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Innovative Creep Testing on Cement Pastes Allows for Deciphering Creep of Concrete at Early Ages

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Introduction

Concrete is a hierarchically organized **microheterogeneous material** consisting of several different constituents arranged at **separated scales** [1] **of observation**, after [2]:

- Macroscopically, concrete is a matrix-I nclusion composite made of stones (diameters ranging from a few millimeter to a few centimeter) embedded in a surrounding cement paste matrix.
- Cement paste, in turn, is a matrix-inclusion composite made of cement particles (diameters from few microns to few tens of microns) embedded in a surrounding hydrate foam matrix.
- The hydrate foam, in turn, is a ramification of gel porous hydrate needles (with characteristic length of a few tens to a few hundreds of nanometer [3]) with capillary pores in between.

Hydrates are the products of the chemical reaction between cement and water. They are the only creeping constituents of concrete [4], i.e. they progressively deform even under constant loading.

Direct creep testing on submicron-sized hydrate needles is desirable, but even nowadays out of reach. As a remedy, we combine **innovative macroscopic creep testing** [5] with **multiscale models** for homogenization of creep of microheterogeneous materials. At first, we identify – in the context of a **top-down approach** – the **creep properties of hydrates** from the measured creep properties of cement pastes [6]. The hydrate creep properties are universal and intrinsic in the sense that they do neither change with time nor with the initial composition of the material. Based on this knowledge, we upscale – in the context of a **bottom-up approach** – the **creep behavior of hydrates to the scale of concrete**. At the concrete scale, we compare. model-predictions with experimental data from macroscopic material testing, enabling us to quantify internal curing processes based on a novel **water migration model** [7].

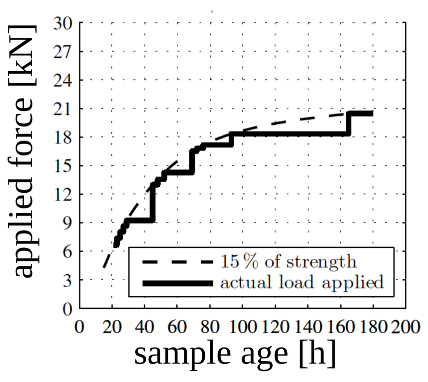
Innovative Creep Testing of Cement Pastes, Mortars, and Concretes

DILEMMA OF EARLY-AGE CREEP TESTING

duration of creep test ≫ characteristic time of hydration
→ materials typically age during an early-age creep tests
→ coupling of aging and creep phenomena

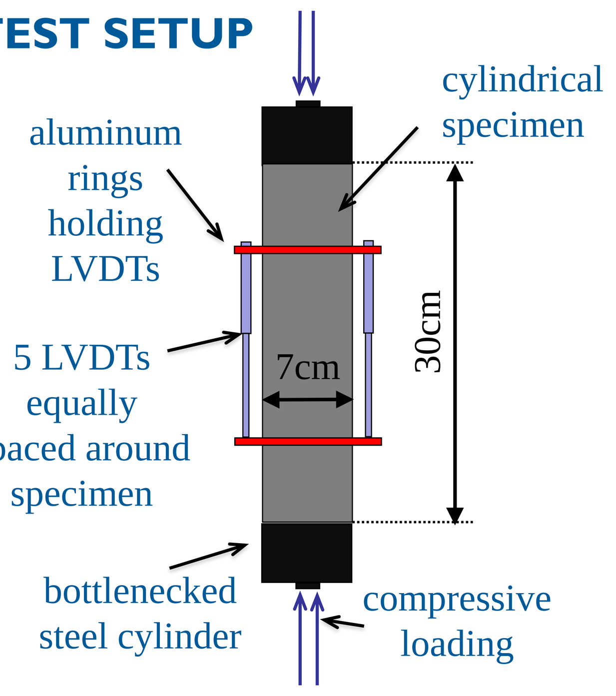
TEST STRATEGY

- 3-min long creep tests are performed
  → specific microstructure
  → nonaging creep properties
- tests repeated hourly (from 21 h to 8 d after mixing)
  → different microstructures, evolution of creep properties during hydration
- nondestructive testing
  → stresses ≤15% of strength during the entire test period



- sealed specimen (no drying)
- isothermal calorimetry relates material age to the hydration degree (based on latent heat of 500 J/g)

TEST SETUP

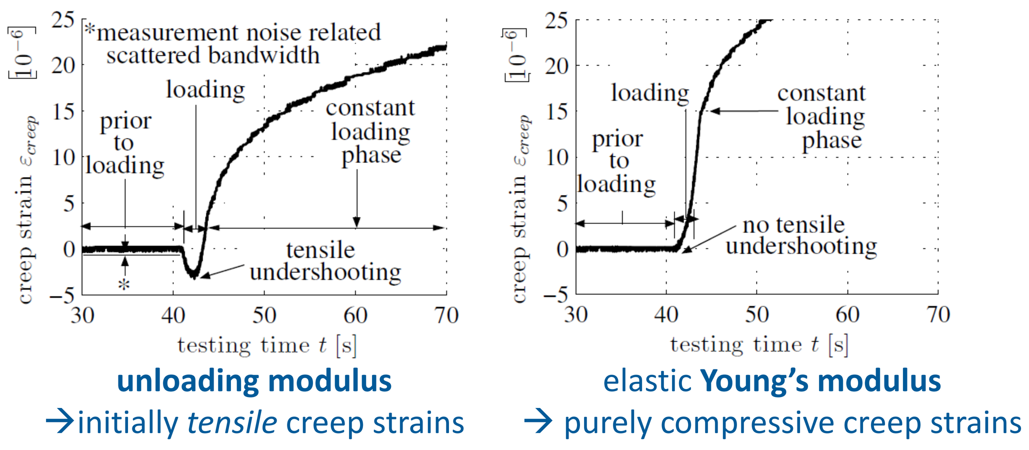


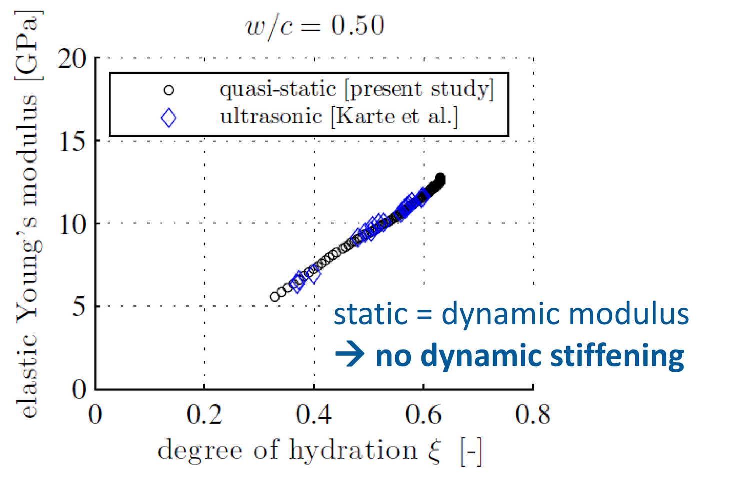
- shear-free stress and strain states in the measurement region [8]
- test performed in temperature chamber at 20°C
- raw materials: CEM I 42.5N, distilled water, quartz sand + quartz aggregates (oven-dried), composition: w/c=0.42/0.45/0.50

RESULTS

Database contains results from ≈2350 three-minutes creep tests: 168 individual tests per sample; 3 compositions of cement paste, 2 of mortar, and 2 of concrete; all tests are repeated one time

Elastic modulus ≠ unloading modulus



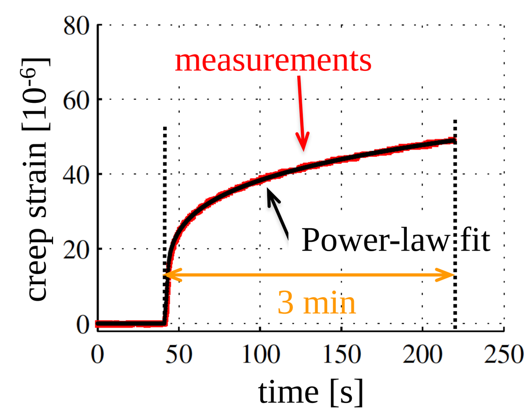


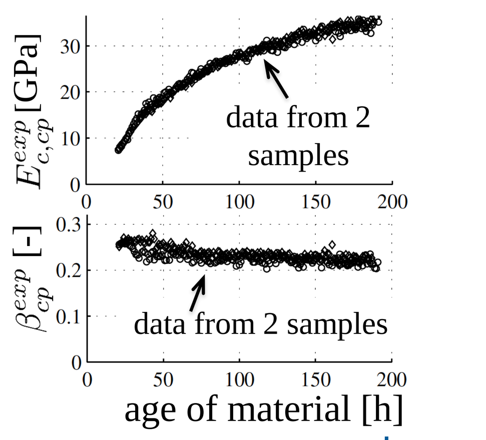
Creep behavior

creep strains can be perfectly fitted with **a Power-law creep function** [5]

$$\varepsilon^{fit}_{creep}(t) = \sum_{i=1}^{n} \frac{\Delta\sigma_i}{E^{exp}_{c,cp}} \left(\frac{t-\tau}{t_{ref}}\right)^{\beta^{exp}_{cp}}$$

creep modulus — Power-law exponent





Top-down Identification of Creep Properties of Hydrates

MOTIVATION

- creep behavior of cement paste depends on hydration degree + water-to-cement ratio [5]

$$J^{exp}_{cp}(t-\tau) = \frac{1}{E^{exp}_{cp}} + \frac{1}{E^{exp}_{c,cp}}\left(\frac{t-\tau}{t_{ref}}\right)^{\beta^{exp}_{cp}}$$

creep function of cement paste — functions of hydration degree and water-to-cement mass ratio

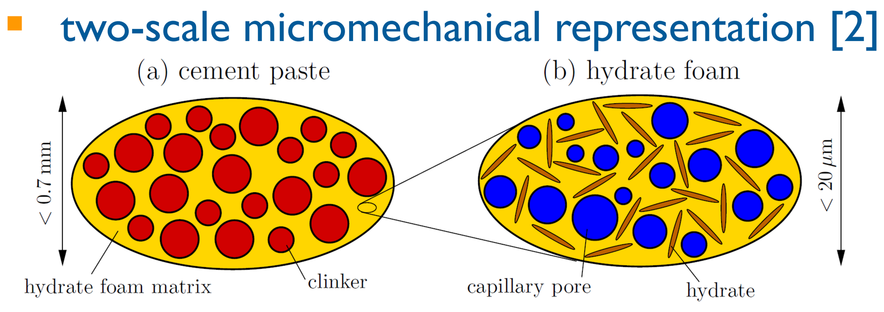
- Hypothesis: creep properties of **hydrates** are **universal** = age- and composition-independent

$$\mathbb{J}_{hyd}(t-\tau) = \frac{1}{3k_{hyd}}\mathbb{I}_{vol} + \frac{1}{2}\left[\frac{1}{\mu_{hyd}} + \frac{1}{\mu_{c,hyd}}\left(\frac{t-\tau}{t_{ref}}\right)^{\beta_{hyd}}\right]\mathbb{I}_{dev}$$

creep function of hydrates — universal viscoelastic properties

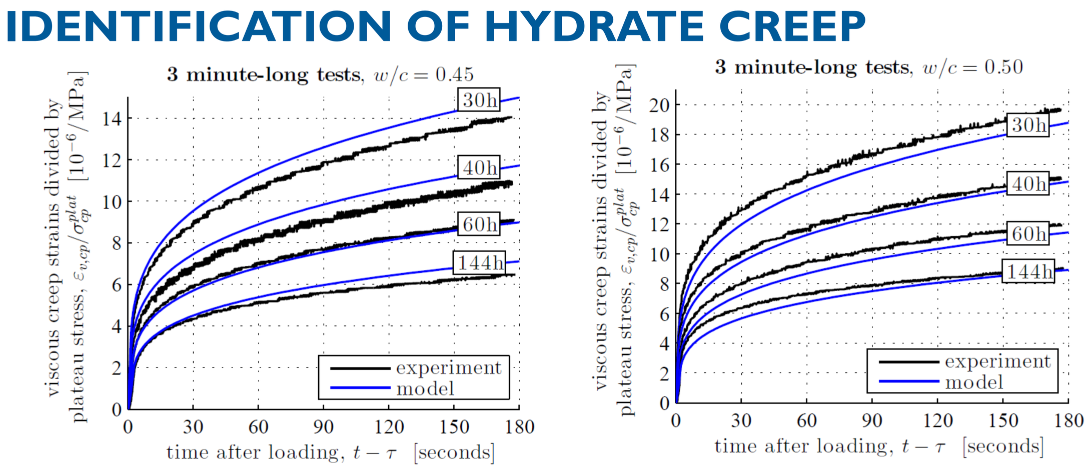
HOMOGENIZATION

- two-scale micromechanical representation [2]



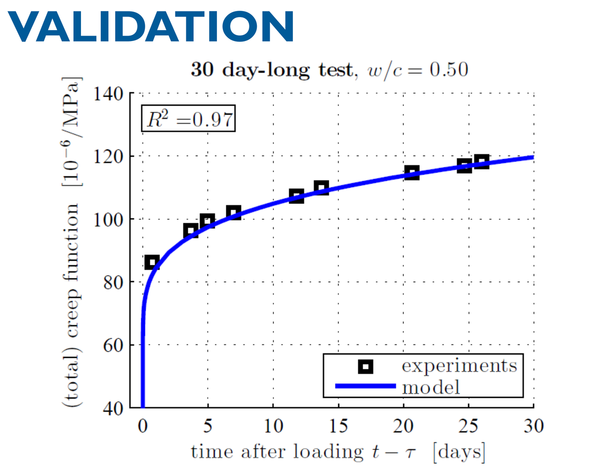
- viscoelastic homogenization based on the **correspondence principle** [9]
  1. Laplace-Carson (LC) transformation of hydrate creep function from time to LC space
  2. quasi-elastic upscaling, in the LC space
  3. numerical back-transformation [10]
- volume evolutions from **Powers' model** [3]

IDENTIFICATION OF HYDRATE CREEP



3 min-long tests on young paste are used for identification of hydrate creep properties, optimization routine yields Power-law constants: $\mu_{c,hyd} = 20.7\,\text{GPa}$, $\beta_{hyd} = 0.25$, model predictions nicely capture the aging-induced reduction of creep activity

VALIDATION



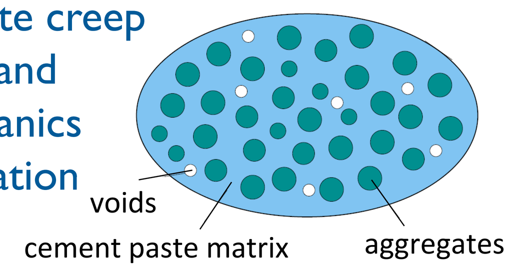
30 days-long tests on 30 years-old paste (→nonaging) from Tamtsia and Beaudin [11] corroborate the micromechanics model

- The **age- and w/c-dependent creep behavior of cement paste** results from … … an age- and w/c-independent (=**universal**) **hydrate creep behavior** (as long as hydrates do not dry)
- Hydrate creep properties identified from 3 min-long tests of very young pastes (with age of 1 to 8 days) allows for predicting the 30 days creep performance of very mature paste (with age of 30 years)

Bottom-up Prediction of Creep Properties of Concretes

MOTIVATION

- accurate prediction of mortar and concrete creep based on measured cement paste creep properties and micromechanics homogenization



- challenge lies in reliable estimations of the correct volume fraction evolutions
- cement paste in mortar/concrete is not a thermodynamically closed system, as assumed in the Powers' model [3], rather water migration from paste into aggregates (and vice versa) occurs

WATER MIGRATION MODEL

- total water in paste and aggregates $w = w_{cp}(\xi) + w_a(\xi)$
- initial water uptake by aggregates:

$$\frac{w}{c} = \frac{w_{cp}(0)}{c} + \frac{w_a(0)}{a}\frac{a}{c} \;\Rightarrow\; \frac{w_{cp}(0)}{c} = (w/c) - \frac{w_a(0)}{a}(a/c)$$

water-uptake capacity of aggregates

- Re-suction of water from aggregates into pastes:

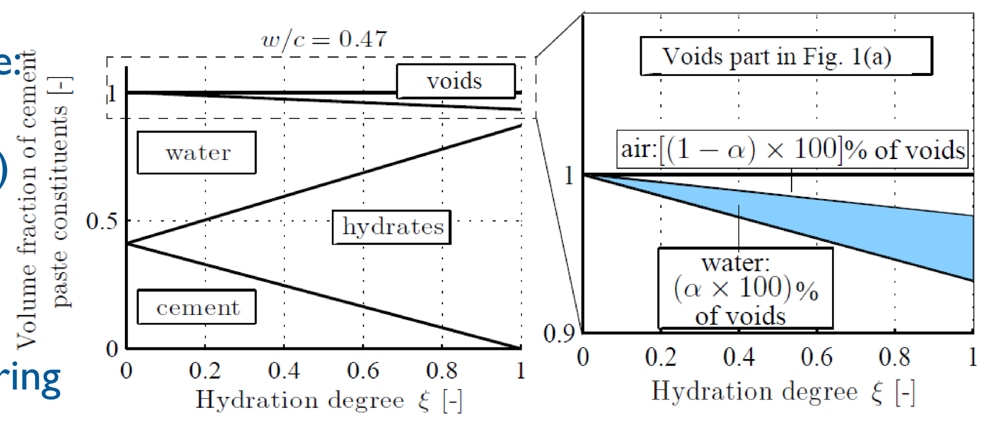
$$\frac{w_{cp}(\xi)}{c} = \frac{w_{cp}(0)}{c} + k\,\xi$$

… is driven by autogeneous shrinkage
→ linear function of the hydration degree (maintaining Powers´ linearity)

$$k = \left[\frac{\rho_{H_2O}}{\rho_{clin}} + \frac{w_{cp}(0)}{c}\right]\frac{3.31\,\alpha}{20 + 63\,\frac{w_{cp}(0)}{c}}$$

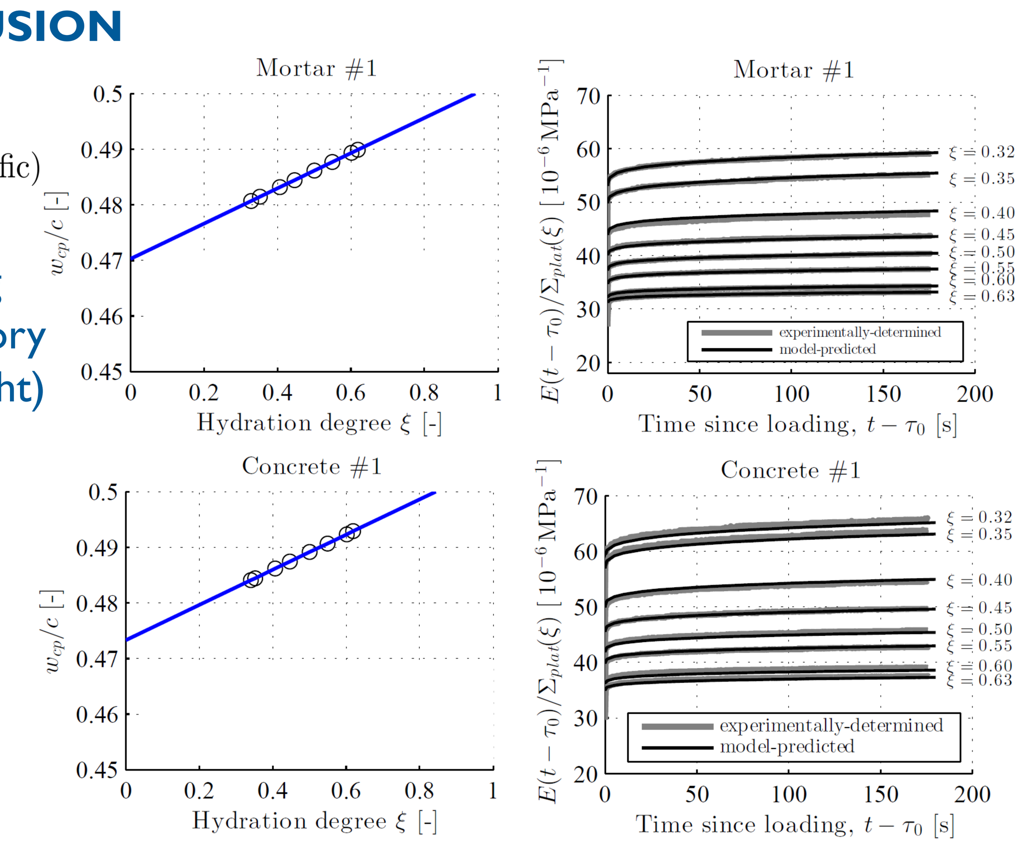
void filling extend

- two parameter model for internal curing



RESULTS AND CONCLUSION

- parameter identification:
  $\alpha = 60\%$ (universal)
  $w_a(0)/a \approx 1\%$ (aggregate-specific)
- air voids in concretes
- considering internal curing effects allows for satisfactory model predictions (see right)



References

[1] Zaoui (2002), *J Eng Mech*, 128(8):808-816
[2] Pichler et al. (2013), *Cem Concr Res*, 45: 55-68
[3] Powers & Brownyard. (1946), *J Am Concr Inst (Proc)*, 43
[4] Acker & Ulm (2001), *Nucl Eng Des*, 203(2): 143-158
[5] Irfan-ul-Hassan et al. (2016), *Cem Concr Res*, 82: 36-49
[6] Königsberger et al. (2016), *J Eng Mech*, in print
[7] Irfan-ul-Hassan et al. (2016), *J Nanomech Micromech*, submitted
[8] Karte et al. (20151), *Strain*, 51(2):156-169
[9] Read (1950), *J Appl Phys*, 21(7):671-674
[10] Abate & Valkó (2004), *Int J Numer Meth Eng* 60(5):979-993
[11] Tamtsia & Beaudoin (2000), *Cem Concr Res* 30(9):1465-1475

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