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High performance fiber reinforced cement composites HPFRCC-4: International workshop Ann Arbor, Michigan, June 16–18, 2003 ☆

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High Performance Fiber Reinforced Cement Composites (HPFRCC) are characterized by a stress–strain response in tension that exhibits strain-hardening behavior accompanied by multiple cracking, and related relatively large energy absorption capacity. This international workshop was the fourth in a series dealing with such composites.

The first international workshop on HPFRCC was organized in Mainz, Germany, June 1991, under the auspices of RILEM and ACI. It was funded in part by US National Science Foundation (NSF) and by the Deutsche Forschungsgemeinschaft (the German NSF). Other co-sponsors included ACBM, the University of Michigan, the University of Stuttgart and the Alexander von Humboldt foundation. The second workshop took place in Ann Arbor, Michigan, in June 1995, and the third in Mainz Germany, in June 1999. In each case hard-cover proceedings were published as a special RILEM publication. While the first workshop in 1991 included mostly US and German participants, subsequent workshops were opened to researchers from other countries. This last workshop assembled about sixty participants from eighteen countries, with essentially same sponsors and co-sponsors.

Since the first workshop, continuous developments have occurred in new materials, processing, standardization, and in improved products for building and other structures. Also, enhanced theory and modeling of HPFRCC can now better describe their behavior and explain their reinforcing mechanisms. While the root definition of HPFRCC is simplest (that is to exhibit strain hardening and multiple cracking behavior in tension) to clearly differentiate them from other cement composites, this is not the only description of desirable performance. Durability, ductility, fire resistance, impact resistance, diffusion, imperviousness, and constructability at reasonable cost, are other important attributes that need to be further clarified. Additional sub-characterization for "deflection hardening" and "deflection softening" to reflect potential applications, has been defined.

One feature of this last workshop, is that the organizers preselected lead topics they believed offer technical challenges at this time. The lead topics were: self-compacting and self-consolidating fiber reinforced cement (FRC) mixtures; fire resistance; impact and blast resistance; constitutive properties under reversed cyclic loading; modeling with discontinuous fibers; scale and size effects; and criteria for seismic applications. Other important topics included hybrid composites, modeling bond, and design recommendations by RILEM TC-162.

1. Significant pointers

Although the discussions addressed many topics and ideas over a three days period, a selection of pointers is presented next, hoping that they will entice the interested reader to consult the proceedings for additional details.

1. A comprehensive overview of computer simulation using rigid body spring networks to model fracture processes and transport phenomena such as moisture migration was presented. New approaches to modeling and characterization are needed, particularly to cover the entire spectrum of fiber reinforcement from discontinuous to continuous fibers, and vice versa. Hybrid combinations of reinforcement

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offer future technical challenges for optimized properties and performance.

2. There is need to better characterize ultra high performance (UHPFRC) composites, versus other HPFRCCs.
3. Bond at the fiber–matrix interface, its characterization and modeling for single and groups of fibers, with and without confinement, remains a broad subject for in-depth research.
4. There is urgent need to develop standards for impact and blast resistance testing to reveal and quantitatively evaluate the true contribution of fiber reinforcement.
5. Scale effects are dependent on the type of loading and the type of material, such as a tensile strain hardening material versus a strain softening one. Softening materials in tension can produce hardening behavior in bending; however, the hardening behavior is strongly scale dependent.
6. Fire resistance of high performance concrete is improved by addition of polypropylene fibers; it is not clear if air voids or properly sized pores or other polymeric fibers can do the same; thus there is need for further research on this subject. Steel fibers did not have a similar effect on fire resistance as PP fibers, although the fire resistance of small slab specimens did improve with the addition of steel fibers.
7. Study and evaluation of mix rheology is a key element for self-compacting and self-consolidating FRC mixtures, especially at high fiber content. For a given volume fraction of fibers, the packing density of the mix varies with the sand content and is optimal at a certain sand content value. Packing density of the fibers themselves in a given volume greatly influences the rheology of the mix. Slump flow decreases with an increase in fiber aspect ratio and volume fraction.
8. In reversed cyclic loading, as long as compressive strength is not reached, no significant effect is observed on tensile response of strain hardening composites. There is need for improved constitutive models to capture cyclic response, and to evaluate energy dissipation capacity under reversed cyclic loading.
9. The advantages of HPFRCCs in seismic applications include improved behavior under shear intensive loading; partial or full elimination of transverse reinforcement; reduced congestion of reinforcement; little damage even at 2% shear distortion; significantly reduced spalling; ability to provide large deformation capacity.
10. Glass aggregates can be ground to a certain size at which ASR is no longer a problem.
11. Innovative formulation of lightweight engineered cementitious composites was presented and offers opportunities for further research and development.
12. Although strain hardening has been the main objective of HPFRCC, crack width and spacing at service load levels are critical requirements for performance and durability and are key to important applications.
13. Hybrids are definitely here. They imply combinations of fibers of different lengths or materials, or combinations of continuous and discontinuous fibers, or combinations of continuous reinforcements of different properties (steel or FRPs), and they are likely to be the subject of increasing research and applications.
14. There is need to develop a meaningful test for HPFRCC as they are not covered in RILEM TC-162, Design Method for Steel Fiber Reinforced Concrete.

2. Performance-based classification of FRC composites

In order to minimize the increasing number of names and acronyms associated with particular mixtures, designs, or production processes, the authors (in an introductory short paper setting the stage for the discussions) suggested the use of a performance-based design classification of FRC composites with four levels of performance, namely:

(1) crack control,
(2) deflection hardening,
(3) strain hardening, and
(4) high energy absorption.

The proposal is illustrated in Fig. 1. This classification has the advantage of following current applications; indeed low fiber content is used in numerous applications in slabs on grade for crack control; deflection hardening composites with a moderate volume content of fibers are used in beams in combination with conventional reinforcement such as in seismic resistant structures; strain hardening composites are used in stand-alone thin sheets applications and require a relatively higher volume fraction of fibers; and very high fiber contents are used in blast and impact resistant structures which require high energy absorption capacity.

Following a discussion of the proposal, there was general agreement that a performance-based classification is desirable. However, it was argued that Fig. 1 can be misleading as it does not show the relationships between strain-hardening and deflection-hardening composites; the discussion led to the development of Fig. 2. It can be observed from Fig. 2 that all strain hardening composites are also deflection hardening; on the other hand, some strain-softening composites can be deflection hardening. Formulae giving the critical volume fractions of fibers to achieve strain-hardening or deflec-

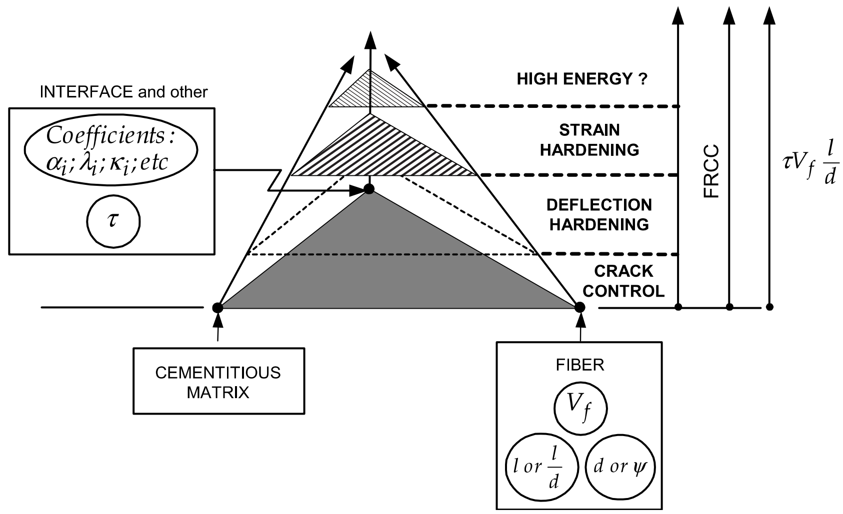

Fig. 1. Spatial relationship illustrating the proposed four levels of performance to characterize FRC composites.

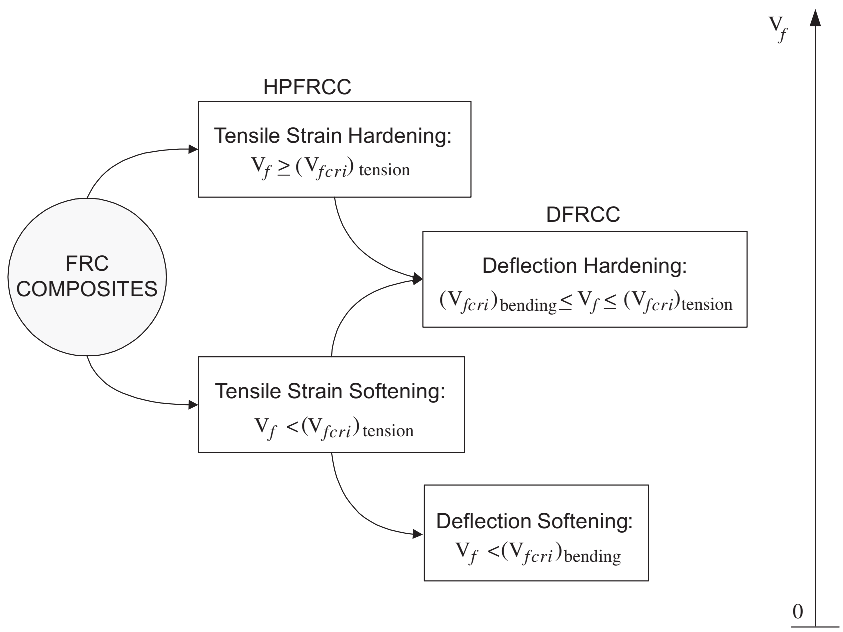

Fig. 2. Behavioral characterization of FRC composites.

tion-hardening composites [$(V_{\text{fcri}})_{\text{tension}}$ and $(V_{\text{fcri}})_{\text{bending}}$] can be found in the proceedings.

The authors wish to encourage additional research carried out in the future on the types of performance requirements and levels of performance specifications needed to allow the full utilization of FRC composites in both structural applications (i.e., in combination with reinforced and prestressed structures) and stand-alone applications.

3. Proceedings

The hard-cover proceedings include 40 papers grouped in seven different parts. They are available from RILEM: "*High Performance Fiber Reinforced Cement Composites (HPFRCC4)*," A.E. Naaman and H.W. Reinhardt, Editors, Proceedings PRO 30, RILEM Publications, S.A.R.L., France; 2003, 546 pp. (info: dg@rilem.com).