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QUASI-STATIC AND HIGH-DYNAMIC COMPRESSIVE STRENGTH TESTING OF YOUNG AND MATURE CEMENT PASTE

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Motivation

The ultimate load carrying capacity of cementitious materials increases with increasing loading rate. Notably, the micro-structures of **cementitious materials are glued together by** the same binder, which is **cement paste**, representing a mix of cement and water at specific water-to-cement mass ratios *w/c*. Improved insight into the loading rate-dependent compressive strength behavior of cement paste will allow for a better understanding of cementitious materials, in general.

We here report on **two experimental campaigns** involving destructive uniaxial compressive strength tests on cylindrical cement paste samples [1]. The tests were designed such as to shed light on the material effects responsible (i) for the moderate strength increase in the regime of quasi-static loading rates and (ii) for the significant strength increase in the regime of high-dynamic loading rates. Thereby, we consider that the water-saturation level is known to influence the mechanical performance of cementitious materials. This is the motivation to investigate two markedly different materials [1].

Materials and Experimental Methods

Young, water-saturated cement paste

In order to study a practically **water-saturated cement paste**, we produced samples with an initial water-to-cement mass ratio ***w/c* = 0.43**. During the **first 24 hours** after production, cylindrical specimens were stored **in sealed formworks**, in a climate chamber conditioned to **25 degrees**. One day after production, the specimens were demolded and their end faces were processed in order to achieve co-planarity. **After that**, the specimens were stored **in lime-saturated solution**, conditioned to 25 degrees centigrade. **Tests** were carried out **48 hours after production**.

Mature, oven-dried cement paste

In order to study a practically **dry cement paste**, we produced samples with an initial water-to-cement mass ratio ***w/c* = 0.60**. For a few days, they were stored in sealed formworks. After that, they **air-cured for six months**. Right before testing, the specimens were **oven-dried** for 20 hours, **at 75°C**. This removed most of the free water from the specimens. Tests were carried out once the specimens had cooled down to room temperature.

Quasi-static testing

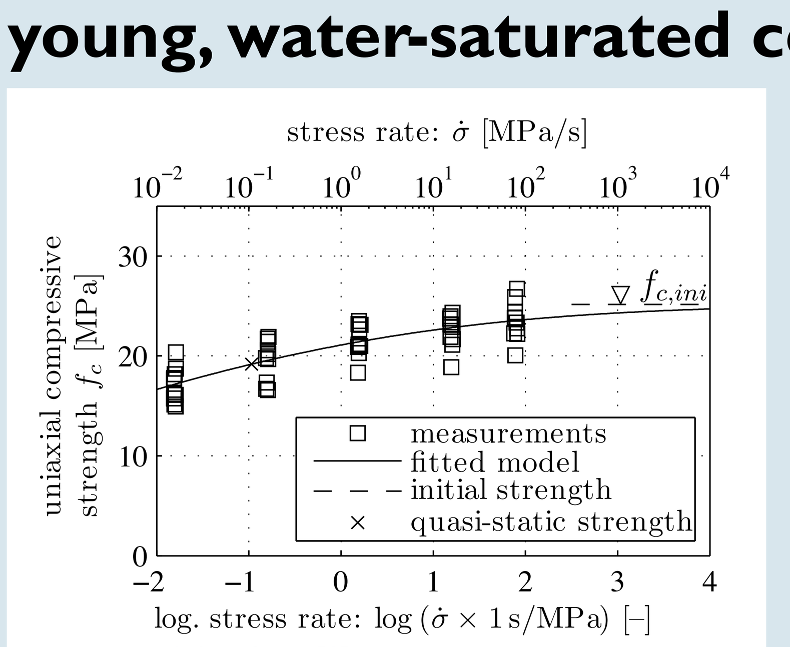
Quasi-static uniaxial compressive strength tests were carried out on a conventional **universal electro-mechanical testing machine** of type Walter and Bai LFM 150, both types of cement paste, on cylindrical specimens with a diameter of 30 mm and a height of 60 mm. The experiments were performed under force control, with **stress rates** ranging from **1.5×10^{-2} MPa/s to $8.2\times10^{+1}$ MPa/s**, covering four orders of magnitude.

High-dynamic testing

High-dynamic uniaxial compressive strength tests were carried out on a **split-Hopkinson pressure bar**. The mature and oven-dried cement paste, on cylindrical specimens with a diameter of 10.1 mm and a height of 6.6 mm. Effective high-dynamic **strain rates** ranged from **$2\times10^{+2}$ s^{-1} to $5\times10^{+3}$ s^{-1}**.

Results, Modeling, and Conclusions

Quasi-static strength of young, water-saturated cement paste



experimental data from [1]

$f_{c,ini}$ … initial strength of cement paste, prior to load-induced damage associated with creep deformation

Note: all figures after [2]

Experimental results:

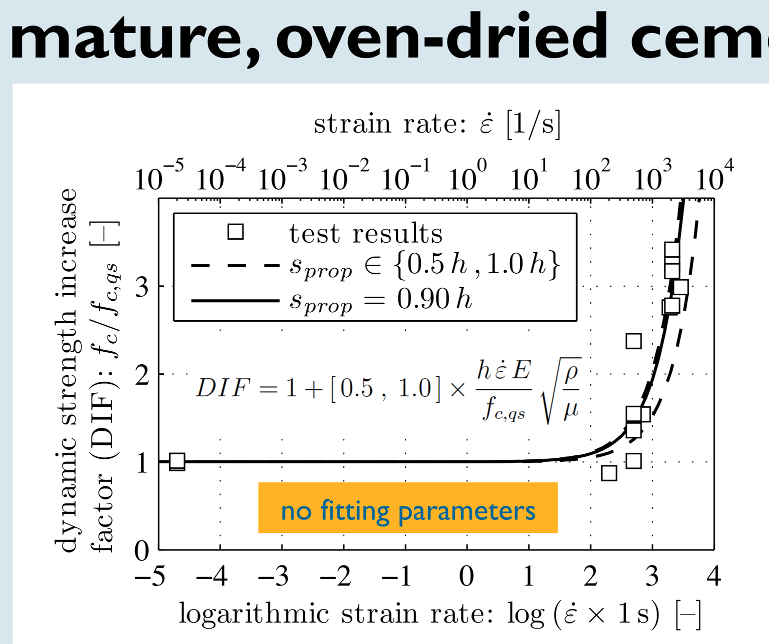
- Strength increases moderately with increasing quasi-static stress rate
- Crack propagation in loading direction

Modeling: viscoelasto-brittle approach [1]

- Non-linear creep model accounting for damage associated with creep
- Ultimate strain criterion for strength

Interpretation: Strength decreases with decreasing loading rate, because the test duration is increased, and this provides creep associated damage mechanisms with more time to reduce the initially available strength

Quasi-static and high-dynamic strength of mature, oven-dried cement paste



experimental data from [1]

$s_{prop} = 0.5\,h$ … first crack nucleates at specimen center
$s_{prop} = 1.0\,h$ … first crack nucleates at specimen surface
h = specimen size in direction of crack propagation
E = Young's modulus $f_{c,qs}$ = quasi-static strength
μ = shear modulus ρ = mass density

Experimental results:

- No quasi-static strengthening
- Significant high-dynamic strengthening
- Crack propagation in loading direction

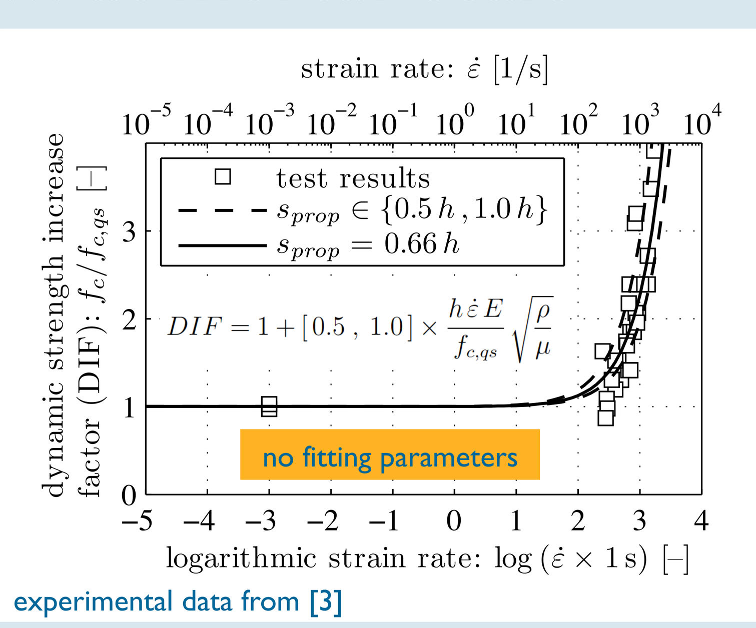
Modeling: elasto-brittle approach [1]

- Time to peak load = time to nucleation of first crack + time required for the first crack to split the sample
- Critical strain criterion for crack nucleation
- Crack propagation at Rayleigh wave speed

Interpretation: Measured strength data scatter stems from uncertainty regarding the position where the first crack nucleates

High-dynamic strength model validation …

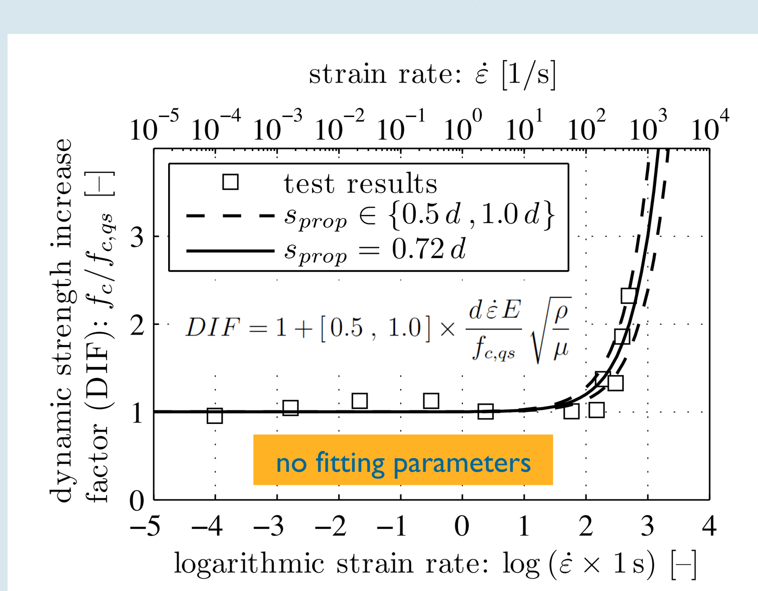
… at mortar scale



experimental data from [3]

$s_{prop} = 0.5\,h$ … first crack nucleates at specimen center
$s_{prop} = 1.0\,h$ … first crack nucleates at specimen surface
h = specimen size in direction of crack propagation
E = Young's modulus $f_{c,qs}$ = quasi-static strength

… at concrete scale



experimental data from [4]

$s_{prop} = 0.5\,d$ … first crack nucleates at level of aggregate equator
$s_{prop} = 1.0\,d$ … first crack nucleates at level of aggregate pole
d = maximum aggregate diameter
μ = shear modulus ρ = mass density

Mortar Similar to cement paste: peak load right before first crack splits the sample.
Concrete Maximum aggregate size matters. Peak load is reached, once the first crack is so large that an aggregate breaks out of the concrete microstructure.

Conclusions

Quasi-static tests provide enough time for creep to be significant. Crack propagation (i.e. "failure") of the specimen is a quasi-instantaneous effect. Creep activity increases with water content. Creep is associated with damage. Strength decreases with decreasing loading rate, because the test duration is increased, and this provides creep associated damage mechanisms with more time to reduce the initially available strength.
High-dynamic tests do not provide enough time for creep to be significant. Crack propagation at Rayleigh wave speed is not a quasi-instantaneous effect. During crack growth in loading direction, material columns form between the cracks, and their loading can be further increased, until the first crack splits the specimen (cement paste and mortar). The concrete peak load is reached, once the first aggregate breaks out of the concrete microstructure. We conclude that high dynamic strengthening is a structural effect rather than a material property.

References:
[1] Fischer, I., B. Pichler, E. Lach, C. Terner, E. Barraud, & F. Britz (2014). Compressive strength of cement paste as a function of loading rate: experiments and engineering mechanics analysis. Cement and Concrete Research 58, 186-200.
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[3] Gary, G. & P. Bailly (1998). Behaviour of quasi-brittle material at high strain rate. Experiment and modelling. European Journal of Mechanics, A/Solids 17 (3), 403–420.
[4] Grote, D., S. Park, & M. Zhou (2001). Dynamic behavior of concrete at high strain rates and pressures: I. Experimental characterization. International Journal of Impact Engineering 25 (9), 869–886.

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