From micron-sized needle-shaped hydrates to meter-sized shotcrete tunnel shells: micromechanical upscaling of stiffness and strength of hydrating shotcrete

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Introduction

If a high degree of flexibility is required during the tunnel excavation process (e.g. in difficult ground conditions), the New Austrian Tunneling Method (NATM) is well suited. After excavation of a cross-section of a tunnel, shotcrete is applied onto the tunnel walls, constituting a thin and flexible shell. For safety reasons, knowledge of the stresses in the tunnel shell is of great importance, as to assess its susceptibility to severe cracking or failure. It turned out to be beneficial to back-calculate, on the basis of elaborate shotcrete material models, shotcrete stresses from shotcrete strains. For this, a hybrid method is applied:

- Prescription of continuously in-situ measured 3D discplacement vectors on structural model for tunnel shell based on suitable shotcrete material law
- Output of stress fields and levels of utilization in the tunnel shell

The success of the hybrid method depends on a realistic material model for shotcrete/cementitious materials ⇒ MULTISCALE MATERIAL MODELS

GOAL:

... explanation of **material behavior of „hierarchical“ composites**

... from the **universal** behavior of a few **basic components** building up these composites, and

... from the **interactions of these components across various microstructures**

Shotcrete

... a **chemically reactive** (hierarchical composite) material

... with **evolving (time-dependent) microstructure**

... with **evolving mechanical properties**

BUT: properties of basic building blocks of material (cement, water, hydrates, air, aggregates) are **non-evolving**

Homogenization of Elasticity

REPRESENTATIVE VOLUME ELEMENT (RVE):

Material within RVE = **macro-homogeneous**, but **micro-heterogeneous**

d_I char. length of microheterogeneity (material phases)

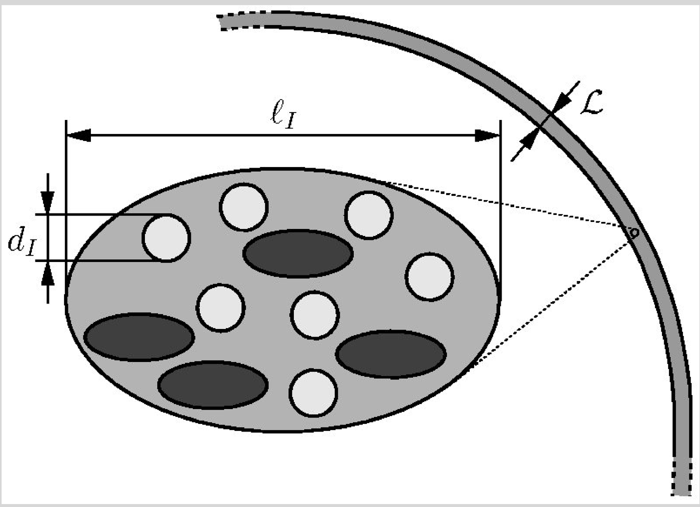
ℓ_I char. length of RVE

$\mathcal{L}$ char. length of structure/loading

$d_I \ll \ell_I \ll \mathcal{L}$

differential calculus can be used for structural analysis

mechanical properties defined on the **RVE**



SEQUENTIAL METHODOLOGY:

1. **Representation of microstructure:** identification of **RVEs** (on **separated scales** of observation), identification of **phases,** of **phase shapes,** and of **phase interactions**
2. Mathematical formulation for **overall mechanical properties** as **functions of phase volume fractions** (sample-specific), and of **mechanical properties of phases** („universal“ for all shotcretes)
3. Identification of („universal“) **mechanical phase properties from suitable experiments** (model input)
4. Identification of (sample-specific) **phase volume fractions from experiments** (model input)
5. Computation of **overall mechanical properties** (model output) from aforementioned **experiment-based model input**
6. **Comparison of model output** with corresponding **(*in*dependent) experiments** for elasticity/strength of cement paste/shotcrete

FUNDAMENTALS OF HOMOGENIZATION:

Linear elasticity on microscopic level $\boldsymbol{\sigma}(\mathbf{x}) = \mathbb{c}(\mathbf{x}) : \boldsymbol{\varepsilon}(\mathbf{x})$ with **microscopic stiffness** tensor **c**(**x**) implies the **superposition principle** $\boldsymbol{\varepsilon}(\mathbf{x}) = \mathbb{A}(\mathbf{x}) : \mathbf{E}$ with **strain concentration** tensor $\mathbb{A}(\mathbf{x})$ ⇒ **Macroscopic stiffness** tensor **C** obtained through

... insertion of strain concentration into microscopic constitutive law ⇒ $\boldsymbol{\sigma}(\mathbf{x}) = \mathbb{c}(\mathbf{x}) : \mathbb{A}(\mathbf{x}) : \mathbf{E}$

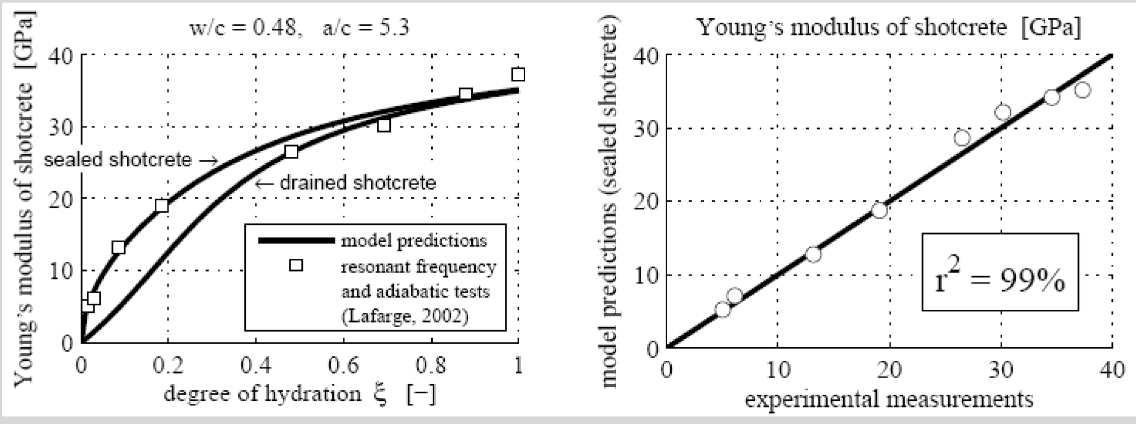
... use of result for stress averaging ⇒ $\boldsymbol{\Sigma} = \langle \mathbb{c}(\mathbf{x}) : \mathbb{A}(\mathbf{x}) \rangle : \mathbf{E}$

... comparison with macroscopic constitutive law ⇒ $\boldsymbol{\Sigma} = \mathbb{C} : \mathbf{E}$

➡ $\mathbb{C} = \langle \mathbb{c}(\mathbf{x}) : \mathbb{A}(\mathbf{x}) \rangle$

- estimation of the strain concentration tensor from **matrix-inclusion problem**
- consideration of morphology by (i) **shape of inclusions** and (ii) **choice of matrix stiffness**

EXPERIMENTAL VALIDATION:



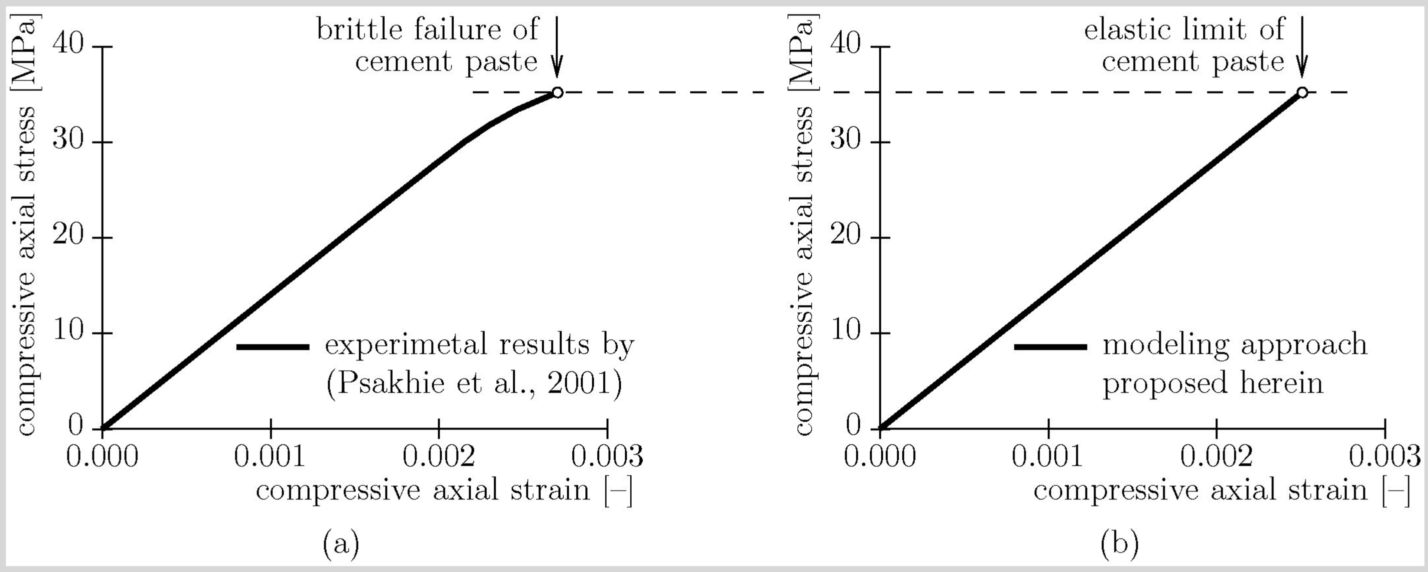
Excellent agreement between model predictions and experimental values for **sealed conditions**:

- relative error = 1.0%
- standard deviation = 6.5%
- r^2 = 98.8%

Homogenization of Strength

RESPONSE OF CEMENT PASTE UNDER UNIAXIAL COMPRESSION [2]:

Experimental observation | **Modeling approach**



Experimental observation:
- linear elasticity
- some pre-peak nonlinearities
- brittle failure

Modeling approach:
- linear elasticity
- sudden brittle failure

➡ Upscaling of **elasticity** is based on **spatial averages** of stress and strain over the material phases

➡ Challenge: microscopic **brittle failure** is related to **stress/strain peaks** rather than to averages

- reasonable represented by **higher-order averages**
- accessed by **equivalence of micro- and macroenergy**

Estimation of **stress peaks** in **micron-sized cylindrical hydrates** within **decimeter-sized RVEs of shotcrete** subjected to **uniaxial compression** [1]:

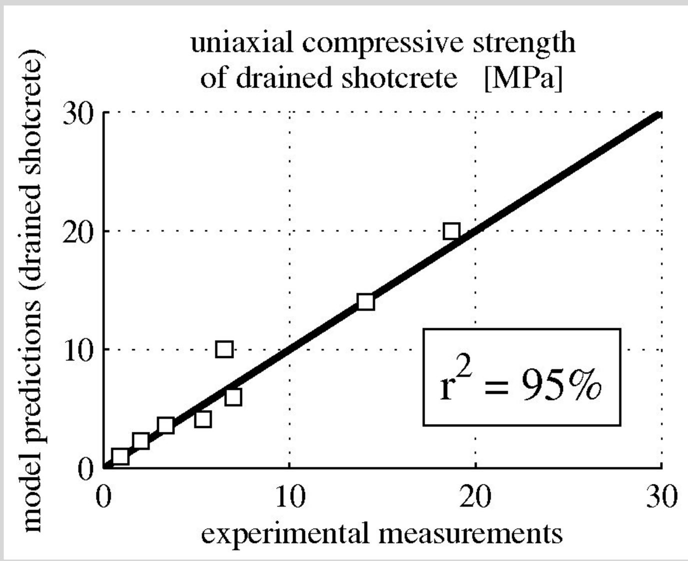
$$\left|\Sigma^{comp,ult}_{sc,11}\right| = \left\{ \max_{\vartheta,\varphi} \left[\lim_{f^{\vartheta,\varphi}_{hyd}\to 0} \left(\frac{\mu^2_{hyd}}{f^{\vartheta,\varphi}_{hyd}} \mathbf{e}_1 \otimes \mathbf{e}_1 : \frac{\partial(\mathbb{C}_{sc})^{-1}}{\partial \mu^{\vartheta,\varphi}_{hyd}} : \mathbf{e}_1 \otimes \mathbf{e}_1 \right)^{1/2} \right] \right\}^{-1} \times \sigma^{dev}_{crit}$$

EXPERIMENTAL VALIDATION:

- w/c = 0.50, a/c = 3.80 and w/c = 0.40, a/c = 3.94
- Tests at early ages: 1h, 2h, 3h, 4h, 5h, 1d, 3d, 7d

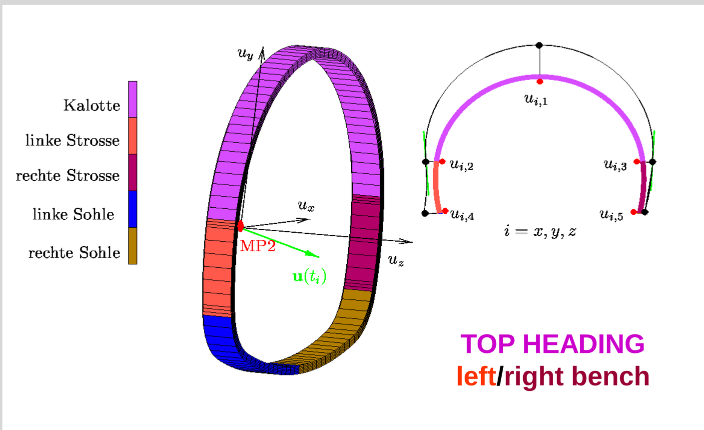
Satisfactory agreement between model predictions and experimental values for **drained conditions** [1,2]:

- relative error = -5.0%
- standard deviation = 19.4%
- r^2 = 95.0%

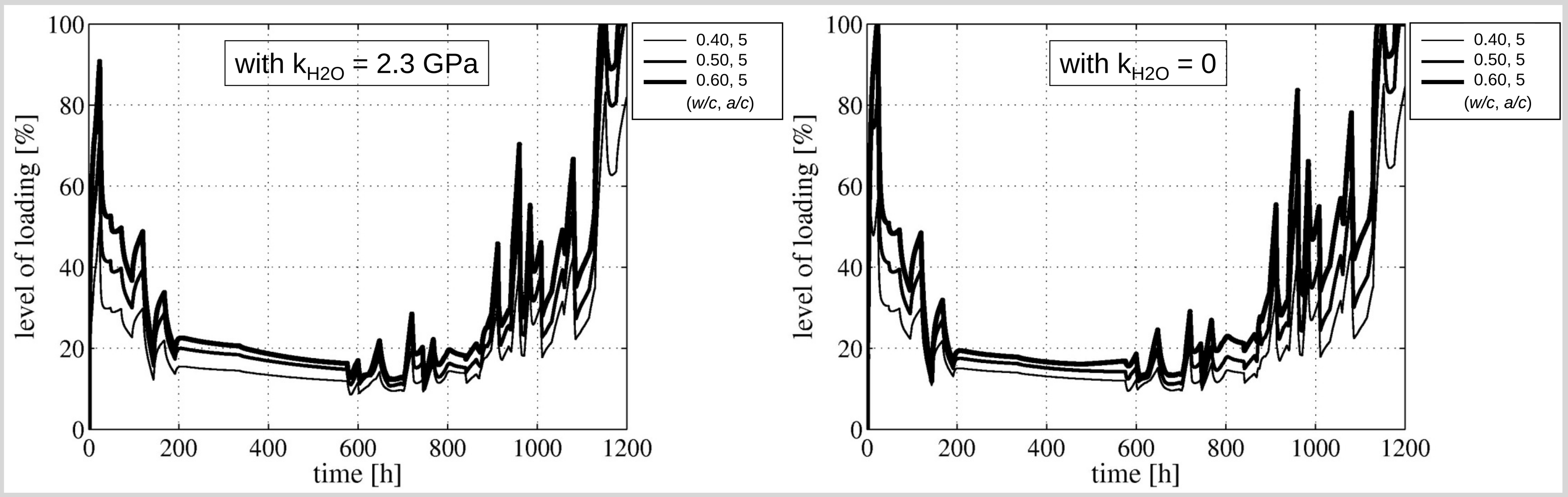


Hybrid Analyses of Tunnel Shells

Prescription of components of spatial **displacement vectors** from laser-optical measurements as boundary values for a **3D Finite Element Model** with appropriate (micromechanics-based) ***multiscale* material model for shotcrete [3]**



sealed conditions | **drained conditions**



➡ **valuable support for daily decision on tunnel site**

➡ **higher cement content** (= lower water/cement-ratio) **increases safety** of tunnel shell

References

[1] B. Pichler, S. Scheiner, and C. Hellmich (2008). From micron-sized needle-shaped hydrates to meter-sized shotcrete tunnel shells: Micromechanical upscaling of stiffness and strength of shotcrete. *Acta Geotechnica* 3, 273-294.

[2] B. Pichler, C. Hellmich, and J. Eberhardsteiner (2009). Spherical and acicular representation of hydrates in a micromechanical model for cement paste: Prediction of early-age elasticity and strength. *Acta Mechanica* 203, 2411-2419.

[3] S. Scheiner, B. Pichler, C. Hellmich, and H.A. Mang (2008). Damage and disaster prevention in NATM tunnels during construction: Micromechanics-supported hybrid analyses. In *Proceedings of NATO-ARW „Damage assessment and Reconstruction after Natural Disasters and Previous Military Activities“*, A. Ibrahimbegovic, M. Zlatar (eds.), Springer Verlag, 145-171.