INFORMATION ON CURRENT RESEARCH OF ENGINEERED CEMENTITIOUS COMPOSITES

Petr Kabele[1], Jaroslav Pekař[2], Luděk Novák[3], Jiří Němeček[4]

Abstract

This paper summarizes some of authors' recent research activities related to ECC and SHCC materials. In particular it reports on multiscale study of durability of ECC materials, development of testing method of tensile performance of SHCC, and the application of finite element analysis to clarify the mechanical phenomena governing structural performance of reinforced ECC.

Keywords: Engineered Cementitious Composites (ECC), strain hardening cementitious composites (SHCC), durability, testing method, structural performance

1 Introduction

Engineered Cementitious Composites (ECCs) are modern building materials with cement-based matrix reinforced by short random fibers. These materials differ from ordinary cementitious composites, such as the popular fiber reinforced concrete (FRC), by the feature that their microstructure and composition are rigorously designed with the objective of both acceptable workability in the fresh state and highly ductile overall behavior under tension in hardened state.

It is well known that the overall tensile and fracture properties of brittle-matrix composites can be radically improved if they are capable of so-called multiple cracking. In a uniform tensile stress field, multiple cracking manifests itself by formation of a large number of distributed sub-parallel matrix cracks bridged by fibers. The cracks are usually very fine (with widths below 100 μm) and closely spaced (with crack to crack distance on the order of millimeters), as shown in Fig. 1. In an overall stress-strain diagram, multiple cracking is associated with a significant hardening behavior (Fig. 2) – the material exhibits so-called pseudo strain-hardening. Consequently, these materials are collectively referred to as High Performance Fiber Reinforced Cementitious Composites (HPFRCC) or Strain Hardening Cementitious Composites (SHCC).

To achieve multiple cracking, a brittle-matrix fibrous composite has to satisfy two criteria formulated on the basis of fracture mechanics: the 'steady state cracking criterion' and the 'further cracking criterion', see e.g. [7], [5]. Employing micromechanics, the conditions for multiple cracking and pseudo stain-hardening can be expressed in terms of micromechanical parameters of fiber, matrix and fiber-matrix interface, e.g. [4]. These parameters include, for example, fiber volume fraction, fiber aspect ratio, fiber Young's modulus, matrix Young's modulus, matrix fracture toughness, initial flaw size, fiber-matrix bond characteristics, etc. Using these criteria, it was possible to optimize the material composition so as to achieve the desired multiple cracking ability and overall ductility with various fiber-matrix systems. To emphasize the use of the rigorous micromechanics-based material design methodology, the materials are called Engineered Cementitious Composites [6].

Presently, the most popular ECC composition uses short PVA fibers; an ECC containing as little as 2% by volume of these fibers typically exhibits tensile strength of over 5 MPa and ductility of about 3-5%. Due to the moderate fiber content, the material can be produced in an ordinary mixer and shaped in various ways (precast, cast in-situ, extruded, sprayed, etc.). This feature makes ECC available for a wide range of practical applications in civil and building engineering. For example, ECC has been used or its use is seriously planned for repairs of dams (Japan), watertight bridge underdeck (Japan), sewage lines (Korea), bridge deck (USA), ductile strips for elimination of shrinkage and temperature-induced cracking in pavements and bridge decks (USA), and others [6].

In order to facilitate the transfer of the technology of SHCC from experimental stage into engineering practice, RILEM technical committee TC-HFC has been established in 2004. The broad objective of this committee is to *identify and develop systematic solutions to obstacles preventing wide use of SHCC, namely in relation to structural design, material property characterization and testing, and field execution*. The TC focuses on *structural use of SHCC*, and emphasizes *the linkage between materials and structures*. To this end, three sub-committees have been formed: subcommittee on characterization of mechanical properties (SC1), subcommittee on durability (SC2), and subcommittee on structural design and performance (SC3).

In the present paper we outline some of current research activities of the authors' group related to the tasks of TC-HFC.

2 Multiscale study of durability of ECC materials

Application of ECC materials is often seen as one of possible ways to improve durability of concrete and reinforced concrete (R/C) structures, especially of those exposed to harsh environment [9]. From the durability point of view, it is important that during the process of multiple cracking, the widths of cracks remain in the sub-millimeter range, even when the overall strain attains the level of several percents. The composite is then much less susceptible to ingress of water and aggressive agents from the environment than ordinary R/C would be at the same structural deformation. It has been also shown that the overall ductility of the composite is essential for the interfacial crack-trapping mechanism and thus ECCs show a very good cohesiveness when applied in a thin layer to concrete substrate.

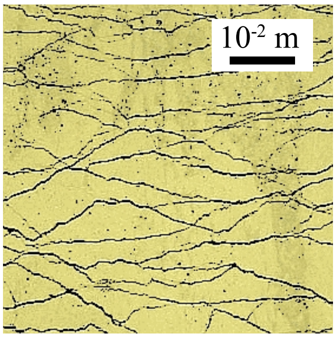

Fig. 1 Multiple cracking in ECC material.

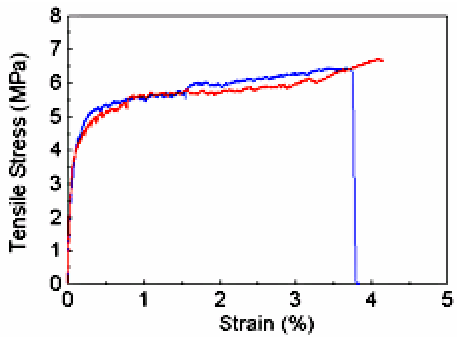

Fig. 2 Typical result of direct tension tests on PVA-ECC coupon specimens (www.engineeredcomposites.com).

It follows that when ECCs are used to improve structural durability, the composites' ability to undergo damage in the form of multiple cracking under severe environmental conditions is essential. Since the overall mechanical behavior of ECC materials is closely related to their tailored microstructure, this ability can be estimated if the effects of aggressive environment on mechanical phenomena that take place at the microscale, are known. In the present study, we experimentally investigated the effects of chloride exposure and calcium leaching by nitrates on the mechanical behavior on various levels of the composites' microstructure. Note that in the real world, chloride attack usually occurs due to use of deicing salt for road maintenance or in seashore and marine structures. Leaching can take place in structures exposed to soft water or water containing ions like SO_4^{2-} , NH_4^+ - underground structures, sewers, dams, etc. In the experiments, the chemical attack was induced in accelerated manner.

2.1 Fiber pullout tests

In order to estimate the basic bond properties of fiber-matrix interface, single-fiber pullout tests were conducted [1]. A fiber, partially embedded into cylindrical matrix specimens, was pulled out in axial direction under displacement control. Pullout force P and pullout displacement Δ were monitored and recorded. From the measured force chemical bond strength G_d and frictional bond strength τ_0 were calculated.

Fig. 3 shows that both chloride and nitrate attacks significantly reduce the chemical bond strength. On the other hand, frictional bond is decreased only by nitrate, while chloride exposure causes its slight increase.

2.2 Nanoindentation

To gain a better understanding of the phenomena observed in the pullout tests, nanoindentation of the fiber-matrix interfacial transition zone (ITZ) was carried out [8]. Fig. 4 shows that in control specimens (O), the local elastic modulus increases as the distance from the fiber increases, before attaining a stable value at about 30 μm from the fiber. This can be attributed to higher porosity of the ITZ close to the fiber. This tendency is almost unaffected by chloride attack (S). On the other hand, nitrate (N3, N6) causes degradation of the matrix by calcium leaching, which manifests itself by low modulus even farther from the fiber.

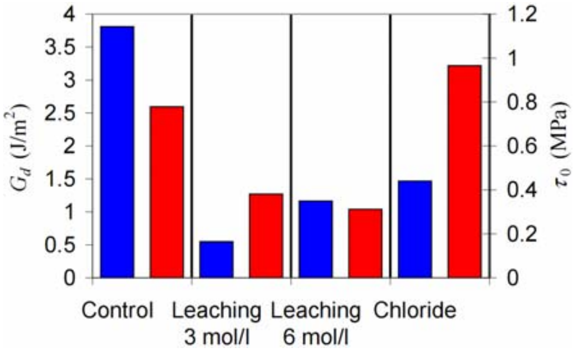

Fig. 3 Effect of chemical exposure on chemical bond (left columns) and frictional bond (right columns)

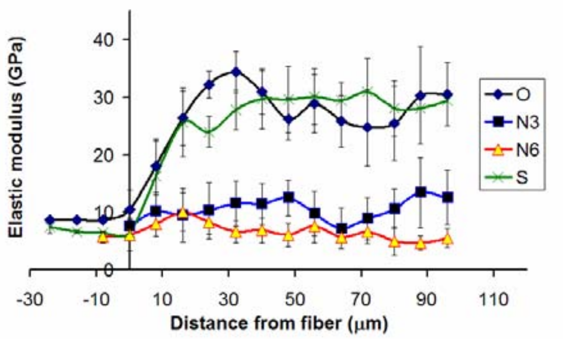

Fig. 4 Effect of chemical exposure on the matrix local elastic modulus

2.3 Fracture tests

Matrix fracture toughness is another important micromechanical parameter, since it controls initiation of multiple cracks from matrix defects. Fracture tests on small 3-point bending notched beams with notch size close to the largest intrinsic flaw (5 mm) were carried out. From the load at initiation of crack propagation, the matrix fracture toughness was estimated. Results show that the fracture toughness is almost unaffected by chloride treatment. Exposure to nitrate causes a severe decrease of this parameter.

From the peak loads attained in these tests, we also calculated the modulus of rupture. Since the peak load is mostly determined by the cohesive traction acting between crack surfaces, we obtained qualitative information on the effectiveness of fiber bridging on a single crack. Results indicate that the bridging effectiveness significantly degrades due to exposure to nitrate, while chloride causes only a slight decrease.

3 Testing method of tensile performance of SHCC

Tensile performance, namely the ability to undergo multiple cracking, the uniformity of multiple-cracks distribution, and the tensile strain capacity, are the most important mechanical properties of SHCC. Presently, there is no unified tensile test method that would allow estimating these properties objectively. Results are strongly affected by the test type (direct tension/bending), boundary conditions (fixed/hinged), and the specimen size, shape, and preparation method (cast/cut). In order to propose a suitable testing method, TC-HFC has organized round-robin experiments, in which participating laboratories performed tensile tests on specimens made of the same reference material (ECC distributed in the form of dry mix).

Our group contributed results of direct tension tests on prismatic specimens with cross-sectional dimensions of 20×10 mm and free length of about 200 mm. The specimens were produced by cutting from larger plates. Boundary conditions were fixed rotations on both ends. It is seen in Fig. 5 that the measured tensile strain capacity of about 0.5% is far below the expected value of about 3% (at the moment of this paper writing, only preliminary results by other groups were available, so direct comparison could not be made). We assume that this is a consequence of using specimens with too small cross-section, which prevents fiber-bridged cracks from developing in a steady-state manner, thus resulting in premature fracture localization and specimen failure.

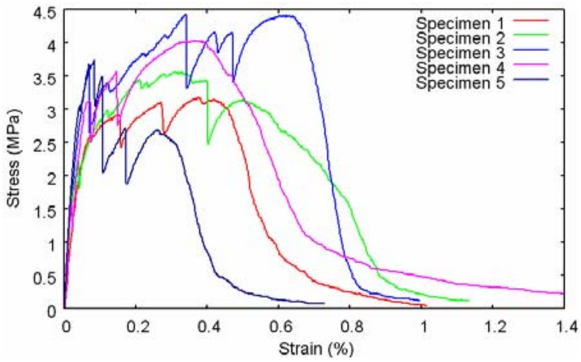

Fig. 5 Typical uniaxial stress-strain curves of prismatic specimens (cross section 20×10 mm).

4 Modeling and analysis of structural shear performance of ECC

Due to their high tensile strain capacity and damage tolerance, ECC materials appear as an attractive alternative for replacing concrete in shear-critical structural elements and details. A large number of experimental studies have shown that using ECC in conjunction with conventional reinforcement (R/ECC) in such elements indeed leads to a significant qualitative improvement of their structural behavior, namely in terms of load and displacement capacity.

Finite element analysis can be employed along with the experimental investigations to clarify the mechanism of shear failure of R/ECC members [2]. Since these structural shear failure phenomena are clearly associated with localization of fracture, the FE model must be sufficiently detailed to capture possible initiators of localization: uneven stress distribution due to details at load application and supports, conventional reinforcement, loading control etc. In addition, the employed constitutive model must reliably represent the material behavior at the scale where localized cracks are initiated – i.e. at the scale of multiply-cracked composite. These requirements are fulfilled by the model proposed in [3]. The model is based on homogenization a of a volume element containing a set of multiple cracks, while considering that opening and sliding of these cracks are resisted by fiber bridging.

Fig. 6 shows results of numerical simulation of an experiment on an R/ECC shear beam. The analysis reproduced fairly well the overall response of the beam, including the load capacity. More important, it allowed us to visualize the change of load carrying mechanism in the course of the experiment. Initially, the specimen exhibited multiple cracking at angle ≈45°. This cracking induced strong anisotropy and significantly reduced the overall shear stiffness of the cementitious material. As a result, fracture localized into a band along the shear span diagonal (load level B). Opening and sliding of these cracks, which virtually interrupted the compressive diagonal, resulted in attaining the ultimate load.

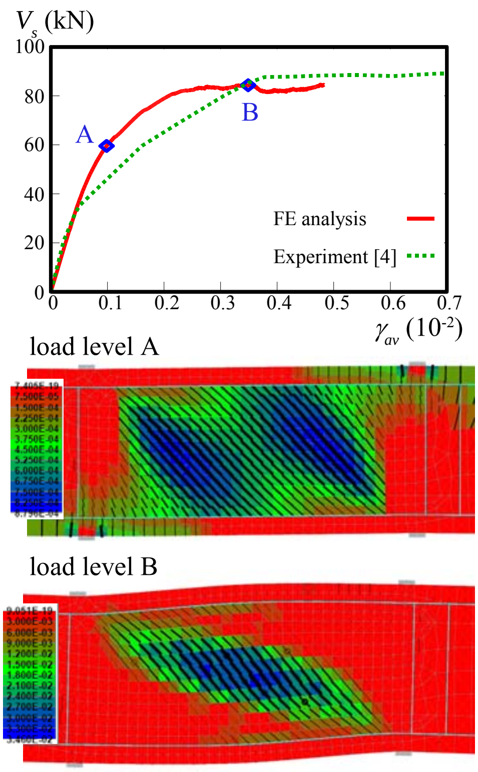

Fig. 6 Shear beam: computed overall response; cracking pattern and distribution of maximum principal cracking strain.

5 Concluding remarks

This paper summarizes some of authors' ongoing research activities related to ECC and SHCC materials.

The multiscale experimental investigation of ECC in aggressive environment showed consistent effects of chemicals across different scales. Exposure to nitrates (calcium leaching) strongly degrades the cementitious matrix, which results in reduction of fiber bond, matrix toughness, and cohesive crack-bridging traction. Chloride treatment almost does not affect the matrix properties. It causes slight change in fiber bond properties, which results in small decrease of the bridging traction.

As for the tensile testing method, no definite conclusions can be drawn before results form all participants of the round-robin tests are compared and analyzed. However, our preliminary results indicate that specimens with too small cross section are not suitable to test the tensile strain capacity of SHCC materials.

Finally, it was shown that finite element analysis can provide a useful insight into the mechanical phenomena governing structural performance of R/ECC.

Acknowledgements

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