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Micromechanical Homogenization of Ultra-High Performance Concrete

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Abstract: Mechanical properties and durability of Ultra-High Performance Concretes (UHPC) are closely associated with composition and microstructure of tested samples. In this work, determination of effective elastic properties of UHPC composite was performed for a representative volume element using combination of microstructural investigations (scanning electron microscope imaging, image analysis of back scattered electron micrographs and nanoindentation) and analytical methods of micromechanics. Based on the volumetric content and micromechanical behavior of individual components an effective elastic modulus of the whole composite was predicted and compared with macroscopically measured value with good agreement.

Introduction

Ultra-High Performance Concrete (UHPC) widely used in building industry represents promising material with excellent durability and mechanical properties. Depending on final application UHPC can be designed by mixing of common raw materials (cement, water and aggregates, plasticizer), reactive powder (e.g. microsilica) and/or small fiber reinforcement improving material parameters in addition. Properties of concrete are commonly assessed from macroscopic point of view, nevertheless, its mechanical behavior is related to its composition and microstructure. Overall mechanical behavior of a heterogeneous material including concrete can be best calculated from measured data on individual phases, their volume fractions and possible interphase interactions. For this task, description of individual UHPC components and their micromechanical characterization can be performed using, e.g., scanning electron microscopy (SEM) equipped with energy dispersive X-ray detector (EDX) and nanoindentation. To determine the effective properties of the concrete sample in a statistical sense homogenization of phase properties from a representative volume element (RVE) involving all the material phases in a sufficient content can be performed with the aid of micromechanics [1,2]. In this paper, we evaluated the effective elastic properties of UHPC containing microsilica and steel fibers using homogenization based on Mori-Tanaka method.

Materials and methods

Phase detection and volume content of the phases was performed on a polished cross section (2.2 cm^2) of UHPC with SEM Mira II LMU (Tescan corp., Brno) equipped with energy dispersive X-ray detector (Bruker corp., Berlin). The content of individual phases in concrete was calculated using Image processing toolbox in MATLAB. Elastic material constants were determined with nanoindenter Nanohardness tester (CSM Instruments) in micrometer scale. Overall elastic stiffness of the composite was estimated assuming spherical inclusion geometry and perfect bond of the phases at the microscale with the Mori-Tanaka homogenization scheme. The resulting effective Young´s modulus was compared with experimental values measured on macroscopic laboratory specimens (100x100x400 mm) with impulse excitation method.

Results

Based on image analysis of BSE micrographs the major phases in concrete were basalt aggregates with grain size ranging from 5 mm to 300 µm, aluminosilicate binder (mainly calcium-silica hydrates and unhydrated clinker), steel fibers and pores. Classification of individual phases and their ratios were determined by means of BSE intensity level image analysis. The aggregate was found to have mineralogically heterogeneous microstructure (composed of apatite, magnetite, olivine and feldspar) and was homogenized separately from the rest of the phases.

Cementitious composite are often characterized with the weak interfacial zones (ITZ) between matrix and aggregate. This is not the case of the UHPC sample where virtually no ITZ was detected by SEM and nanoindentation as a possible result of low water/binder ratio and presence of microsilica in the composition. The results of the image analysis and a two-step homogenization (step 1 = homogenization of aggregate, step 2 = homogenization of other composite phases) are summarized in Tab. 1.

Table 1: UHPC composition based on image analysis, elastic moduli of individual phases from nanoindentation and effective values of composite elastic modulus.

Phase	Phase content [%]	Elastic modulus [GPa]	Poisson's ratio	Effective elastic modulus [GPa]
Aggregate (composed of apatite, magnetite, olivine, feldspar and pores in aggregate)	37.5	131.3*	0.2	46.6
Binder (incl. clinker and microsilica)	57.9	29.4†	0.2	
Pores (in cement matrix)	2.8	0	0	
Fibers	2	200	0.3	

*value from nanoindentation on individual phases and homogenized (step 1), †from nanoindentation

Summary

Combination of image analysis and analytical homogenization was used to estimate effective elastic modulus of a heterogeneous UHPC sample. The homogenized sample Young's modulus was assessed as 46.6 GPa. The value is generally in accordance with the value measured on laboratory specimens with the impulse excitation method which gives dynamic elastic modulus (51 GPa). The small discrepancy between the values can be caused by dissimilar testing methods. Dynamic methods are known to give higher elastic moduli compared to static tests (which is the case of nanoindentation). The other possible reason lies in not exact representativeness of the area scanned in image analysis causing underestimation of the real volumetric content of some phases (especially large aggregate volume). The image analysis could be refined by an extension of the analyzed area.

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