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Upscaling quasi-brittle strength of cement paste and mortar: A multi-scale engineering mechanics model

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ABSTRACT

It is well known from experiments that the uniaxial compressive strength of cementitious materials depends linearly on the degree of hydration, once a critical hydration degree has been surpassed. It is less known about the microstructural material characteristics which drive this dependence, nor about the nature of the hydration degree–strength relationship before the aforementioned critical hydration degree is reached. In order to elucidate the latter issues, we here present a micromechanical explanation for the hydration degree–strength relationships of cement pastes and mortars covering a large range of compositions: Therefore, we envision, at a scale of fifteen to twenty microns, a hydrate foam (comprising spherical water and air phases, as well as needle-shaped hydrate phases oriented isotropically in all space directions), which, at a higher scale of several hundred microns, acts as a contiguous matrix in which cement grains are embedded as spherical clinker inclusions. Mortar is represented as a contiguous cement paste matrix with spherical sand grain inclusions. Failure of the most unfavorably stressed hydrate phase is associated with overall (quasi-brittle) failure of cement paste or mortar. After careful experimental validation, our modeling approach strongly suggests that it is the mixture- and hydration degree-dependent load transfer of overall, material sample-related, uniaxial compressive stress states down to deviatoric stress peaks within the hydrate phases triggering local failure, which determines the first nonlinear, and then linear dependence of quasi-brittle strength of cementitious materials on the degree of hydration.

1. Introduction

Cement paste is the binder for cementitious materials, including cement mortar, concrete, shotcrete, and soilcrete. Therefore, a reliable prediction of mechanical properties of cement paste is paramount for subsequent modeling activities, be they related to material behavior of cementitious composites or to the structural behavior of engineering constructions built up from these materials. Challenging applications even require modeling of the evolution of mechanical properties of *hydrating* cementitious materials. This is e.g. the case for drill and blast tunneling according to the principles of the New Austrian Tunneling Method (NATM), where shotcrete tunnel shells are loaded by the inward moving rock, while the material still exhibits rather small maturities and undergoes the chemical hydration process. This provides the motivation for the present contribution which focuses on upscaling elasticity and strength of hydrating cement paste and mortar, by means of continuum micromechanics.

Within cement paste, hydration products (also called hydrates) establish the links that lead to a network of connected particles. The hydrates' non-spherical phase shape (evidenced by microscopic [1–11] and neutron scattering [12] studies) has been recently shown to probably play an important role in micromechanics-based prediction of the quasi-brittle strength evolution of cementitious materials [13,14]. Thereby, hydration degrees have been estimated from elasticity measurements by means of a (validated) microelastic model, and corresponding measured strength values could be successfully predicted by a microelastic-brittle model with the hydration degrees as input. In this context, a mixture-invariant deviatoric hydrate strength was back-calculated. Having, in this way, gained confidence into the modeling approach, we here aim at a much stricter experimental model test: We wish to predict directly measured hydration-degree–strength relationships for different mixtures, with possibly avoiding any back-calculated strength values. Accordingly, the manuscript is structured as follows:

Section 2 recalls fundamentals of continuum micromechanics. In Section 3, we introduce a micromechanical representation of cement paste and mortar (Section 3.1), followed by corresponding mathematical expressions for upscaling elasticity (Section 3.2) and quasi-brittle strength (Section 3.3). Subsequently, we discuss model input values (Section 3.4). Therefore, we consider dense hydrate foams with very low porosity, from which we identify elastic properties that are, on average, representative for all hydration products. On this basis, our micromechanics models predict elasticity and strength of cement pastes and mortars as functions (i) of hydration degree and (ii) of

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