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# MULTISCALE ASSESSMENT OF EARLY-AGE PERFORMANCE OF SHOTCRETE TUNNEL LININGS

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## ABSTRACT

Cement-based materials are partially saturated, porous media gaining strength and stiffness in the course of the hydration process, i.e., during the chemical reaction between anhydrous cement and water. Inelastic material behaviour of concrete such as *viscoelasticity* (time-dependent deformation under sustained loading) and *autogenous shrinkage* [bulk deformation of the (closed) cement-based material system associated with capillary depression of the pore liquid] are strongly affected by the extent of the hydration reaction. Unlike material models formulated exclusively at the macroscopic scale of observation, the multiscale model proposed in this paper (see Figure 1) allow the explicit link of the complex macroscopic behavior of concrete to its origin at finer scales of observation with a sound physical/chemical basis of the employed constitutive laws at these finer scales.

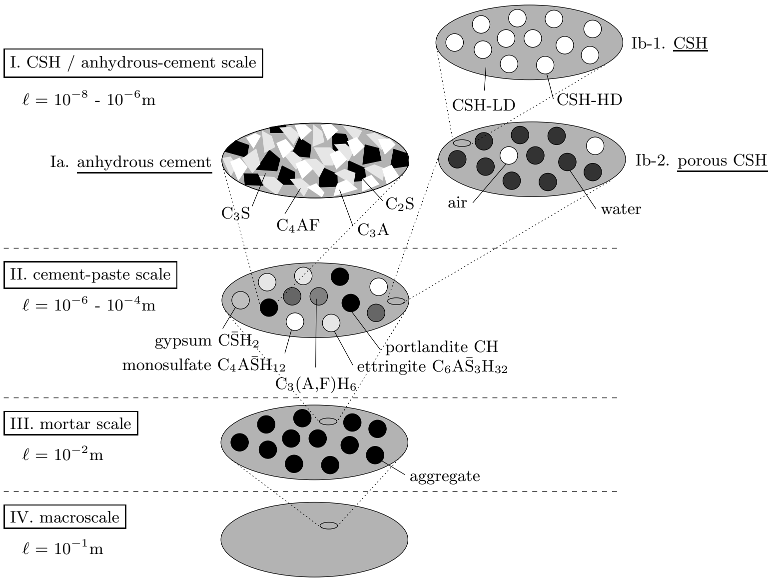

**Figure 1**: Scales of observation for upscaling of creep and shrinkage properties of early-age cement-based materials [*l* = size of representative volume element (RVE)]

Hereby, the finer-scale composition (and its history) is a function of the hydration reaction and accessible through recently developed hydration models for the main clinker phases in ordinary Portland cement (OPC). Nanoindentation (NI) is employed for experimental characterization of cement-based materials at the micrometer range [8,5,10] (see Figure2).

Hereby, the creep behavior of calcium-silicate-hydrates (CSH) is found to be of logarithmic type [6], characterized by a creep compliance proportional to $\ln(1+t/\tau^{v})$, where $\tau^{v}$ denotes the characteristic time of the underlying creep process. In fact, the corresponding model response agrees very well with the obtained NI-test results. Whereas elastic material behavior is considered for hydrostatic loading, the *viscoelastic* deviatoric creep compliance function

$$J^{dev}(t) = \frac{1}{\mu} + J^{v,dev} \ln\left(1 + \frac{t}{\tau^{v,dev}}\right)$$

is introduced, defining the time-dependent behavior of CSH at the micrometer range. Hereby, $\mu$ [Pa] denotes the shear modulus (as given from the unloading curve of NI-test data [4]), and $J^{v,dev}$ [Pa$^{-1}$] and $\tau^{v,dev}$ [s] are creep-compliance parameters to identify (see Figure 2).

With the parameters of the logarithmic-type model at hand, classical homogenization schemes for elastic properties based on continuum micromechanics, e.g., the Mori-Tanaka scheme, are used for upscaling of information towards the macroscale. For this purpose, the extension of the Mori-Tanaka scheme towards consideration of (i) eigenstresses for upscaling of autogenous-shrinkage deformations [7] and (ii) viscoelastic behavior of CSH for upscaling of creep properties [9] was required. As regards the latter, the Laplace-Carson transformation of the Mori-Tanaka scheme is employed, considering the aforementioned logarithmic-type creep of CSH. In contrast to upscaling of elastic and viscoelastic properties, upscaling of strength properties is characterized by a localized mode of material failure. This type of failure is well captured by the *discretized form of limit analysis* which has recently been proposed for upscaling of strength properties of hierarchically organized building materials [1,2].

Finally, the proposed multiscale model is employed to specify the early-age properties of shotcrete within a so-called hybrid analysis of a shotcrete tunnel lining [3], allowing consideration of the actual mix design and the conditions at the construction site. The performed hybrid analysis provides access to the level of loading of the tunnel lining. Thus, by using the developed multiscale model in structural analyses, the actual composition and (microstructural) loading of early-age concrete can be considered. Moreover, since the link between the macroscopic behavior of the material and its composition is established, performance-based optimization of the mix design is possible.

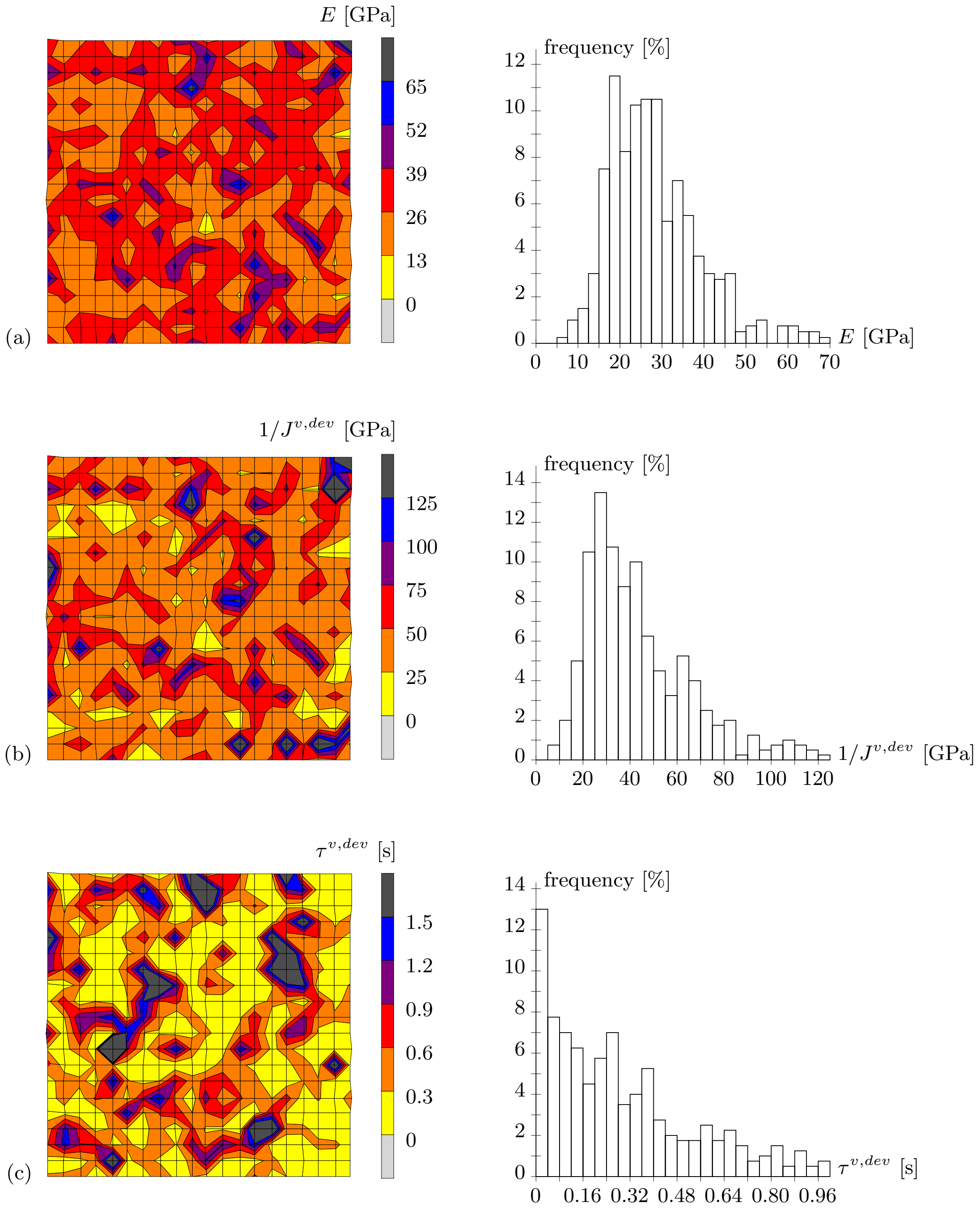

**Figure 2**: Spatial distribution and frequency distribution of (a) Young's modulus *E* and (b) creep parameter $J^{\mathrm{v,dev}}$ obtained from nanoindentation tests (grid-indentation with 20 x 20 indents and distance between adjacent grid points of 5 μm on OPC paste characterized by w/c=0.4 and a Blaine fineness of 3890 $\mathrm{cm}^2$/g)

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