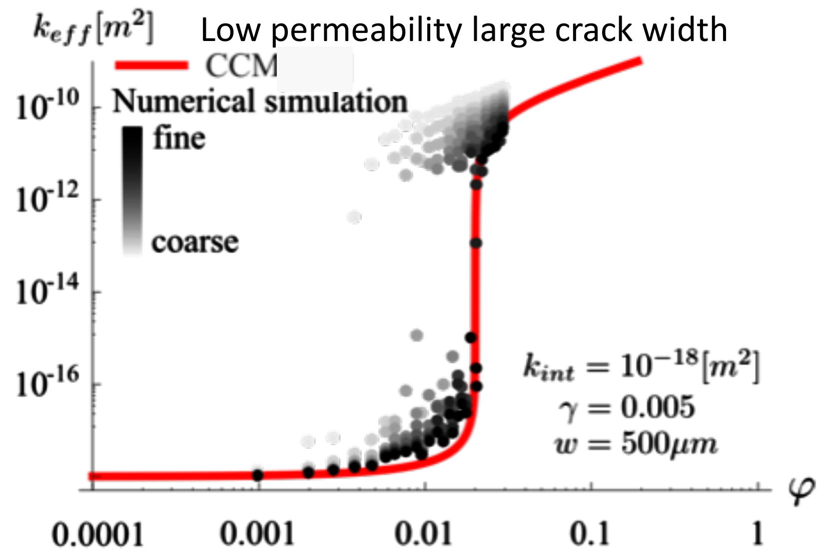
RUB

Computational Meso-scale Analyses vs. Cascade Micromechanics Model

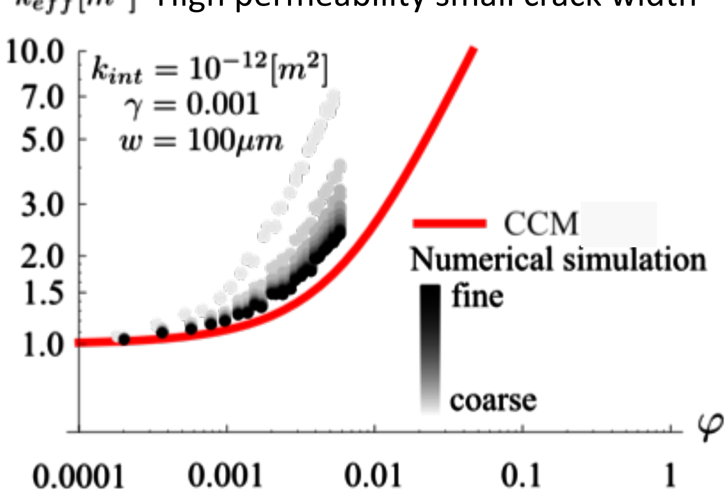
High permeability large crack width



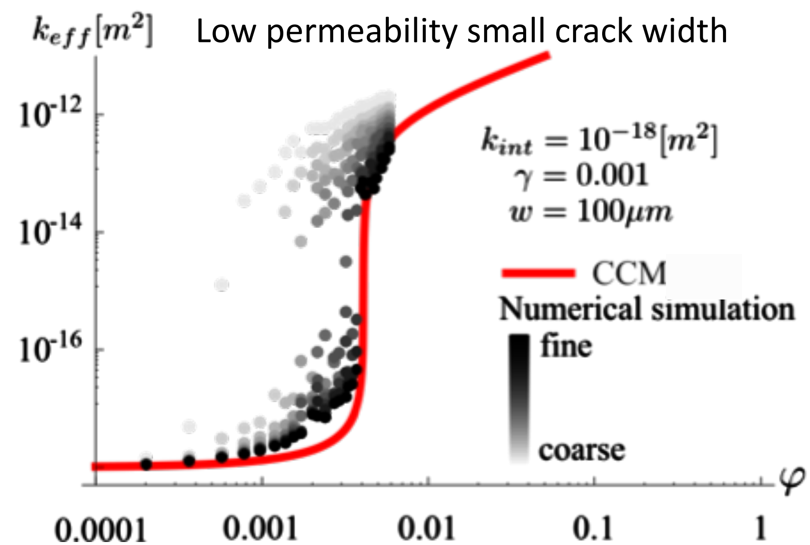
Low permeability large crack width



High permeability small crack width



Low permeability small crack width



Effective permeability of cracked porous materials

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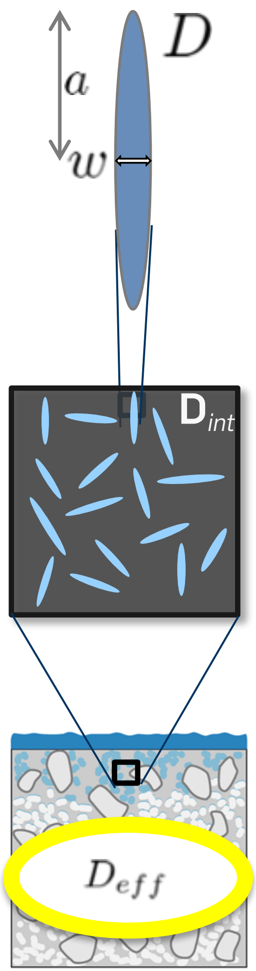
Transient diffusion:



Isotropic Distribution

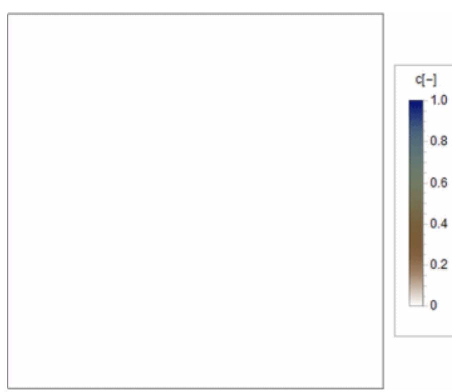
Anisotropic Distribution

0 microcracks

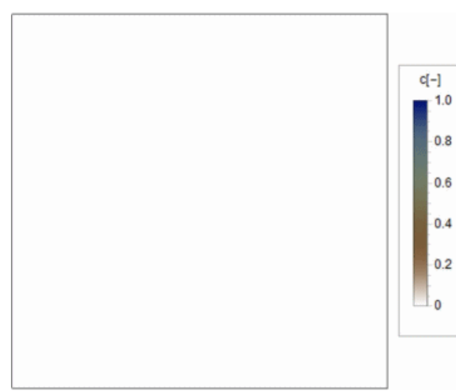
100 microcracks

100 microcracks

0 microcracks



500 microcracks

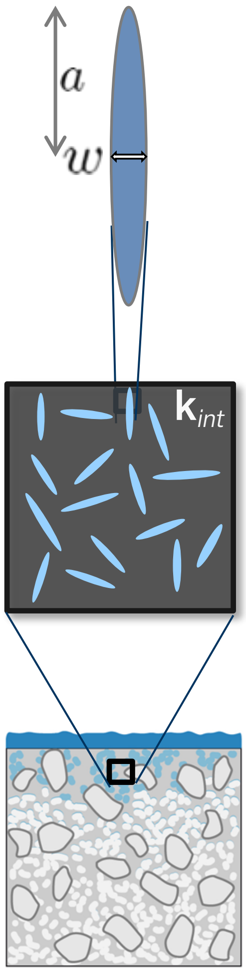


500 microcracks

Timothy, J. J. & GM, (2017) Transport in Porous Media, in review

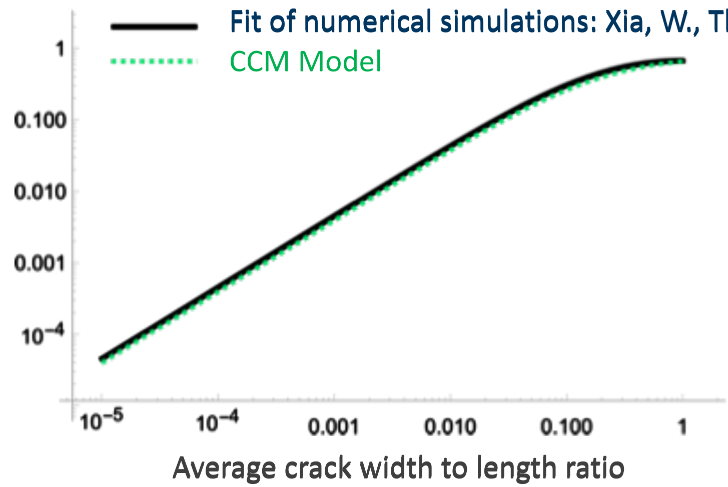
RUB

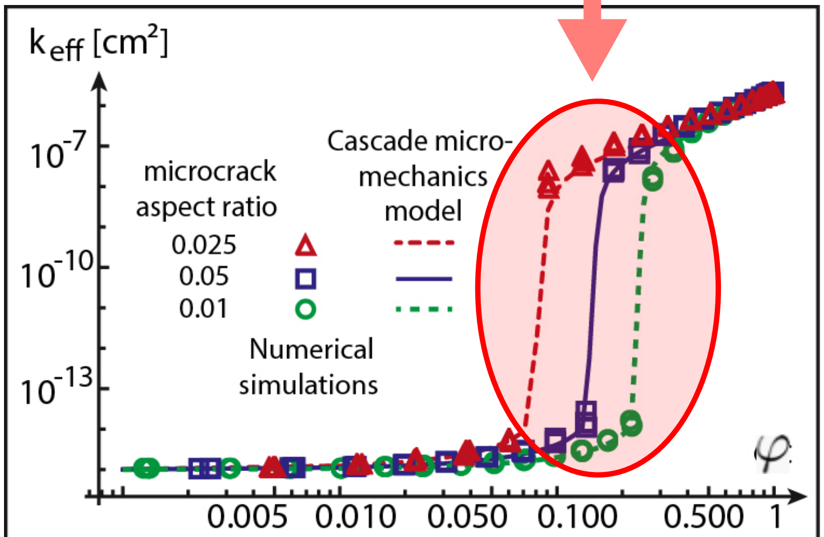
Cascade Continuum Micromechanics Model: Upscaled flux



$$\mathbf{k}_{eff}^{(n+1)} = \left(k_{int}\,(1-\varphi)\,\mathbf{A}_{int}^{(n+1)} + k_c \varphi \mathbf{A}_c^{(n+1)}\right) \cdot \mathbf{B}^{(n+1)}$$

Percolation threshold





Power-law relation with aspect ratio of cracks!

Effective permeability: Connected cluster – fractality

RUB

At percolation: how does the microcrack cluster look like?

- Pixel update formula (Cellular Automata)

$$p^{t+1}(x,y) = H\left[p^{t}(x,y)\right] + (p_p - 1)\,H\left[p^{*}(x,y) - T\right]$$

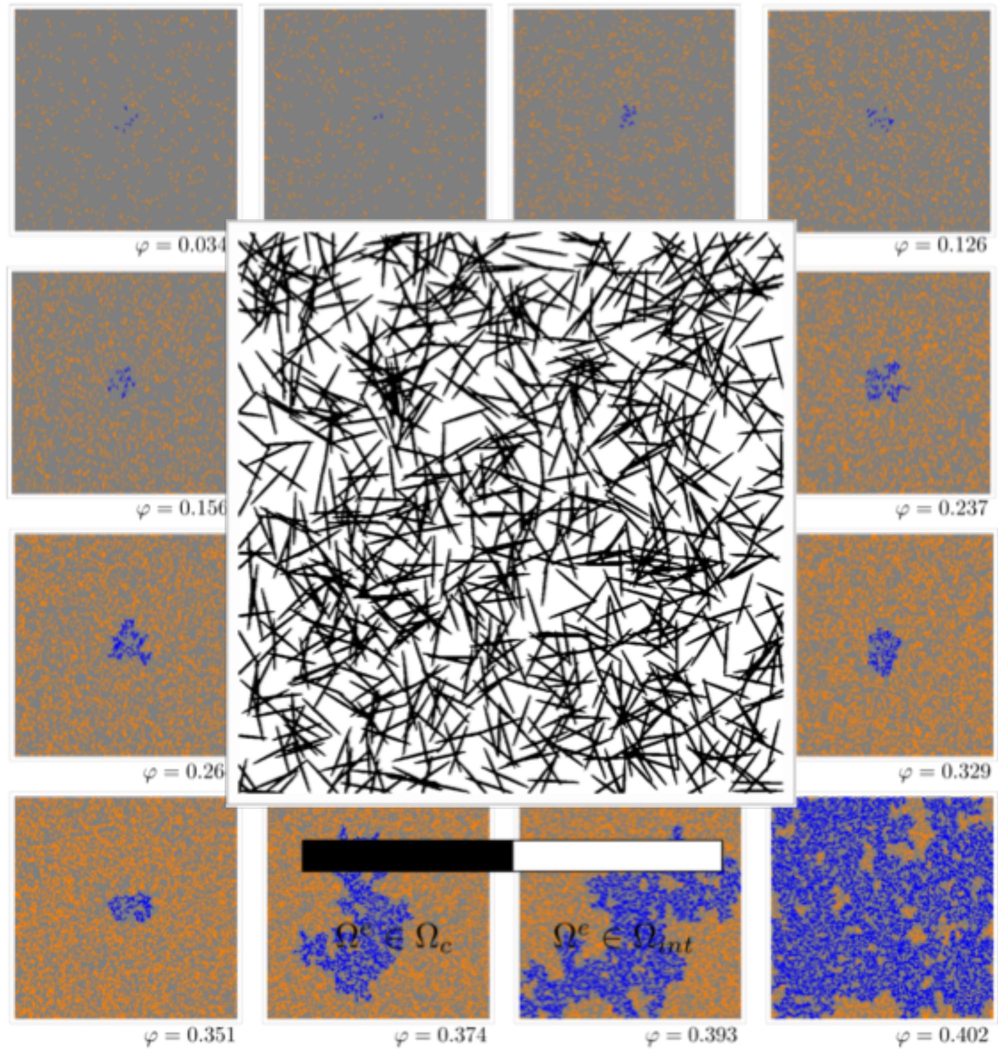
- Moore-Neighbourhood weighting

$$p^{*}(x,y) = \sum_{i=-1}^{1}\sum_{j=-1}^{1} p^{t}(x+i, y+j)\,k(i,j)$$

$$k = \begin{bmatrix} 1 & 1 & 1 \\ 1 & z & 1 \\ 1 & 1 & 1 \end{bmatrix}$$

- Connected microcrack cluster is highly complex with sub-clusters of multiple sizes

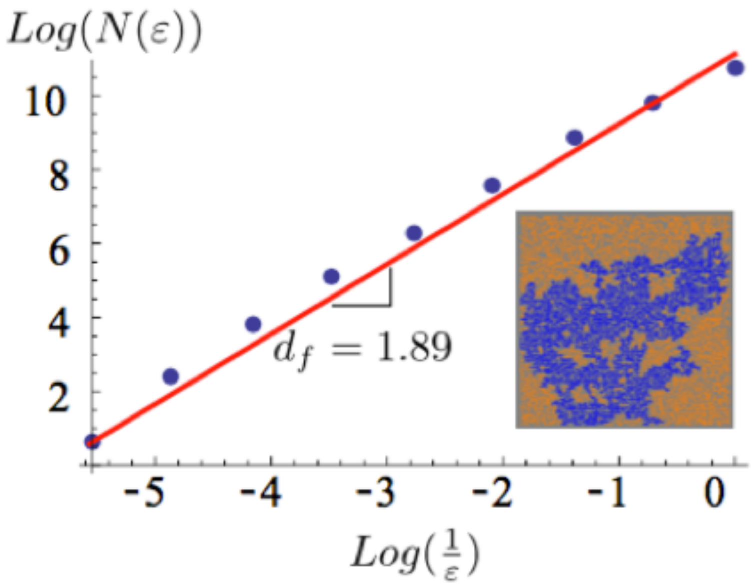
$$\gamma_c = 0.2$$

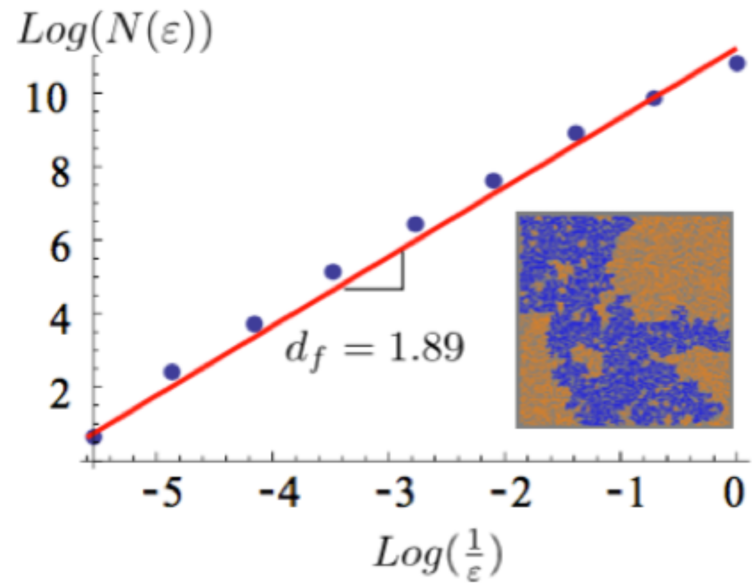


J.J. Timothy & GM., (2017) Cascade continuum micromechanics model for the effective permeability of solids with distributed microcracks: Self-similar mean-field homogenization and image analysis. *Mechanics of Materials*, 104:60-72.

Effective permeability: Connected microcracj cluster – fractality

Fractal dimension around the percolating microcrack cluster (self -similarity):

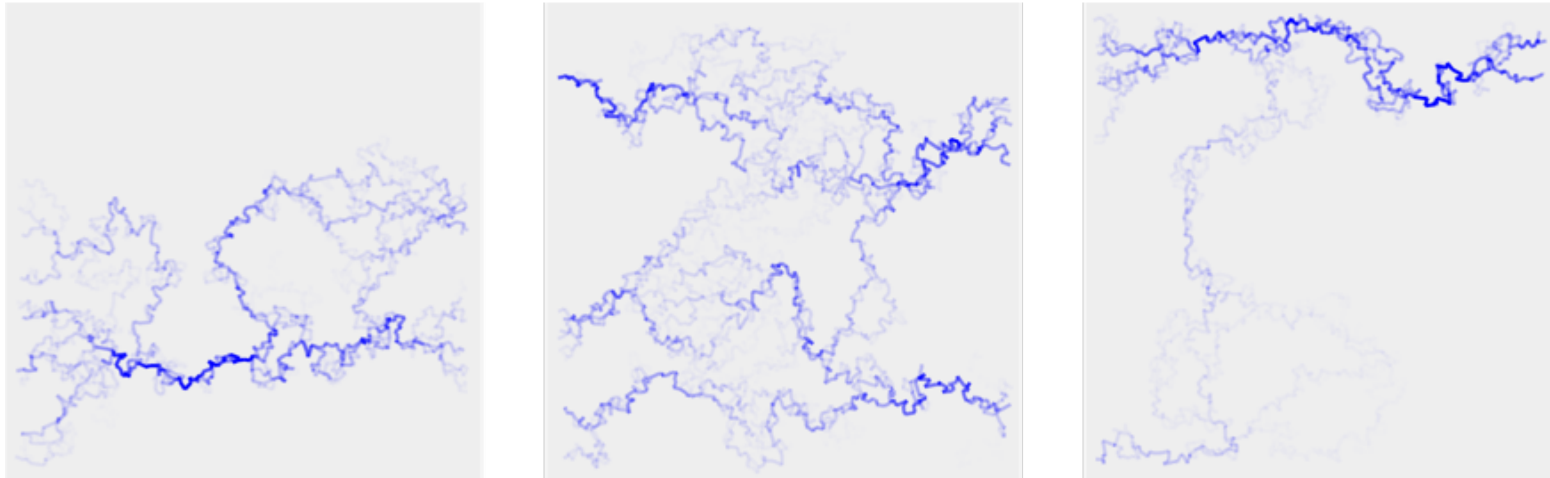




J.J. Timothy & GM (2016) A cascade lattice micromechanics model for the effective permeability of materials with microcracks. *Journal for Nanomechanics and Micromechanics*, 6(4):04016009.

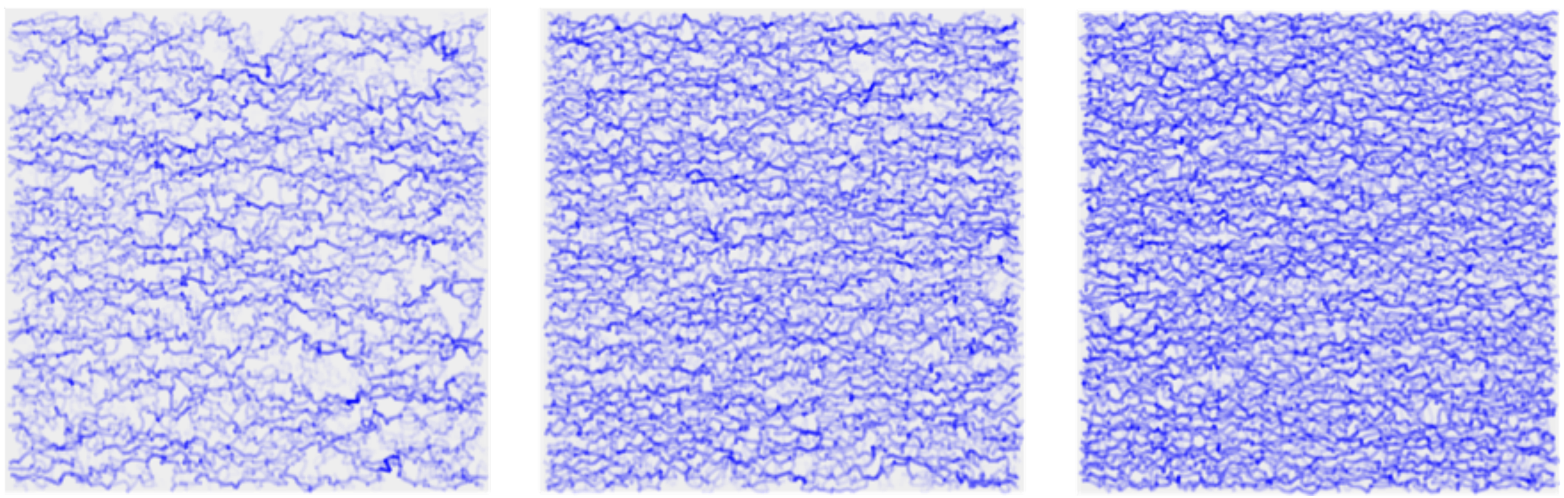
Effective permeability: Connected cluster – fractality

Normalized fluid flux around percolation threshold



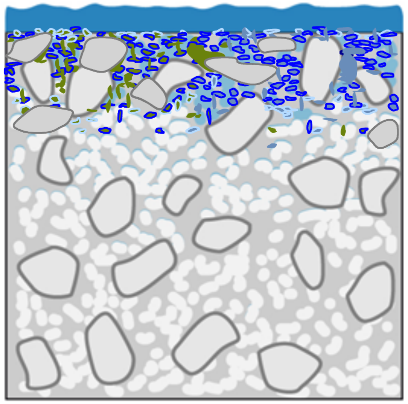
A backbone pathway characterizes the overall transport property

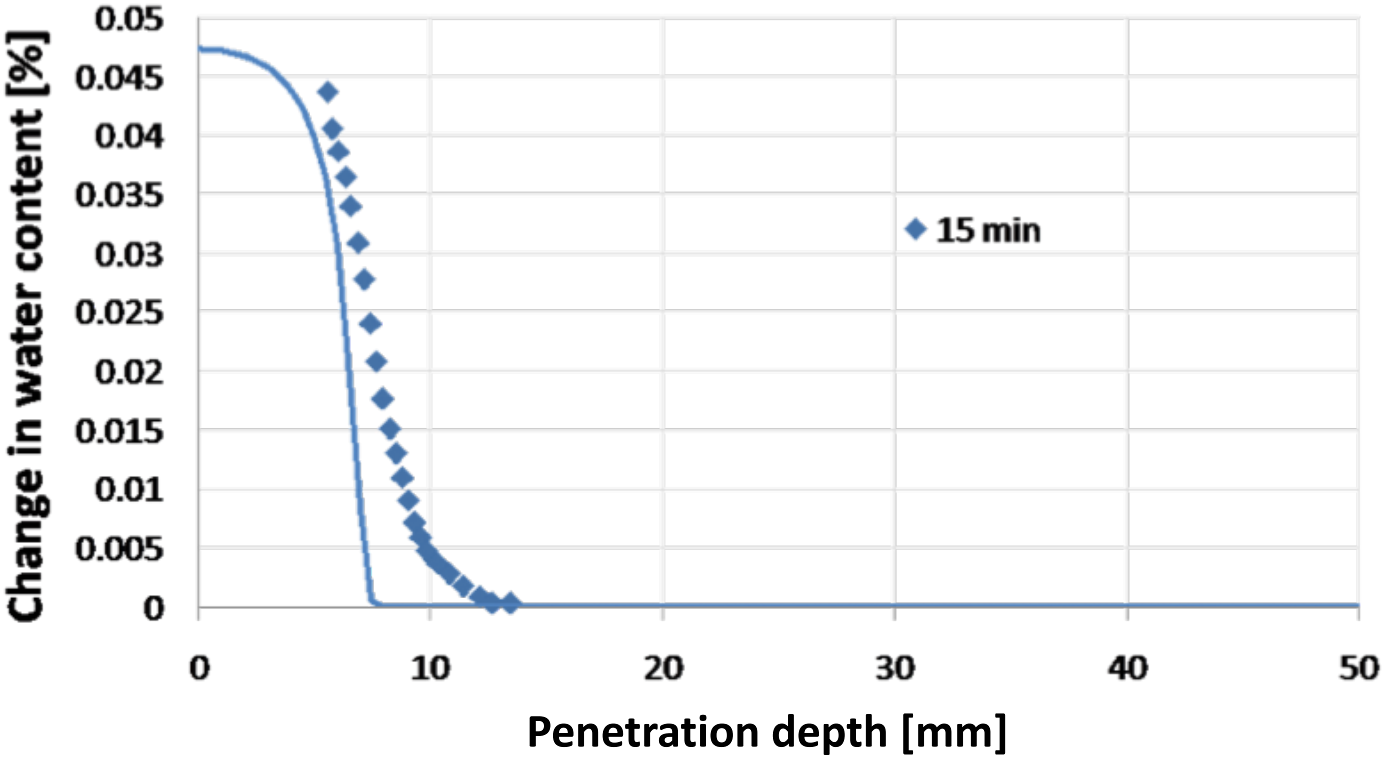
Normalized fluid flux above percolation threshold



J.J. Timothy & GM (2016) A cascade lattice micromechanics model for the effective permeability of materials with microcracks. *Journal for Nanomechanics and Micromechanics*, 6(4):04016009.

Validation: Capillary suction in intact concrete (not pre-damaged)





Experiments: Zhang, Wittmann, Zhao, Lehmann & Vontobel. Neutron radiography, a powerful method to determine time-dependent moisture distributions in concrete, Nuclear Engineering and Design, 2011

Fluid Transport in Cracked Porous Materials: Experimental Validation

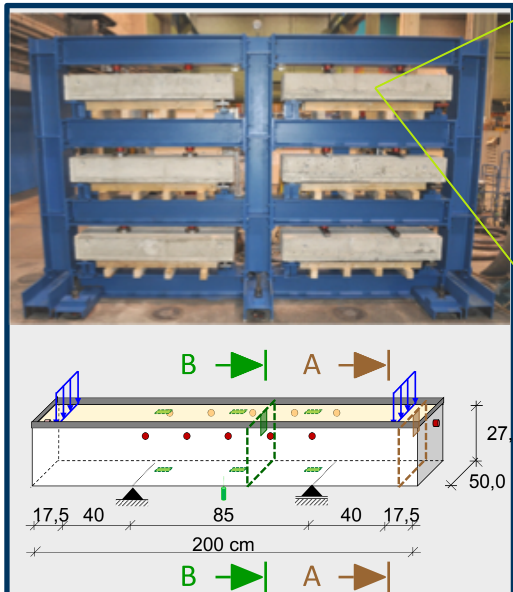
RUB

Validation: Capillary suction in pre-damaged concrete

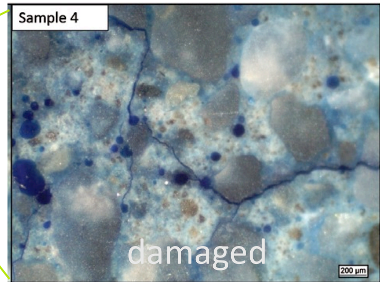
Cyclic Mechanical Loading

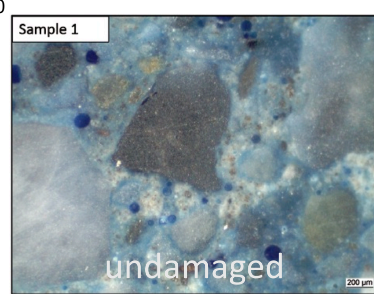
Microscopic Analysis

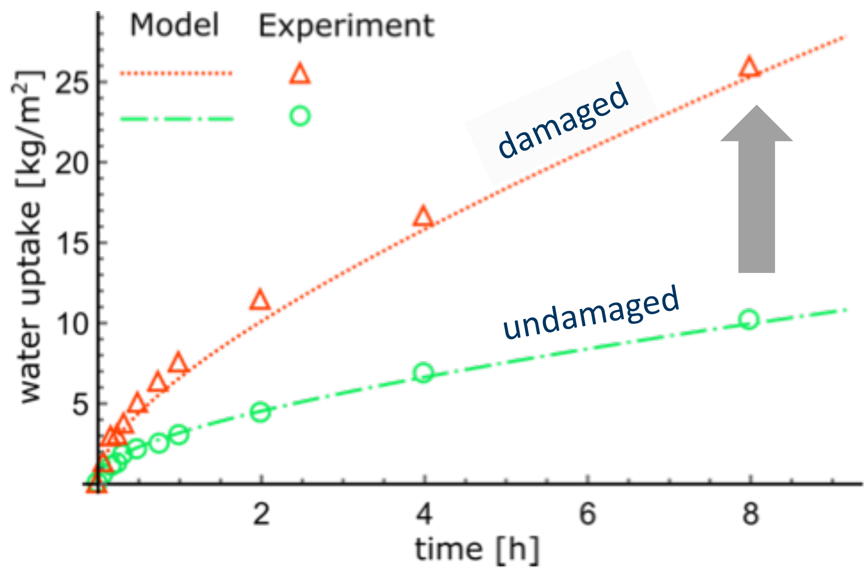
Computed vs. Measured water uptake



5 Mio. Load cycles



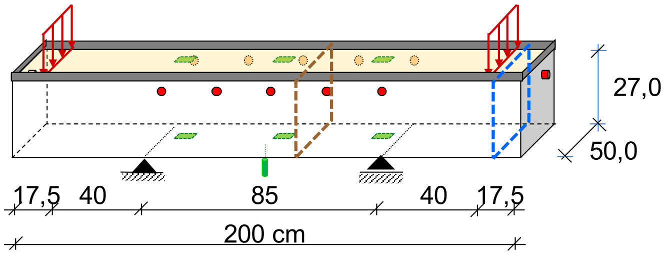




Permeability computed from measured microcrack density from microscopic crack analysis via homogenization

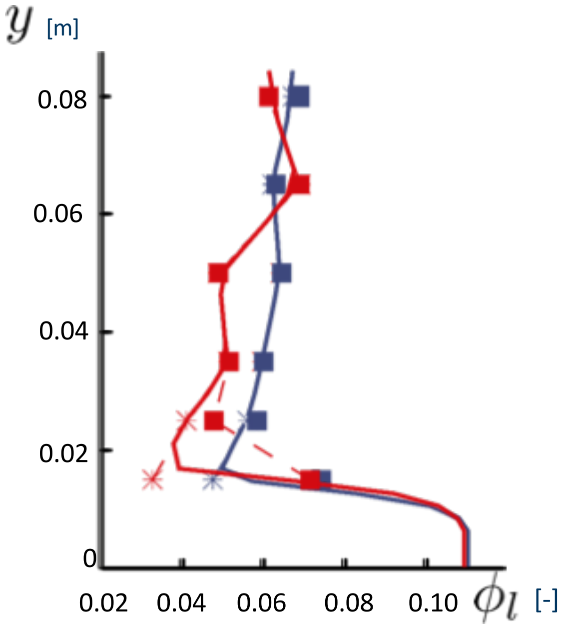
Przondziono, R., Timothy, J. J., M., Weise, Krutt, E., F., Breitenbücher, R., GM & Hofmann, M. (2017). Degradation in concrete structures due to cyclic loading and its effect on transport processes - Experiments and Modelling. *Structural Concrete*

Influence of diffuse fatigue cracks on water transport

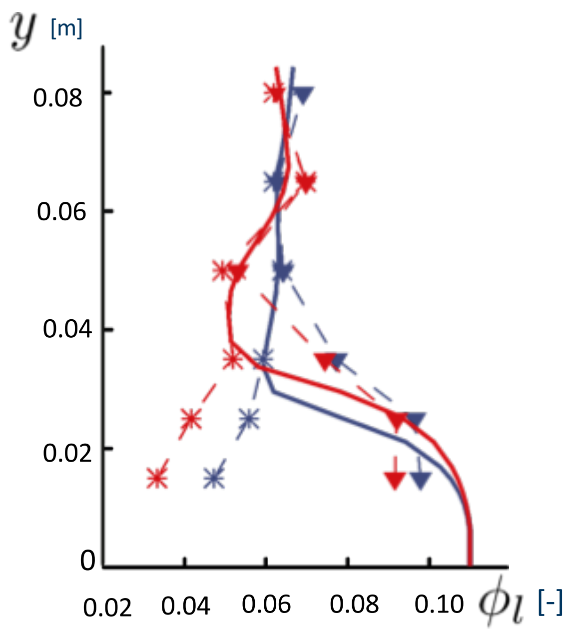


	Experiment	Model
Intact concrete	✱ ■ ▼ ▲	——
Cracked concrete	✱ ■ ▼ ▲	——

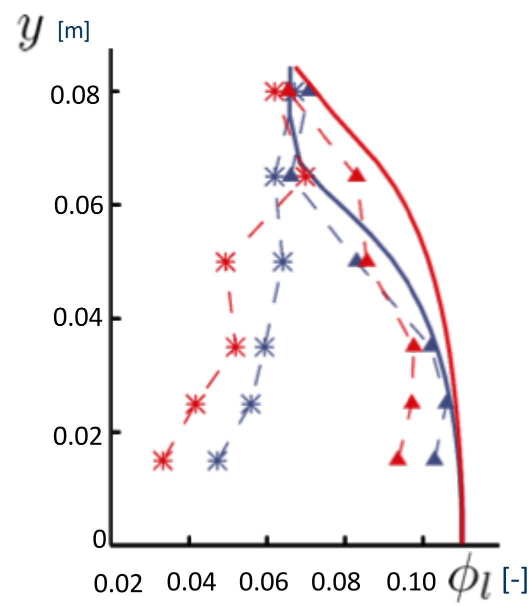
3 hours



24 hours



163 hours

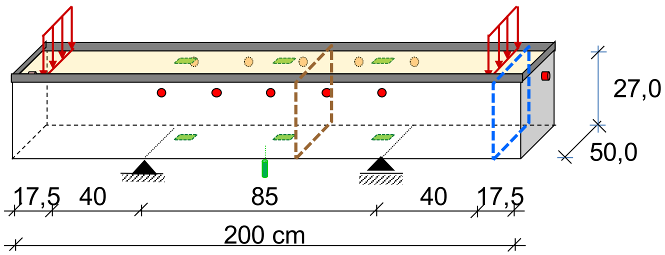


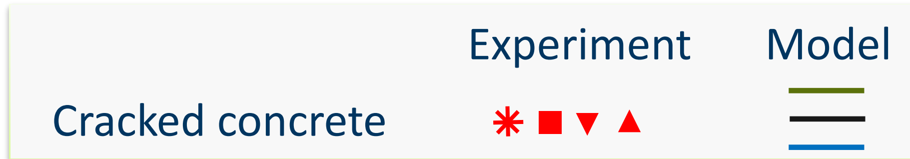
TDR Messungen: BAM – FOR 1498, TP 4, siehe Weise, Meng et al. IBAUSIL 2011

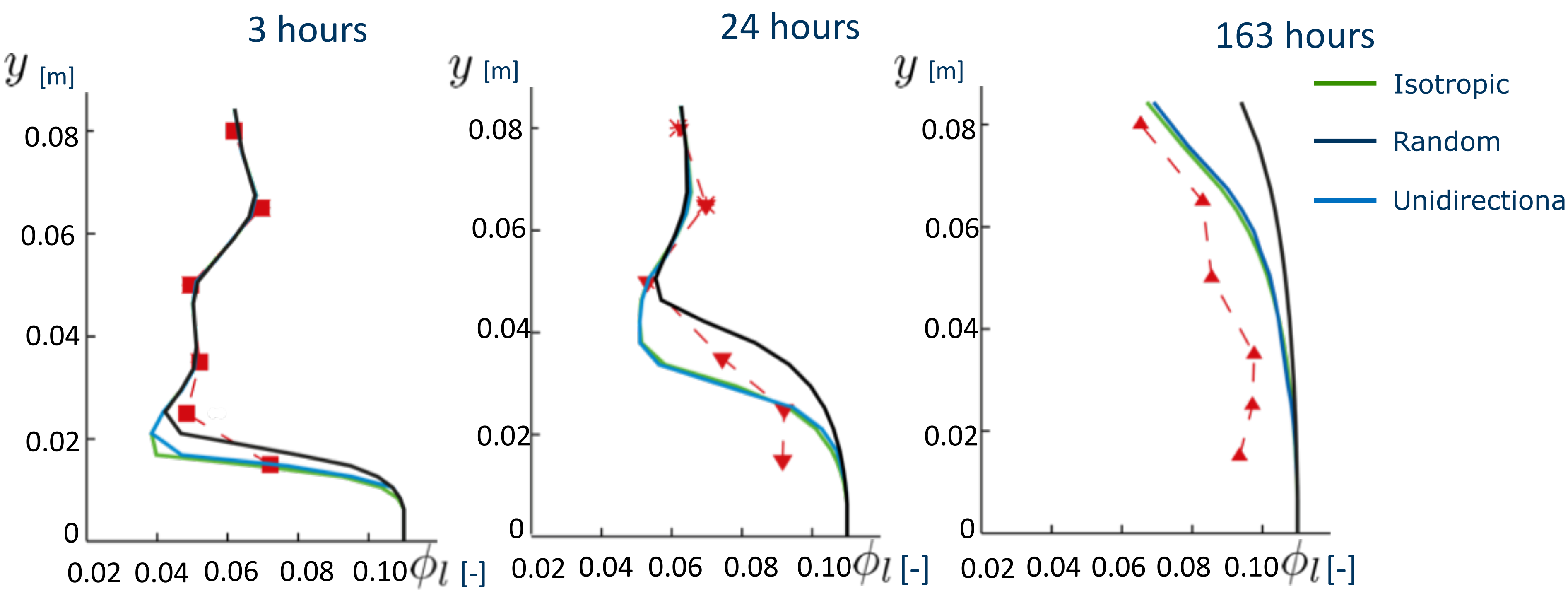
Fluid Transport in cracked concrete: Experimental Validation

RUB

Influence of crack topology



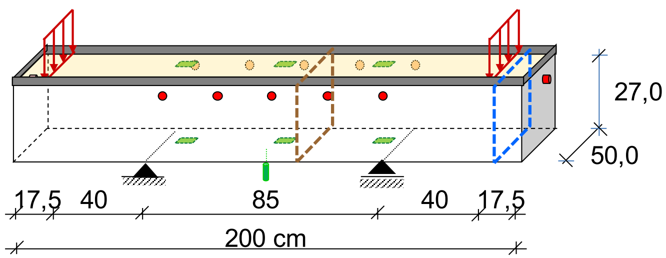




TDR Measurements: BAM 2015

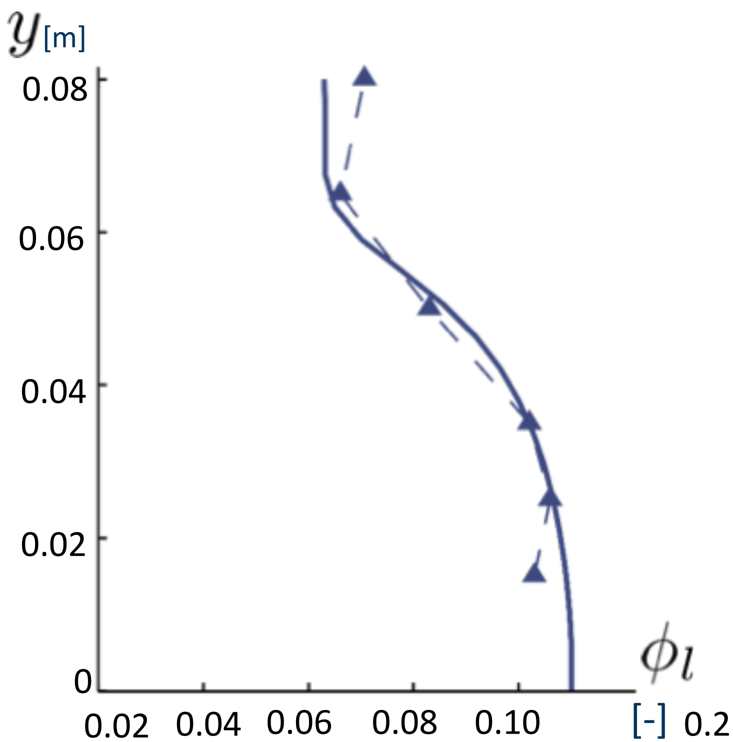
Coupled Ion-Fluid Transport in cracked concrete: Validation

RUB

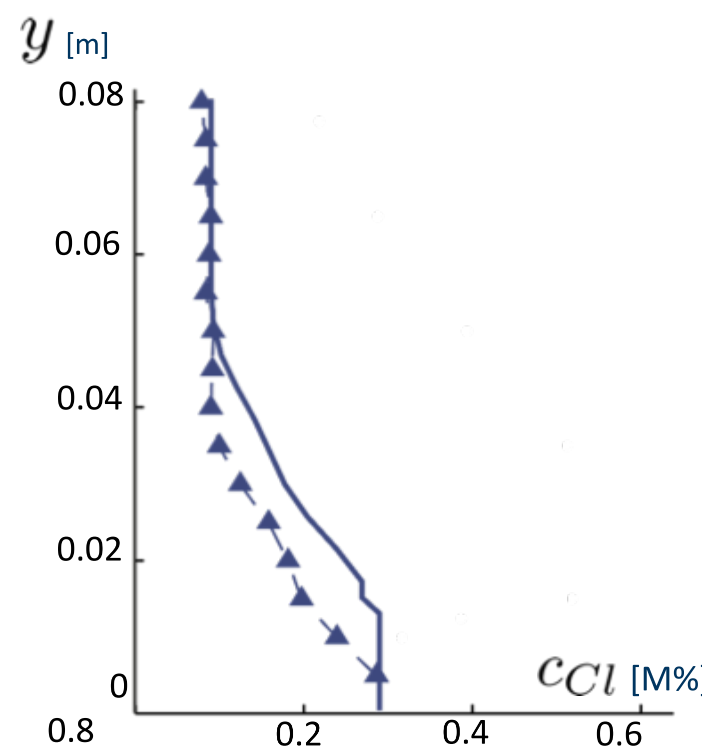


Experiment	Model
▲	—

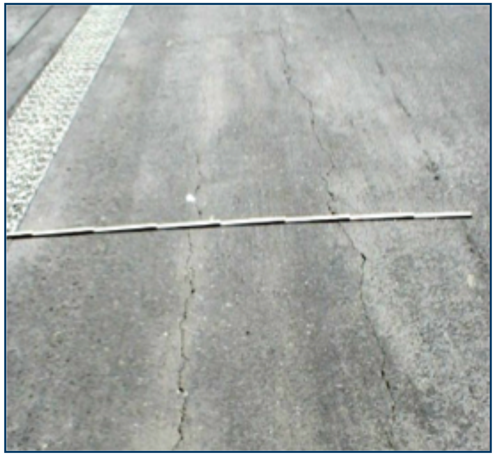
Fluid transport after 163 hours

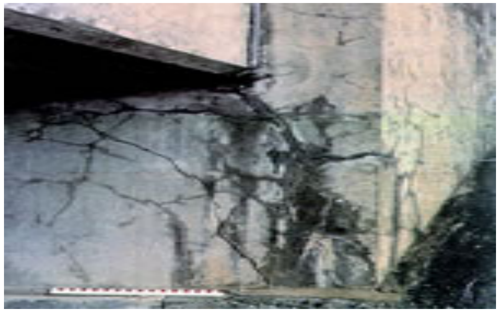


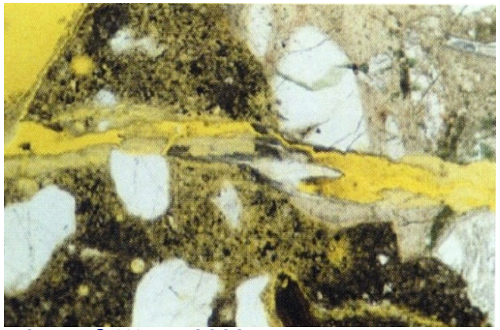
Cl- ion profile after 163 hours



Messungen: BAM 2016





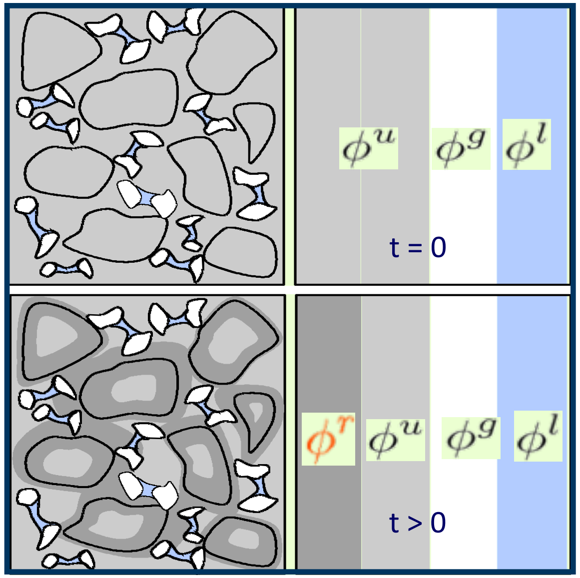


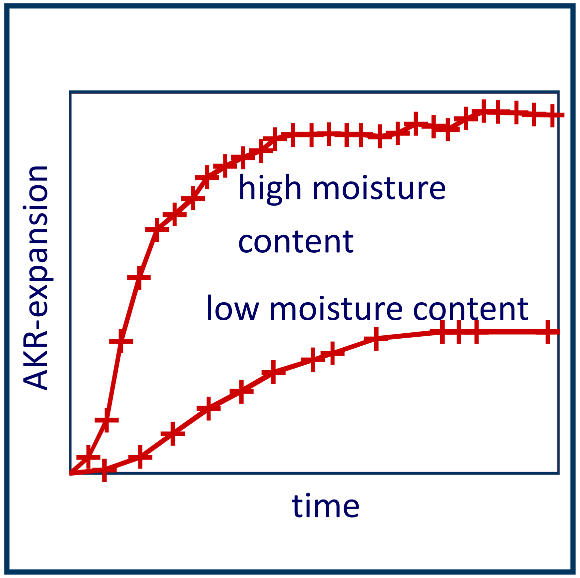
STARK & WICHT 2000

- Chemical reaction between silica (SiO_2) in aggregates and alkalihydroxids in pore solution results in formation of a gel
- Gel swells by imbibition of water and exerts pressure on skeleton
- Reaction rate and level depends on moisture content

- Consequences:
- Macroscopic expansion
- Opening and propagation of cracks
- Reduction of stiffness and load carrying capacity

Phenomenological model of ASR-induced deterioration in concrete





Solid skeleton φ^s
- Unreacted, unswollen constituent φ^u
- Reacted, swollen constituent φ^r

mass exchange between unreacted and reacted phase

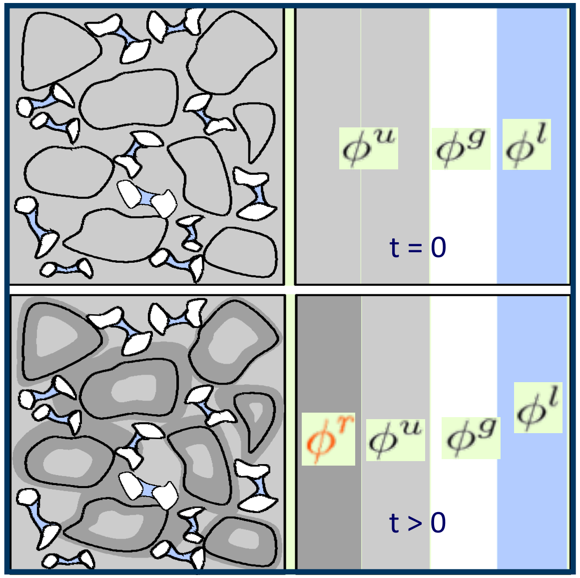
$$\varrho^u \frac{\partial \phi^u}{\partial t} = \varrho^u \frac{\partial \phi^{u \to r}}{\partial t} \qquad \varrho^r \frac{\partial \phi^r}{\partial t} = \varrho^r \frac{\partial \phi^{r \leftarrow u}}{\partial t}$$

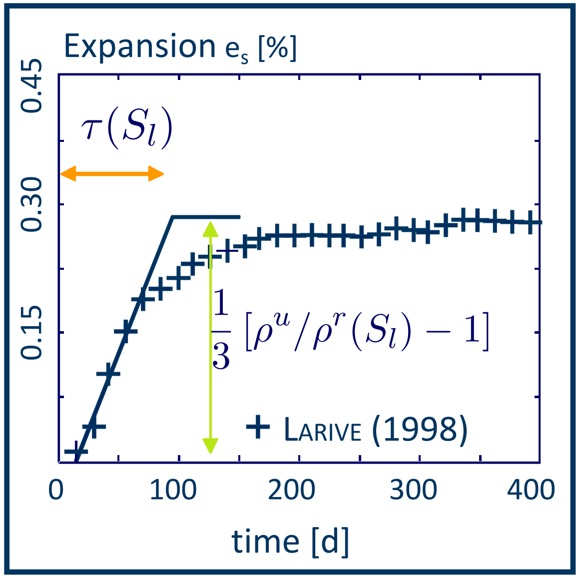
1st order kinetic law: $\varrho^u \frac{\partial \phi^{u \to r}}{\partial t} = -\frac{1}{\tau(S_l)} \varrho^u \phi^u$

$\frac{1}{\tau(S_l)}$: reaction velocity: depends on S_l

Phenomenological model of ASR-induced deterioration in concrete

RUB





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$\dfrac{1}{\tau(S_l)}$: reaction velocity: depends on S_l

Macroscopic ASR expansion: $\varepsilon_s^a = \dfrac{1}{3}\left[\dfrac{\varrho^u}{\varrho^r} - 1\right]\xi$

Reaction degree: $\xi = 1 - e^{-t/\tau}$

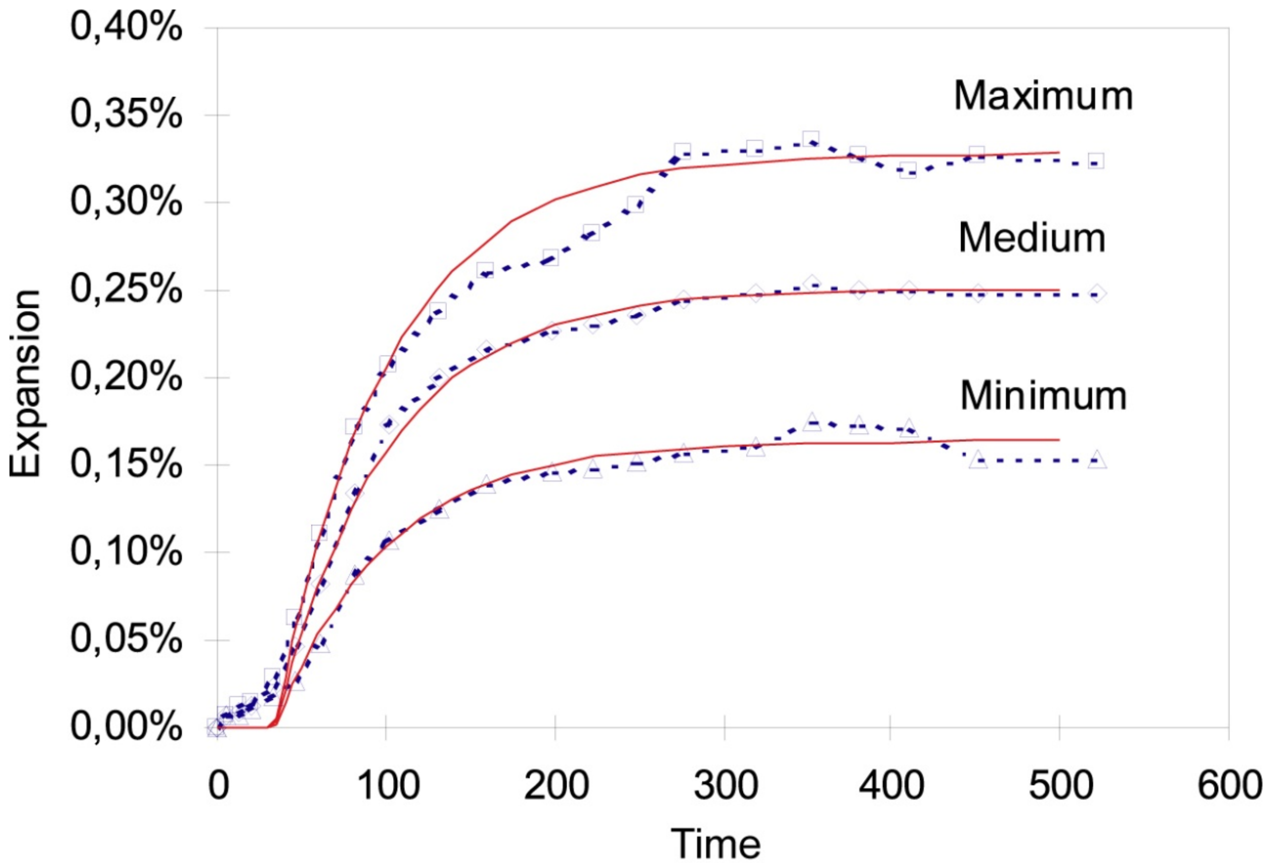
Effective density: $\varrho^s = \dfrac{\varrho^u\ \varrho^r}{\varrho^r + \xi[\varrho^u - \varrho^r]}$

Gradient enhanced isotropic damage model

Bangert, F.; Grasberger, S.; Kuhl, D. & GM (2003), Engineering Fracture Mechanics
Bangert, F.; Kuhl, D. & GM (2004), Int. J. Numerical and Analytical Methods in Geomechanics

Phenomenological model of ASR-induced deterioration in concrete

Calibration of ASR model [Multon 2003, Poyet 2003]



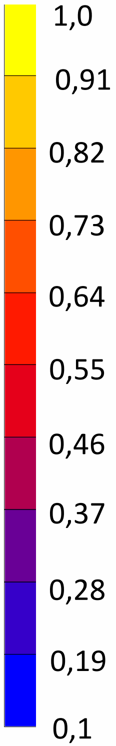
Bangert, F.; Grasberger, S.; Kuhl, D. & GM (2003), Engineering Fracture Mechanics

Bangert, F.; Kuhl, D. & GM (2004), International Journal for Numerical and Analytical Methods in Geomechanics

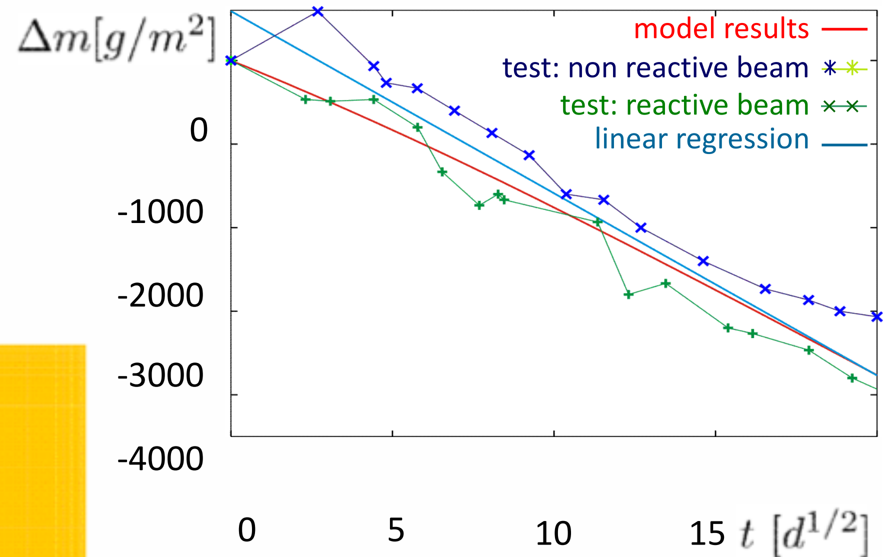
Phenomenological model of ASR-induced deterioration in concrete

RUB

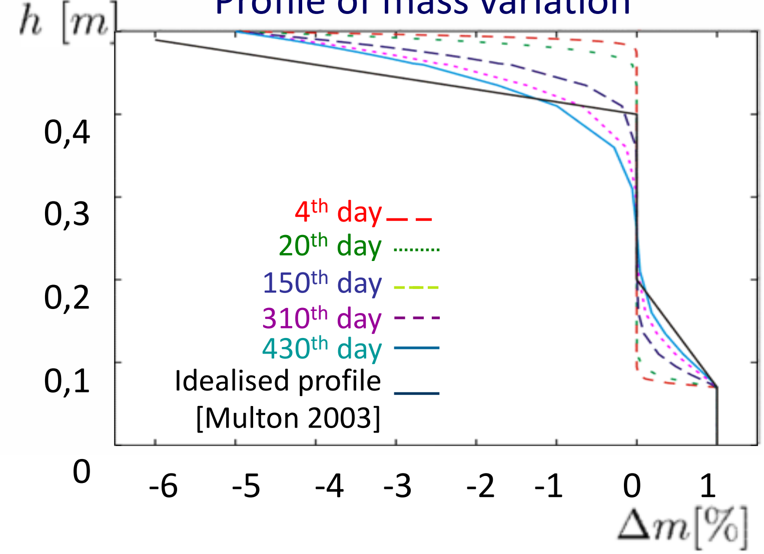
Numerical simulation of a concrete beam affected by ASR

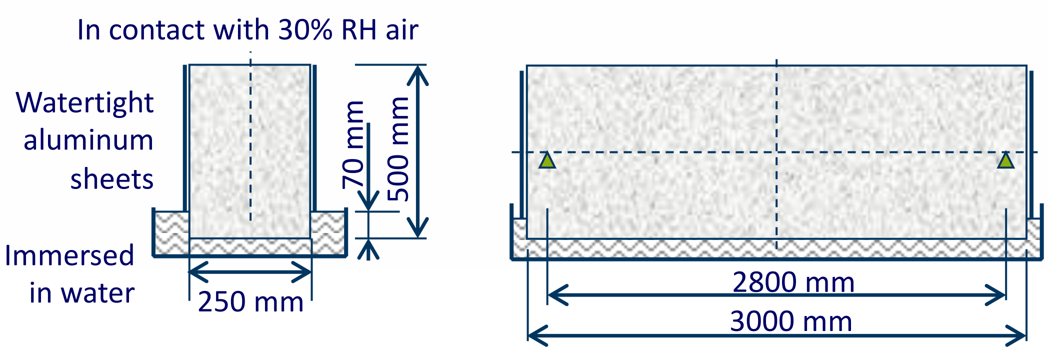


Saturation distribution in concrete beam



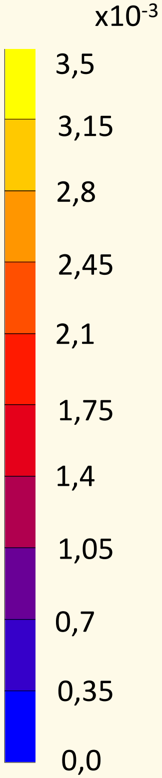
Profile of mass variation



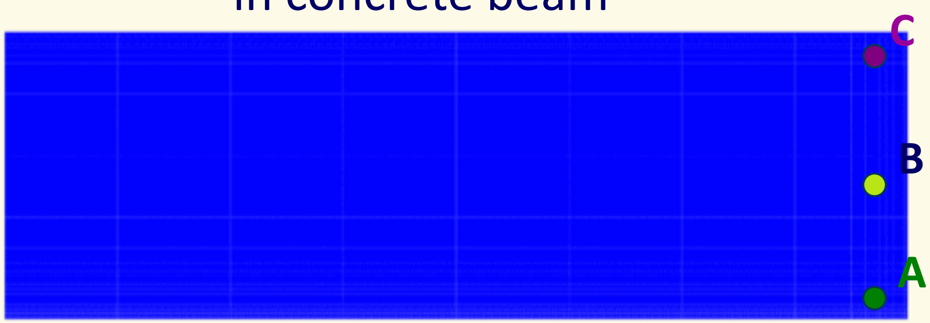


RUB

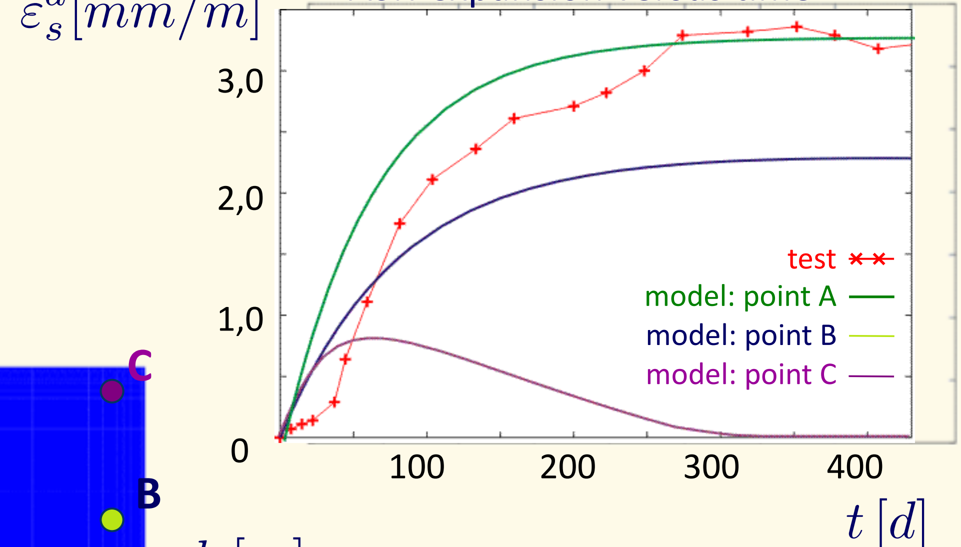
Numerical simulation of a concrete beam affected by ASR



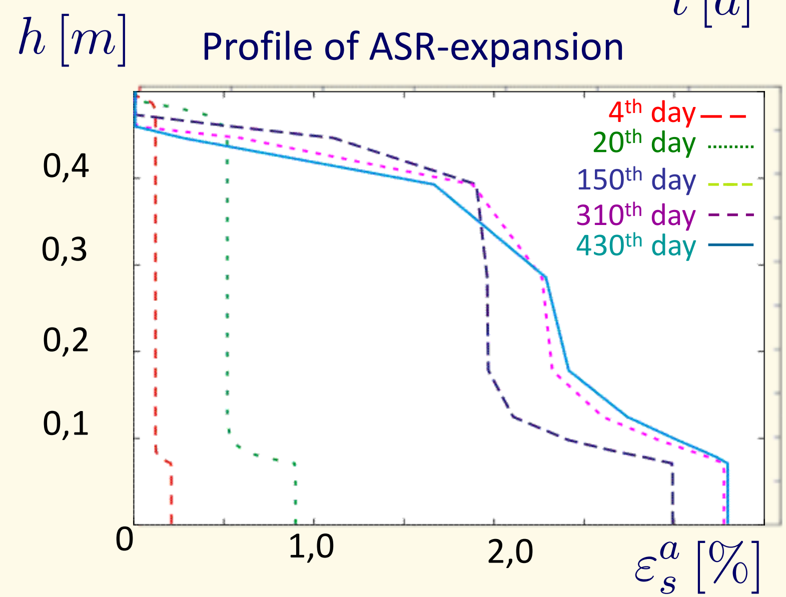
ASR-expansion distribution in concrete beam



ASR-expansion versus time

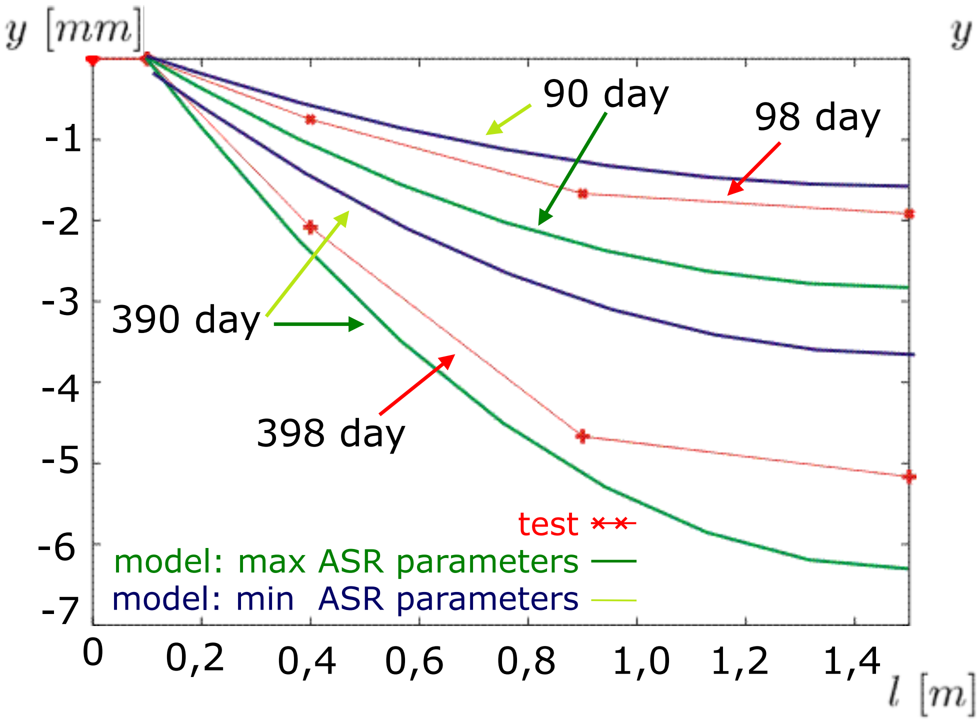


Profile of ASR-expansion

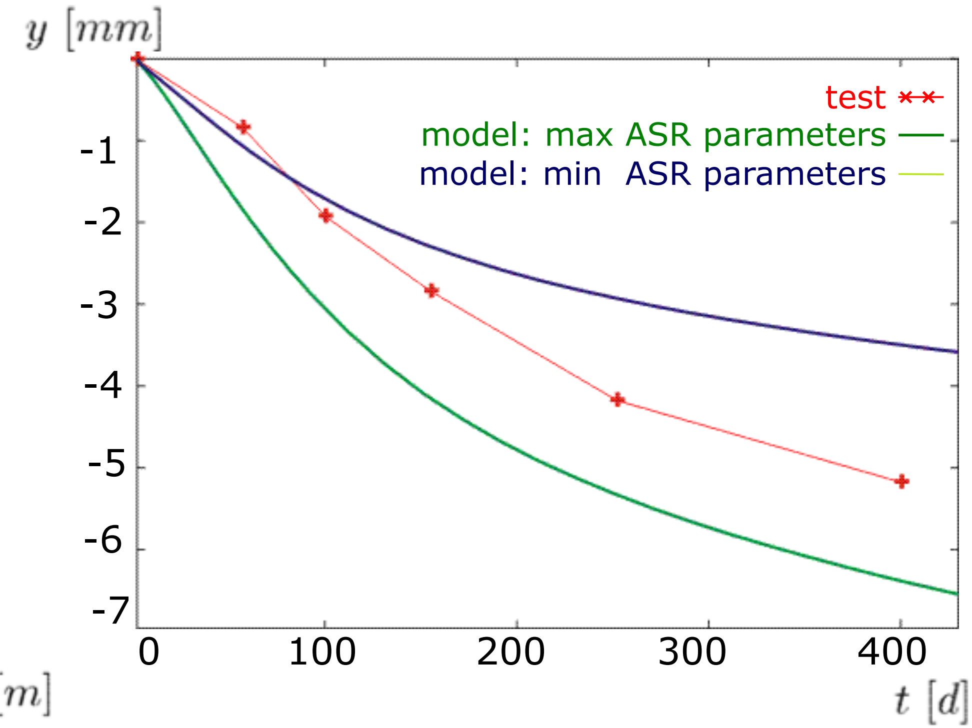


Numerical simulation of a concrete beam affected by ASR

Deflection along length of beam



Maximal deflection versus time

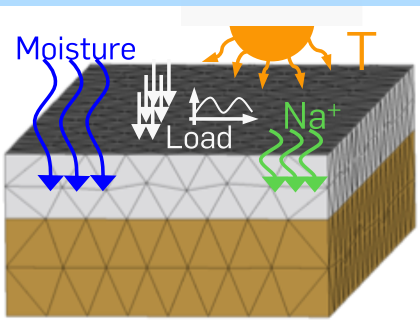


ASR-Expansion in concrete: A multiscale problem

RUB

Macroscale [m]

Durability Analysis

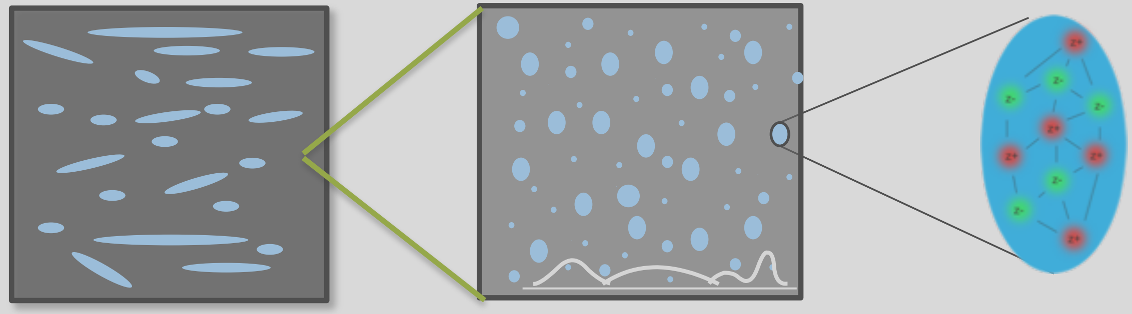


Finite Element Model

Macroscopic Laws

Transport

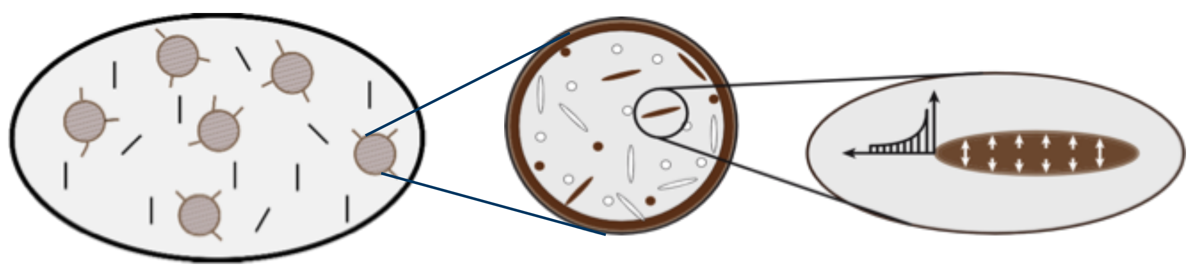
Multiscale model for Alkali and fluid transport (nm - mm)



Microcracks | Pore Space | Pore fluid

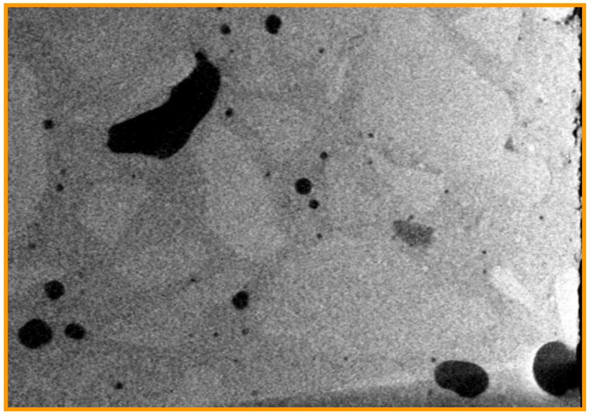
Deterioration

Multiscale model for damage (μm - cm)



Concrete | Aggregates | Microcracks

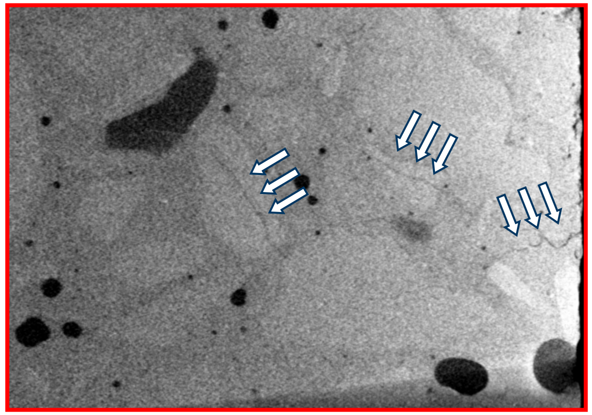
No microcracking observed



t = 0

Experimentally observed ASR-induced microcracking (3D-CT)

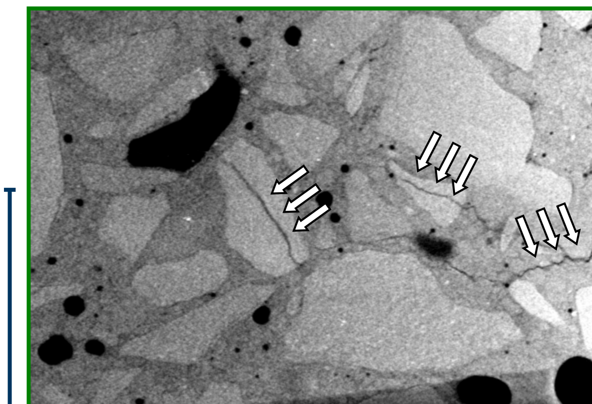
Microcracks in aggregates



t = 2 months

Crack propagation into cement paste

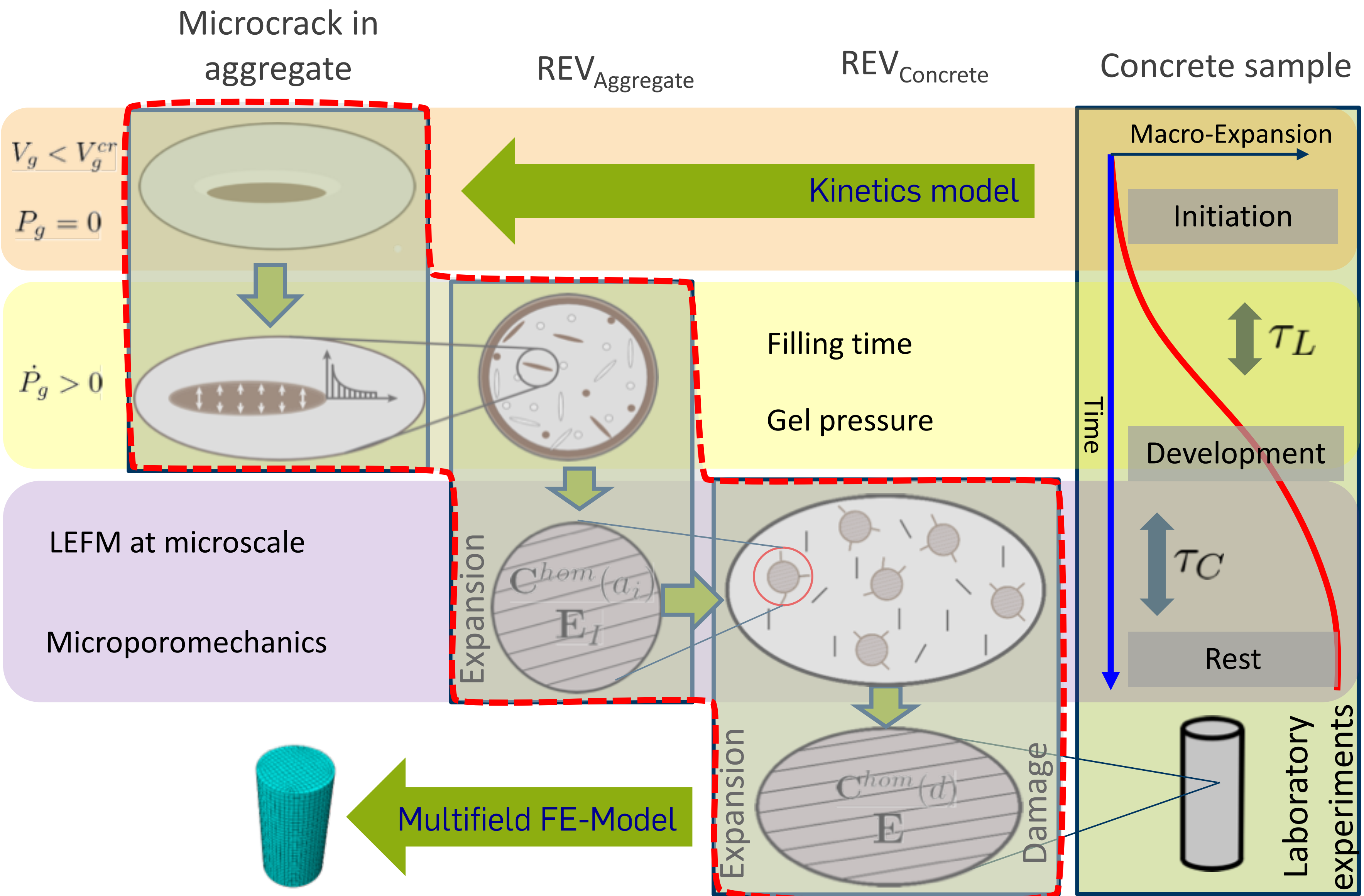
10 mm



t = 5 months

Weise, 2016: BAM (Federal Institute for Materials Research and Testing)

ASR-Expansion in concrete: A multiscale problem



ASR-Expansion in concrete: a multiscale problem

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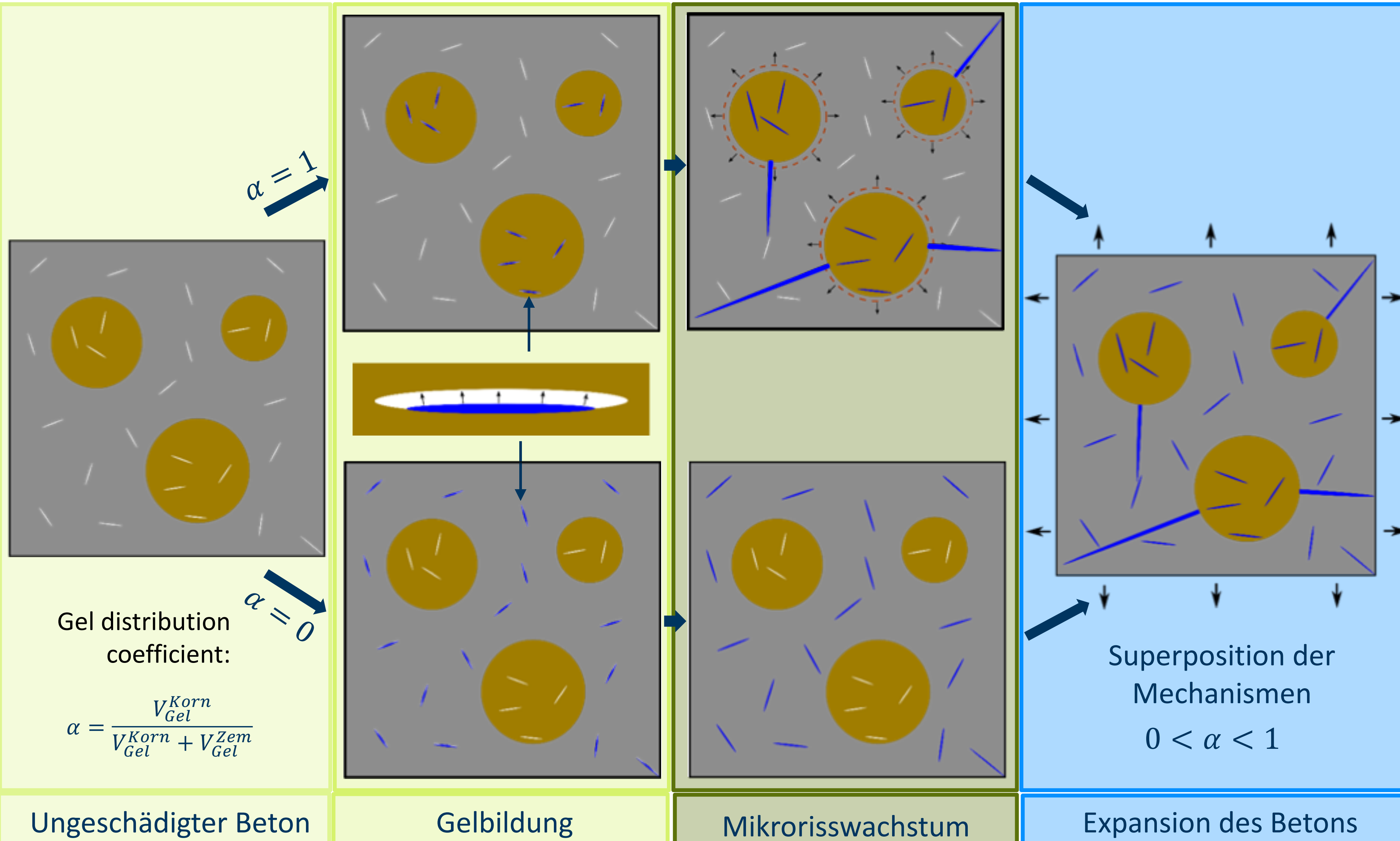
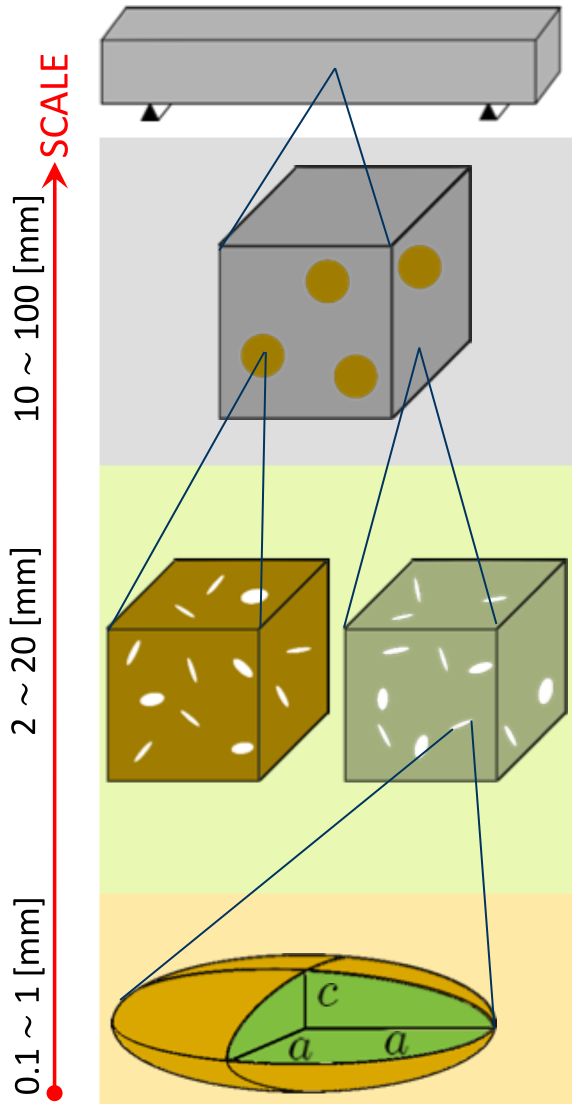
Macroscopic expansion and damage: upscaling of microcrack propagation



ASR-Expansion in concrete: a multiscale problem

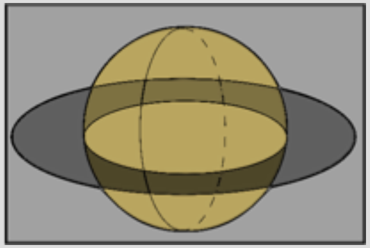
RUB



- Micromechanics based modelling
- Mean-field homogenization

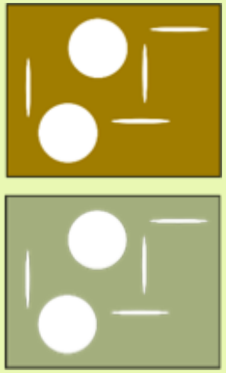
Concrete

- Concrete = cement paste + embedded spherical aggregates
- Damage localization in cement matrix = annular crack due to aggregate expansion



Aggregate/cement paste

- Penny-shaped microcracks in aggregate and cement represent pore space
- Microcrack density = const, i.e. no new microcracks are formed
- Microcracks form 3 orthogonally aligned families*



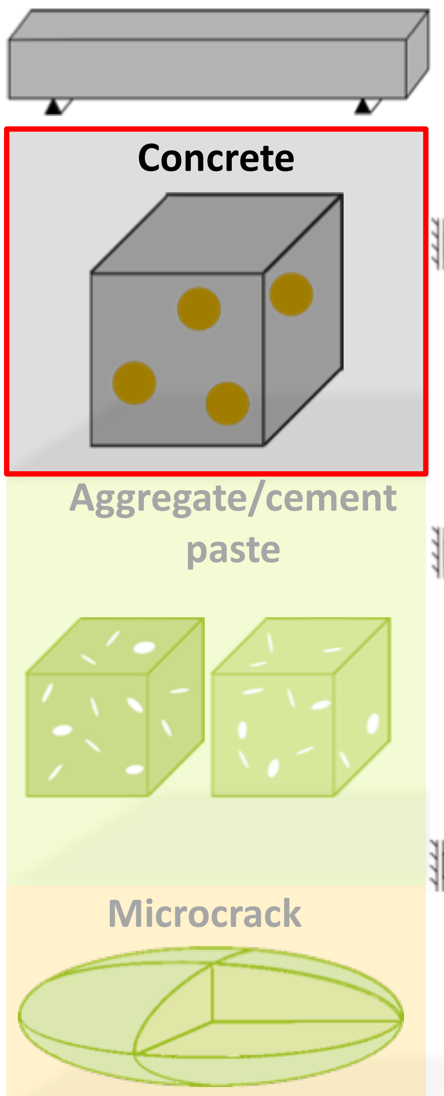
Microcrack

Microcracks = penny-shape: $X = \frac{c}{a} \ll 1$

* Charpin & Ehrlacher 2012, Esposito, 2016, Ph.D. thesis

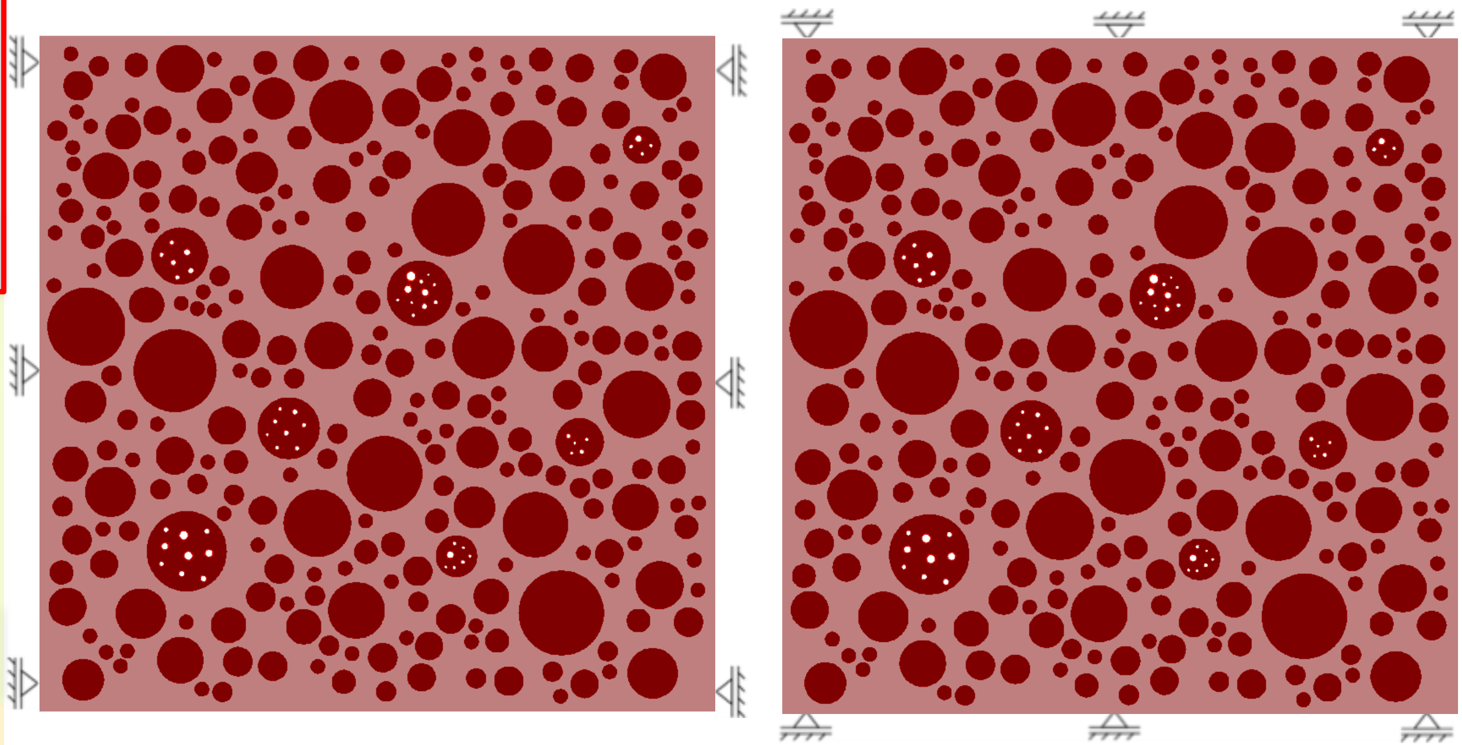
ASR-Expansion in concrete: a multiscale problem

RUB



Cracking due to pressure in gel pockets in aggregates: mesostructure simulation of horizontal and vertically constrained expansion

Crack propagation simulation: Variational Interface fracture model*

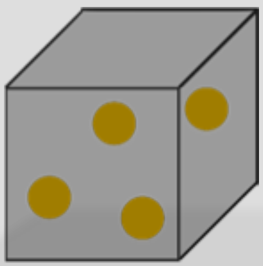


- Cracks initiate within the aggregate, propagate and coalesce
- After cracks reach the cement, they propagate into cement paste, forming ring-shaped cracks
- Formation of **radial cracks in cement paste -> Annular crack concept**

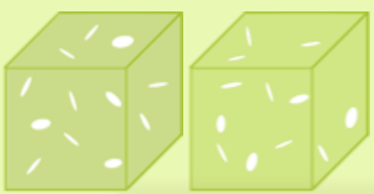
I. Khisamitov & GM, CMAME, submitted 2017

ASR-Expansion: Combine micromechanics with fracture mechanics

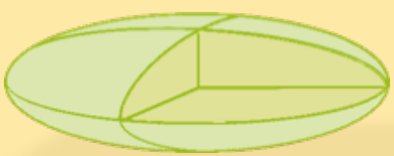
Concrete



Aggregate/cement paste



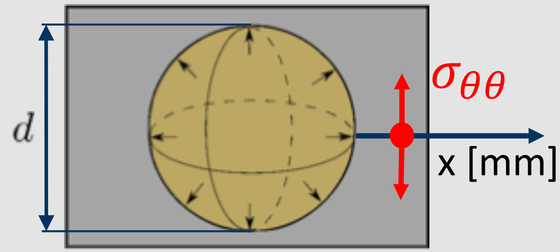
Microcrack



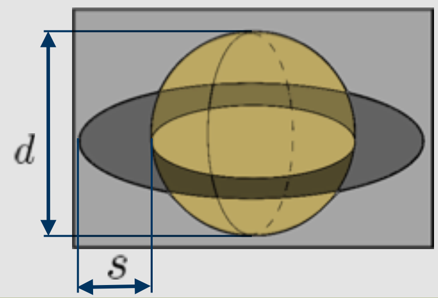
Annular crack around the aggregate

Initiation

Aggregate expansion -> tensile stresses in cement paste around it

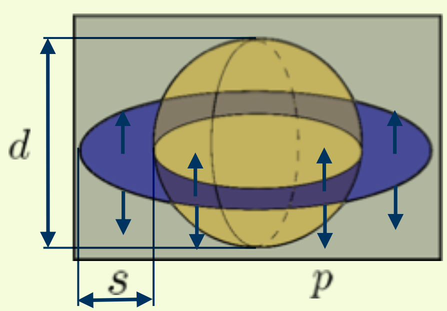


Initiation of annular of crack of size *s*

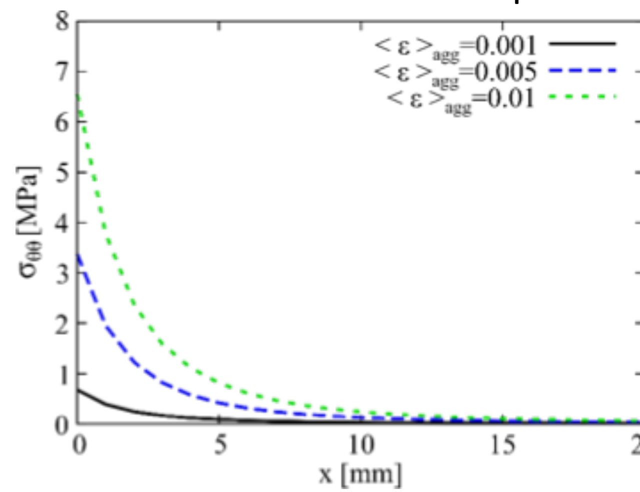


Propagation

Annular crack growth due to gel pressure



Tensile stress in cement paste



(using exterior point Eshelby tensor)

Ju & Sun, 1999

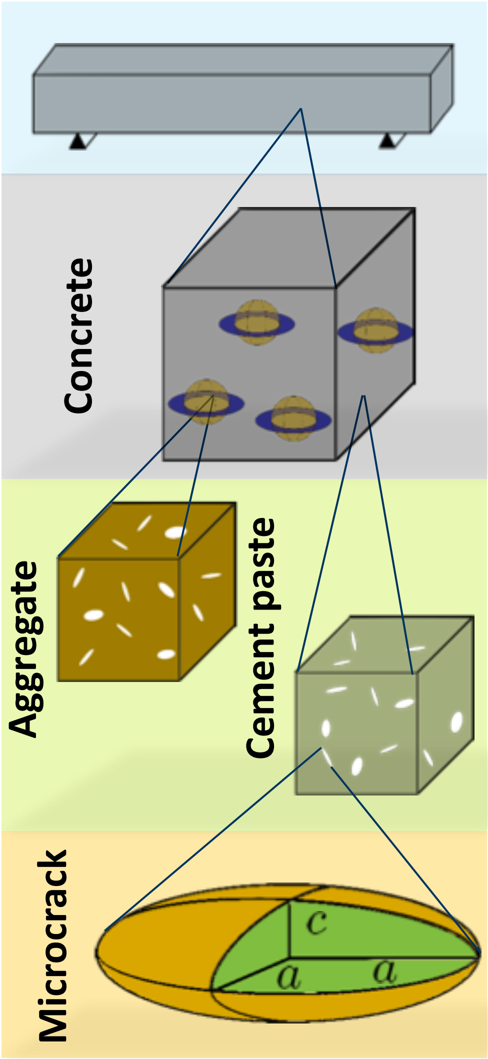
Annular crack formation criterion:

$$K_I(s) - K_{Ic} \leq 0$$

$$K_I(s) = \int_0^s h(x, s, d)\sigma_{\theta\theta}(x)dx$$

Fett & Rizzi, 2007, Forschungszentrum Karlsruhe

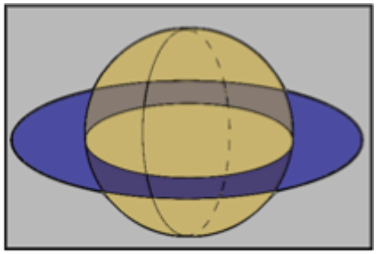
Macroscopic damage: upscaling of microcrack propagation



Macroscopic expansion and damage

$$\mathbb{C}^{hom}_{macro}, \mathbf{E}_{macro}$$

Annular crack initiation and propagation



$$\sigma_{\theta\theta} = f(\mathbf{E}_{agg}, \mathbb{C}^{hom}_{agg}, \mathbb{C}^{hom}_{cem})$$

$$K_I(\sigma_{\theta\theta}) - K_{Ic} \leq 0$$

Aggregate expansion due to microcracking

$$G(a, \boldsymbol{\Sigma}, p) = \frac{\partial \Psi(\phi_c, \boldsymbol{\Sigma}, p)}{\partial \phi_c} \leq G^c$$

pressure p at which microcrack starts propagating → aggregate expansion

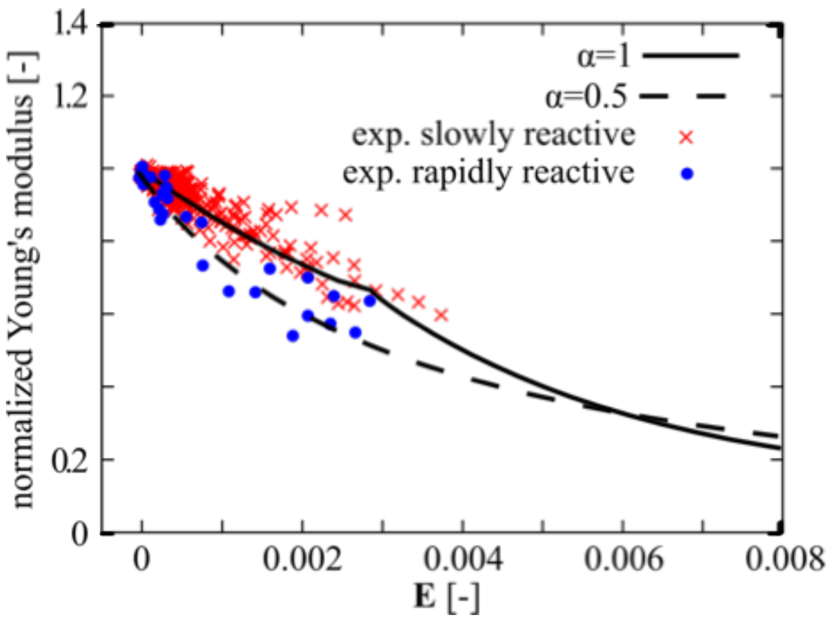
Growth of penny shaped microcracks in aggregates

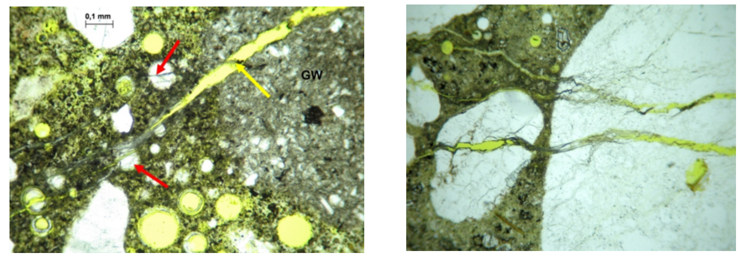
$$\begin{cases} G(a, \boldsymbol{\Sigma}, p) - G_c \leq 0 \\ \dot{a} \geq 0 \\ (G(a, \boldsymbol{\Sigma}, p) - G_c)\dot{a} = 0 \end{cases}$$

ASR expansion of concrete: Comparison with experimental data

Elastizitätsmodul *vs.* freie Expansion

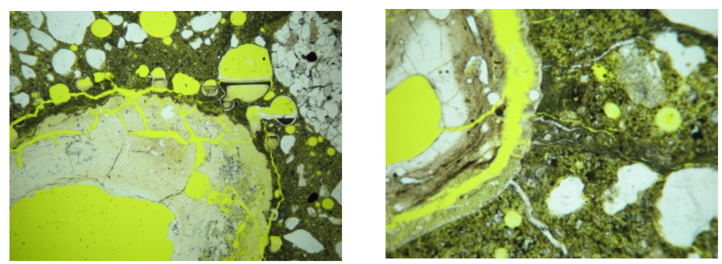
Vergleich mit experimentellen Daten *(Giebson, 2013)*





Slowly reactive (Giebson, 2013)

$\alpha = 1$: Microcracking begins in the aggregate and propagates into the cement paste



Rapidly reactive (Giebson, 2013)

$\alpha = 0.5$: Microcracking begins in the cement paste and aggregate simulataneously

Modell könnte den Unterschied zwischen Schädigungsprozessen in Betonen mit verschieden Arten von Gesteinskörnern erklären

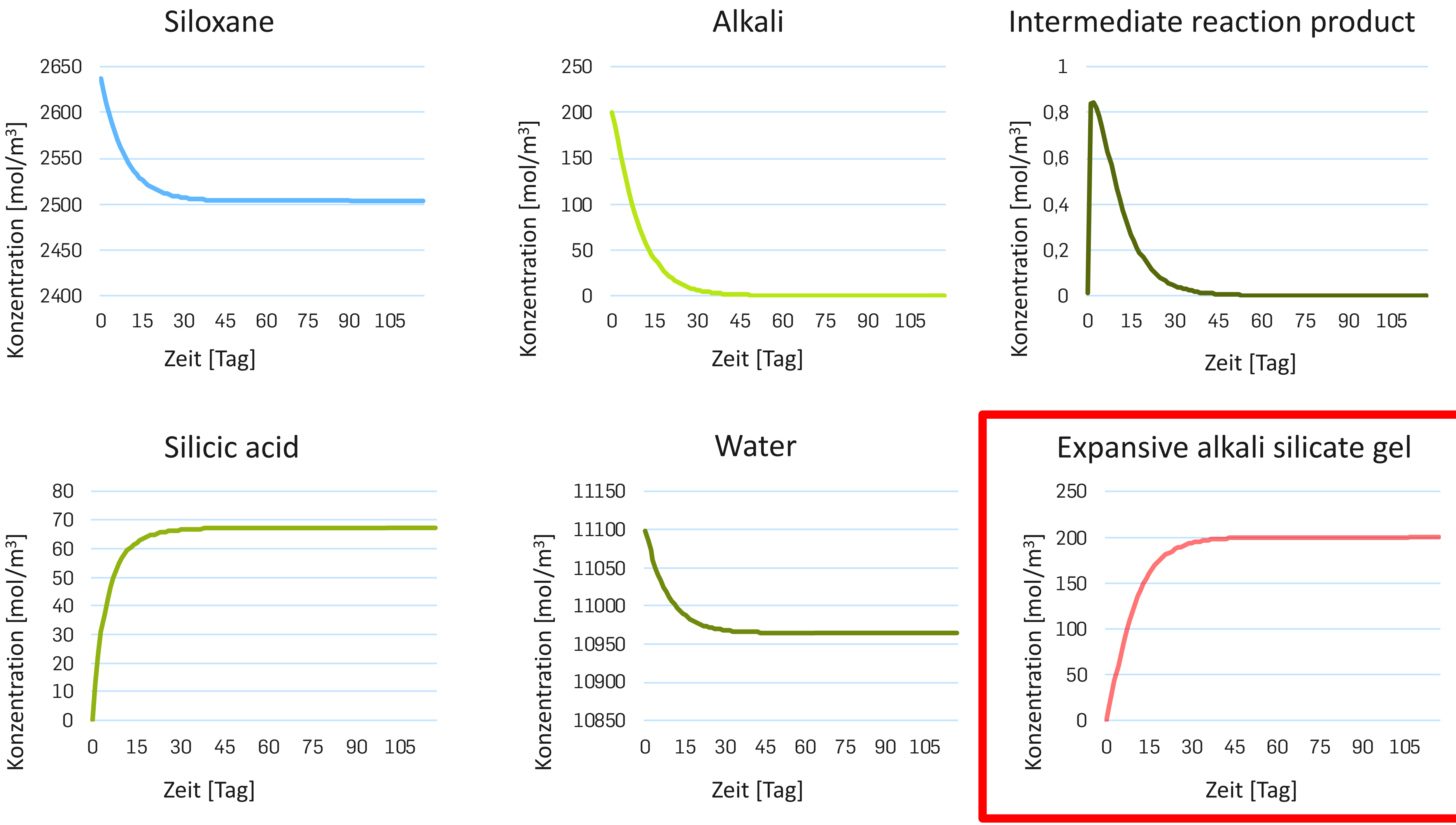
Iskhakov, T., Timothy, J.J., Meschke, G. "Expansion and deterioration of concrete due to ASR: micromechanical modeling and analysis" - wurde eingereicht

RUB

Reaktionsprozesse	Mathematische Beschreibung
Schritt 1	
$\overset{A}{\underbrace{\text{Si-O-Si}}_{\text{Siloxane}}} + \overset{B}{\underbrace{R^{+}+OH^{-}}_{\text{Hydroxyl ions}}} \xrightarrow{k_1} \overset{C}{\underbrace{\text{Si-O-R}}_{\text{Alcali-silicate (gel)}}} + \overset{D}{\underbrace{\text{H-O-Si}}_{\text{Silicic acid}}}$	$\partial A/\partial t = -k_1 A(t)B(t)$ $\partial B/\partial t = -k_1 A(t)B(t) - k_2 D(t)B(t)$
Schritt 2	
$\overset{D}{\underbrace{\text{H-O-Si}}_{\text{Silicic acid}}} + \overset{B}{\underbrace{R^{+}+OH^{-}}_{\text{Hydroxyl ions}}} \xrightarrow{k_2} \overset{C}{\underbrace{\text{Si-O-R}}_{\text{Alcali-silicate (gel)}}} + \overset{E}{\underbrace{H_2O}_{\text{Water}}}$	$\partial C/\partial t = k_1 A(t)B(t) + k_2 D(t)B(t) - k_3 C(t)E(t)$ $\partial D/\partial t = k_1 D(t)B(t) - k_2 D(t)B(t)$
Schritt 3	
$\overset{C}{\underbrace{\text{Si-O-R}}_{\text{Alcali-silicate (gel)}}} + \overset{E}{\underbrace{nH_2O}_{\text{Water}}} \xrightarrow{k_3} \overset{F}{\underbrace{\text{Si-O}^{-}+(H_2O)_n+Na^{+}}_{\text{Expanded alcali-silicate (gel)}}}$	$\partial E/\partial t = k_2 D(t)B(t) - k_3 C(t)E(t)$ $\partial F/\partial t = k_3 C(t)E(t)$

Geschwindigkeitskonstanten $k_1{:}k_2{:}k_3 \approx 1{:}30{:}60$ *(Saouma et al., 2015)* basierend auf Dauer der Reaktionen

Reaction kinetics leading to formation of expansive ASR gel



ASR expansion of concrete: Coupling kinetics + Mechanics

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Reaktionsmodell

Reaktionsdiffusions-
gleichungen

↓

Zeitabhängige Konzentration des Gels $C_{Gel}(t)$

↓

Zeitabhängiges Volumen des Gels $V_{Gel}(t)$ im Korn* und Zementstein**

Mikromechanisches Modell

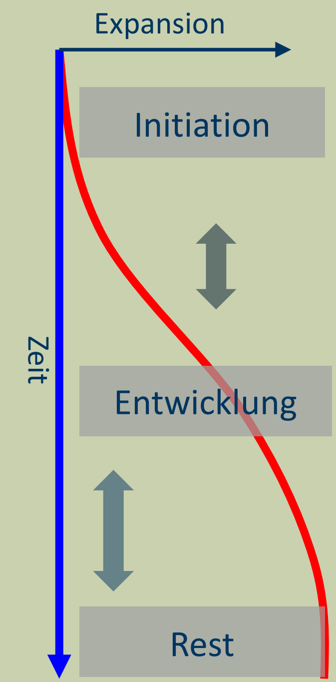
Wenn $V_{Gel}(t)$ < Volumen der Mikrorisse:

Kein Risswachstum

Wenn $V_{Gel}(t)$ > Volumen der Mikrorisse:

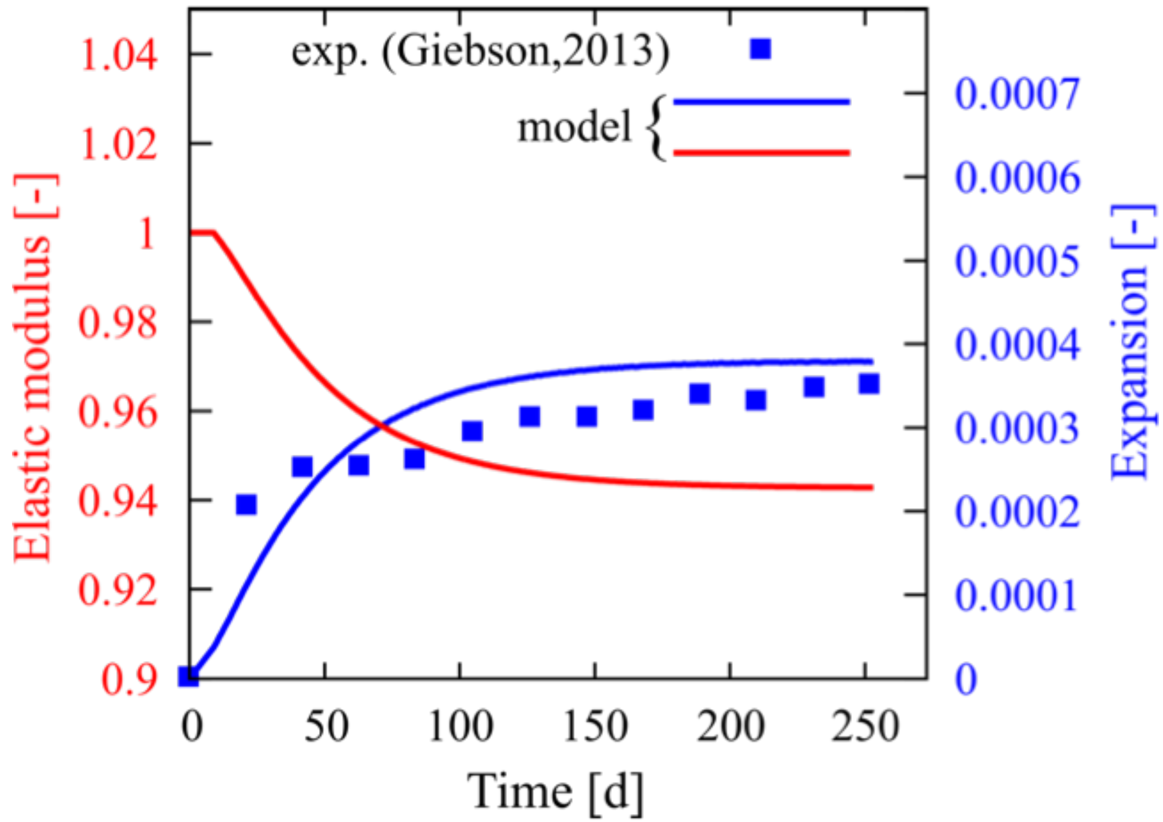
Risswachstum

Makro-Expansion des Betons



ASR expansion of concrete: Coupling kinetics + Mechanics

Macroscopic expansion due to ASR: Comparison with experimental data



Connectivity of defect distribution must be considered -> Expansive gel does not fill all initial defects in concrete

Conclusions

- Durability of concrete: Multiphysics models supported by multiscale models
- Multiscale models provide input for macroscopic models
  - Macroscopic stiffness, diffusivity & permeability for given pore structure, and state of damage
  - Cascade Continuum Micromechanics (CCM) Model able to predict percolation threshold
  - Dramatic difference of effective permeability below and beyond threshold -determines the effect of damage on transport of aggressive substances
- Example for durability model: Alkali Silica Reaction
  - Phenomenological model: calibration needs specific tests for specific aggregate and concrete composition
  - Multiscale model: attempt to replicate physico-chemical processes of ASR gel production, expansion and deterioration on meso (aggregate) scale
  - Consequence of aggregate type and concrete composition predicted!
  - Upscaling by means of micromechanics methods – macroscopic expansion strains and damage

Research presented was supported by the German Science Foundation

DFG

FOR 1498
ALKALI-SILICA REACTION
IN CONCRETE STRUCTURES

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