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Springer

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Dedication

The Sixth International RILEM Conference on High Performance Fiber Reinforced Cement Composites (HPFRCC6) and its proceedings are dedicated to three outstanding members of our international community who have made significant and lasting contributions to broaden the safe application of fiber reinforced cement and concrete composites through fundamental understanding, testing, analysis, modeling and design.

Andrzej M. Brandt

Professor Andrzej Marek Brandt was born on November 15, 1930 in Bydgoszcz, Poland. He graduated from the Warsaw University of Technology, Faculty of Civil Engineering, in 1955, then joined the Institute of Fundamental Technological Research (IFTR) of the Polish Academy of Sciences in Warsaw, where he has been employed ever since. In 1958-1959, he completed advanced studies at the Centre de Hautes Etudes de la Construction in Paris, France. Professor Brandt holds two doctoral degrees, one in 1962, and one, a DSc, in 1967, both from IFTR. He was promoted Associate Professor in 1967 and Full Professor in 1979. His positions included Chairman of the Committee for Civil Engineering of the Polish Academy of Sciences, and Head of the Section on Strain Fields.

Professor Brandt's main interests have been focused on structural mechanics and bridge design, optimization of structures and materials, strain measurements and analysis, fracture mechanics and mechanics of brittle matrix composites. He is the author or co-author of more than 100 technical papers and 20 books among them a classic titled "Cement Based Composites - Materials, Mechanical Properties and Performance" published in 2009. He has been the main instigator and co-organizer of the continuous series of International Symposia on Brittle Matrix Composites (BMC) in Poland since 1985, a topic that encompasses fiber reinforced cement and concrete composites.

Professor Brandt received an Honorary Doctorate from the University of Paisley, Scotland, in 1997. He was a Visiting Professor at University of Poitiers in France, Delft University of Technology in The Netherlands, Koriyama and Tohoku Universities in Japan, and Drexel and North Carolina State Universities in the USA.

Professor Brandt has been active on numerous scientific committees and technical organizations in Poland and abroad, among them, the Polish Standardization Committee, the Euro-International Concrete Committee (CEB), the International Organization for Standardization (ISO), the American Concrete Institute (ACI) and RILEM. He also served as member of the editorial board of a number of national and international journals.

Professor Brandt is being honored for his contributions to the in-depth understanding of the mechanics of brittle matrix composites and optimization of their properties including high performance fiber reinforced cement composites.

Wei Sun

As a distinguished scholar, Professor Wei Sun has been engaged in teaching and scientific research at Southeast University, China, since her graduation from Nanjing Institute of Technology (previous name of Southeast University) in 1958. During her 53 years of teaching and research, she has supervised more than 60 master students and over 40 doctoral students. Professor Sun is currently director of the institute of fiber reinforced concrete and also director of the Jiangsu Key laboratory for Construction Materials. During her career she also was Head of the Department of Materials Science and Engineering, Southeast University, and deputy editor-in-chief of "Journal of the Chinese Ceramic Society". Due to her significant contributions to the theory and application of cementitious composites (including preparation, mechanical behavior, microstructure and modeling of ultra high performance fiber reinforced cementitious composites; service life prediction under the coupled action of load and environmental factors), she was selected to be a member of the Chinese Academy of Engineering in 2005. Together with over 20 of her team members, Professor Sun is still very active in research and teaching. With her team, she has successfully carried out over 50 important national or international projects and co-authored more than 400 technical publications.

Professor Sun is being honored for her long-term and numerous contributions to the investigation of HPFRCC materials, specifically their physical, mechanical, and impact properties, as well as their durability modeling.

Pietro G. Gambarova

Pietro G. Gambarova was born in Milan, on September 1st, 1941. He received his MS Degree in Aeronautical Engineering in March 1966 from the Politecnico di Milano. After two periods spent as an officer in the Corps of Engineers of the Italian Air Force (1966-67 and 1971), he joined the Department of Structural Engineering at the Politecnico di Milano, where he held the position of Assistant Professor from 1968 to 1974, Associate Professor from 1975 to 1980, and Full Professor since 1980. He teaches courses on Structural Analysis and Design, Reinforced Concrete Plates and Shells, and Fire Safety of Materials and Structures. He has been visiting professor (1976) at the National Somali University in Mogadisho, visiting scholar (1978 and 1982) at Northwestern University (Evanston, USA) and at EPFL-Ecole Polytechnique Fédérale de Lausanne (2006).

Pietro Gambarova has conducted research on non-destructive analysis of structures and materials, shear and punching shear in R/C, bond mechanics in R/C, high-performance and fiber-reinforced concrete, non-linear analysis of R/C structures, and lately high-temperature degradation of high-performance concrete and R/C structures. He is the author or coauthor of two books on structural analysis and R/C plates, and of more than 180 technical papers. In 2009, he coauthored the translation into Italian of the book "Structural Design for Fire Safety" by Andy Buchanan.

Pietro Gambarova is an active member of several Italian and international technical committees. He chaired the subcommittee for the preparation of the introductory chapter of fib Bulletin No.10 "Bond of Reinforcement in Concrete" (August 2000). He co-organized the workshop "Fire Design of Concrete Structures: What now? What next?" (Milan, December 2004) and the International Conference FraMCoS-6 (Catania, Italy, June 2007). He is one of the authors of fib Bulletin No.46 "Fire Design of Concrete Structures: Structural Behavior and Assessment" (2008).

Professor Gambarova is being honored for his outstanding contributions to the identification of the physical mechanisms that govern the behavior of high performance and fiber reinforced concrete subjected to high temperature, including fire.

Preface

HPFRCC6 will be the sixth workshop in a series dealing with High Performance Fiber Reinforced Cement Composites (HPFRCC). The five prior workshops have led to a definition of HPFRCC that mostly suggests a technical challenge. That is, composites that exhibit a strain hardening tensile stress-strain response accompanied by multiple cracking (and relatively large energy absorption capacity). Researchers have tried to reduce fiber content to a necessary minimum. By reducing fiber content, they are simplifying the production process, helping make standard mixing procedures acceptable, and opening the way to large-scale practical applications.

The first international workshop on High Performance Fiber Reinforced Cement Composites took placein June 1991 in Mainz, Germany, under the auspices of RILEM and ACI. It was funded in part by the US National Science Foundation (NSF) and the Deutsche Forschungsgemeinschaft (the German NSF). Other cosponsors included the center for Advanced Cement Based Materials (ACBM), the University of Michigan, and the University of Stuttgart. The second workshop took place in Ann Arbor, Michigan, in June 1995, the third in Mainz Germany, in June 1999, the fourth in Ann Arbor, Michigan, in June 2003, and the fifth in Mainz, Germany, in July 2007, all supported bythe same sponsors. 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 top researchers in the field from other countries. The last workshop in Mainz 2007 assembled researchers from 22 countries. The proceedings included 56 papers grouped in 6 different sections.

Since the first workshop in 1991, continuous developments have taken place in new materials, processing, standardization, and improved products for building and other structures. Also, enhanced theory and modeling techniques forHPFRCC now allow a better description oftheir behavior and reinforcing mechanisms. While in the first workshop HPFRCC implied relatively high fiber volume fractions (over 4%), today HPFRCC can be designedwith as little as 1% fiber volume content. While the root definition of HPFRCC is simplest (that is,fiber cement composites withstrain 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, fire resistance, impact resistance, diffusion resistance, imperviousness, and constructability at reasonable cost are other important attributes that need to be further investigated.

In each workshop, a broad range of technical issues, ranging from microstructure characterization to design recommendations, are typically covered; however, some selected themes are emphasized. In this sixth workshop, the organizers identified the following themes for which research information is needed:

- Composite properties in the fresh and hardened states
- bond and pull-out mechanisms
- durability
- structural elements: design, detailing, shear, tension stiffening
- impact, cyclic and seismic loading
- ultra high performance fiber reinforced concrete
- textile reinforced concrete and hybrid composites.

Papers addressing these themes are grouped in seven separate sections of the proceedings.

The organizers hope that this new volume will help foster the continuous development and increasing utilization of HPFRCC in both stand-alone and structural applications.

G.J. Parra-Montesinos
H.W. Reinhardt
A.E. Naaman

HPFRCC6 - Workshop

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The organizers would like to thank all members of the Scientific and International Committees for enthusiastically supporting the organization of this sixth workshop, and all the authors who have contributed with the valuable papers that make these proceedings. Special thanks are due to Ms. Simone Stumpp for preparing with great care and efficiency the camera-ready material for printing. Once more, H.W. Reinhardt and A.E. Naaman would like to express their deep gratitude to the Alexander von Humboldt Foundation for giving them the opportunity to initiate, in 1990, a long-term continually productive cooperation.

G.J. Parra-Montesinos
H.W. Reinhardt
A.E. Naaman

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Part 1

Composite Properties in the Fresh and Hardened States

Strength Dependent Tensile Behavior of Strain Hardening Fiber Reinforced Concrete

D.J. Kim[1], K. Wille[2], A.E. Naaman[3], and S. El-Tawil[3]

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[2] Civil and Environmental Engineering, University of Connecticut, USA
[3] Civil and Environmental Engineering, University of Michigan, USA

Abstract. The influence of matrix strength on the tensile behavior of Fiber Reinforced Cement Composites [FRCC] is investigated. The test parameters included four cementitious matrices with compressive strength of 28 MPa (4 ksi) [M1], 56 MPa (8 ksi) [M2], 84 MPa (12 ksi) [M3] and 190 MPa (28 ksi) [M4], respectively, two types of high strength deformed steel fibers, Hooked [H-] and Twisted [T-] fibers, and two volume fractions of fibers, 1% and 2%. It is observed that while the first cracking strength, post cracking strength and energy absorption capacity of FRCC are strongly influenced by the compressive strength of the matrix their strain capacity at peak stress and cracking behavior are not as much affected. While both H- and T- fibers led to improved performance when the matrix strength was increased, T- fibers take better advantage of higher strength matrices. A post-cracking tensile strength exceeding 15 MPa at a peak strain of 0.5% was achieved by using 2% T- fibers with an ultra-high strength matrix (M4).

1 Introduction

It is challenging to achieve strain-hardening behavior using relatively small amounts of fibers (1% to 2% by volume). In this study an attempt is made to address this issue through the use of deformed high strength steel fibers in cementitious mortar matrices with four different compressive strengths ranging from 28 MPa (4 ksi) to 190 MPa (28 ksi). Details about the ultra high performance concrete (UHPC) matrix with 190 MPa (28 ksi) compressive strength and the development of strain hardening ultra high performance fiber reinforced concrete (UHP-FRC) with low fiber content can be found in Wille et al. [1, 2]. Details about the three other mixtures and their use in developing high performance concretes are given in Kim et al. [3, 4]. This paper links both sets of studies and examines trends in the behavior of strain-hardening fiber reinforced cement composites over an extremely wide range of matrix strengths (28 MPa to 190 MPa). The study focuses in particular on the use of high strength deformed steel fibers used in quantities ranging from 1% to 2% by volume. The use of metallic steel fibers in such small

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quantities is deemed to be economically viable and hence suitable for practical applications.

2 Research Background

There is a little experimental information about the influence of matrix characteristics on the overall pullout behavior of a single deformed steel fiber (Shannag et al. [5], Robins et al. [6] and Chan and Chu [7]); however, it is difficult to find its relationship to the overall tensile behavior of the composite. Kim et al. [8] performed a pullout test program designed to investigate the influence of matrix strength on the pullout behavior of deformed steel fibers, H- and T- fibers. They noted that the pull-out energy of T- fiber embedded in the highest strength matrix was more than twice that for the lowest strength matrix, while the pullout energy of H- fiber improved by only 44%. They attributed the superior pullout behavior of T- fibers in higher strength matrices to the un-twisting pullout mechanism of T-fiber, which leads to superior overall performance. The research, however, did not clarify whether the significant advantage observed in single fiber pull-out behavior translates into a similar advantage in the tensile response of the composite. An experimental program was therefore undertaken to investigate this issue.

3 Experiments

The test parameters included four cementitious matrices with compressive strength of 28 MPa (4 ksi) [M1], 56 MPa (8 ksi) [M2], 84 MPa (12 ksi) [M3] and 190 MPa (28 ksi) [M4], respectively, two types of high strength deformed steel fibers, Hooked [H-] and Twisted [T-] fibers, and two volume fractions of fibers, 1% and 2%. Table 1 provides the mortar mixture composition for the four matrices used and their average compressive strength. The key properties of the fibers used in this study are provided in Table 2. A Hobart type laboratory mixer was used to prepare the mix. For M1, M2, and M3, cement, fly-ash and sand were first dry mixed for about 2 minutes. Water mixed with superplasticizer and Viscosity Modifying Agent (VMA) was then added gradually and mixed for another 5 to 10 minutes. The detailed mixing procedure for M4 is described by Wille et al. [2].

Table 1. Composition of matrix mixtures by weight ratio and compressive strength

Matrix	M1	M2	M3	M4
Cement	0.70 (Type III)	1.00 (Type III)	0.80 (Type III)	1.00 (Type I)
Fly Ash°	0.30	0.15	0.20	-
Sand1	3.50	1.00	1.00	-
Sand2	-	-	-	0.28
Sand3	-	-	-	1.10
Silica Powder	-	-	-	0.25
Silica Fume	-	-	0.07	0.25
Superplasticizer A	0.009	0.009	0.04	-
Superplasticizer B	-	-	-	0.0054
VMA*	0.024	0.006	0.012	-
Water	0.65	0.35	0.26	0.22
f_c', ksi (MPa)	4 (28)	8 (55)	12 (84)	28 (190)

* Viscosity Modifying Agent; ° TYPE C;
1 #16 flint silica sand; 2 max. grain size 0.2 mm; 3 max. grain size 0.8 mm;
A Rhobuild 1000; B Polycarboxylate Ether;

Table 2. Properties of high strength Hooked and Twisted fibers

Fiber Type	Diameter in (mm)	Length in (mm)	Density g/cc	Tensile strength ksi (MPa)	Elastic Modulus ksi (GPa)
Hooked	0.015 (0.38)	1.18 (30)	7.9	420 (2900)	29000 (200)
Twisted	0.012 (0.3)*	1.18 (30)	7.9	304 (2100)**	29000 (200)

* Equivalent diameter ** Tensile strength of the fiber after twisting

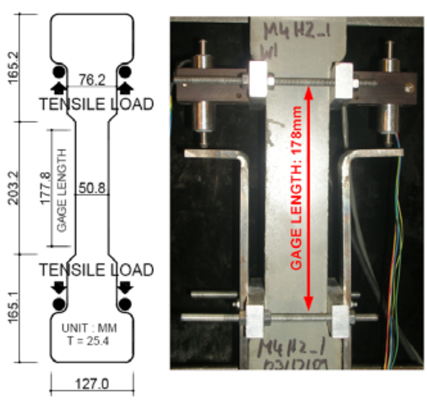


Fig. 1. Tensile test specimen and setup

The geometry of the specimen and test set up are shown in Fig. 1. Elongation of the tensile specimen under load was obtained from the average measurements of two LVDTs placed on each side of the specimen as shown in Fig. 1, and the load was obtained from the load cell pre-built into an MTS810 hydraulic machine.

Fig. 2 shows average tensile stress versus strain (up to peak stress) curves for each series. All the results show strain hardening behavior, which confirms that the use of slip hardening H- and T- fibers can produce strain hardening behavior at the low fiber contents considered. It is also observed that a higher tensile load resistance is generated as matrices with higher compressive strength are used regardless of the type of fiber employed. Moreover, even though a tensile strength increase is noticed with higher strength mortar, no reduction in strain capacity, i.e. strain value at maximum post cracking strength is noticed.

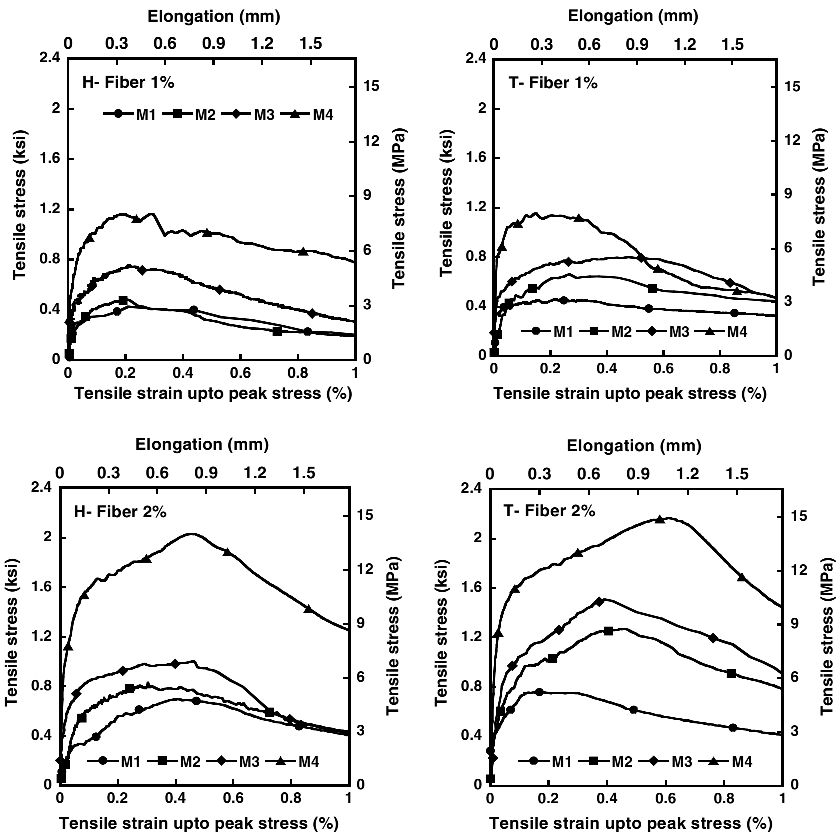
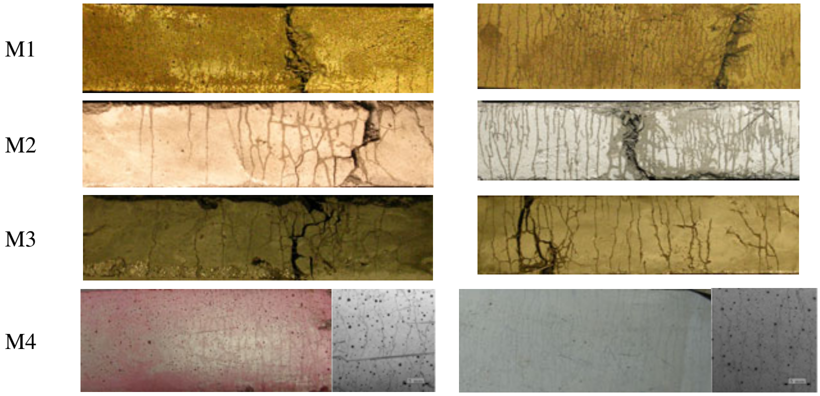


Fig. 2. Average tensile stress – strain curves

The tensile behavior of HPFRCC can be characterized by using several tensile parameters, e.g., first cracking strength, post cracking strength, strain capacity (strain value at post cracking strength), number of cracks within gage length and average crack width. To minimize the subjectivity of how first cracking is determined, the first cracking strength in this study is determined from the intersection of two lines, the first of which corresponds to the elastic region, while the second corresponds to the hardening region.

The cracking behavior of specimens with 2% fiber content for the different matrices is illustrated in Fig. 3. Average values of tensile parameters, each obtained from three to four specimens, and the influence of matrix strength on tensile parameters are graphically illustrated in Fig. 4. Since the process of estimating the number of cracks could be highly subjective, the number of cracks is counted from both front and back surface of specimens and the numbers are averaged.



(a) Hooked Fiber 2% (b) Twisted Fiber 2%

Fig. 3. Tensile cracking behavior

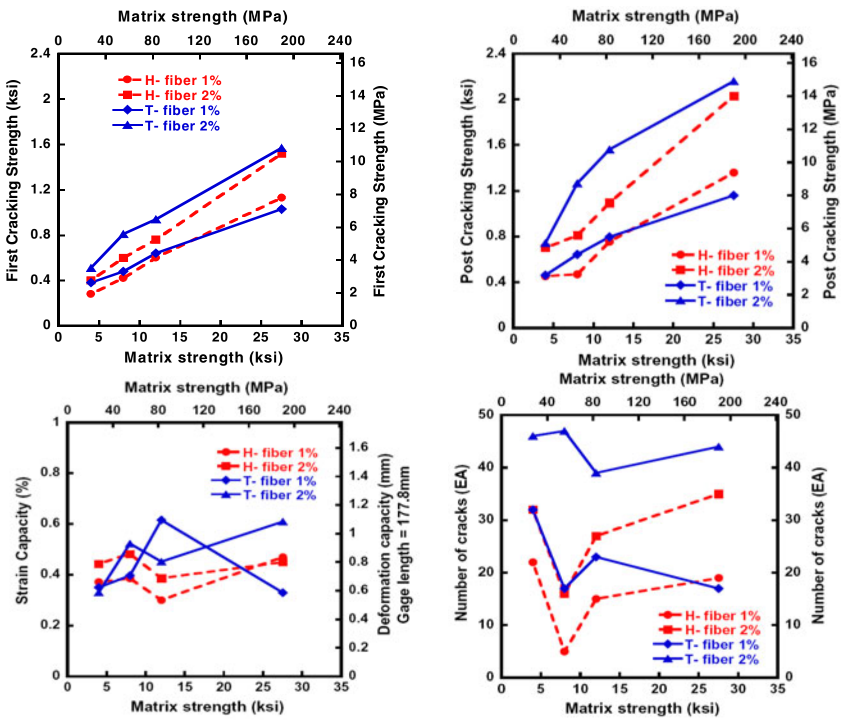


Fig. 4. Influence of matrix strength on tensile parameters: (a) first cracking strength; (b) post cracking strength; (c) strain capacity; and, (d) number of cracks

Fig. 4d shows the effect of matrix strength on the number of cracks within the gage length. As with strain at peak stress, there no clear dependency on matrix strength.

The first cracking strength is mainly influenced by the tensile strength of the matrix, which correlates strongly to its compressive strength as shown in Fig. 4a. Post cracking strength appears to be even more sensitive to the strength of the matrix than the first cracking strength as illustrated in Figs. 4a, 4b and Table 3. Also evident from the test data is that, in general, a higher post cracking strength is obtained by when T-fibers are used. The lower post cracking strength of M4 with 1% T-fibers (1.16 ksi, 8.0 MPa) in comparison to M4 with 1% H-fibers (1.36 ksi, 9.4 MPa) is attributed to fiber failure of some of the T-fibers during the test (which was audible); suggesting that higher strength fiber would have provided better performance. The strain capacities of the test specimens as a function of matrix strength are shown in Fig. 4c, from which it is clear that strain capacity at maximum stress that ranges from 0.35% to 0.6% with no clear dependency on matrix strength.

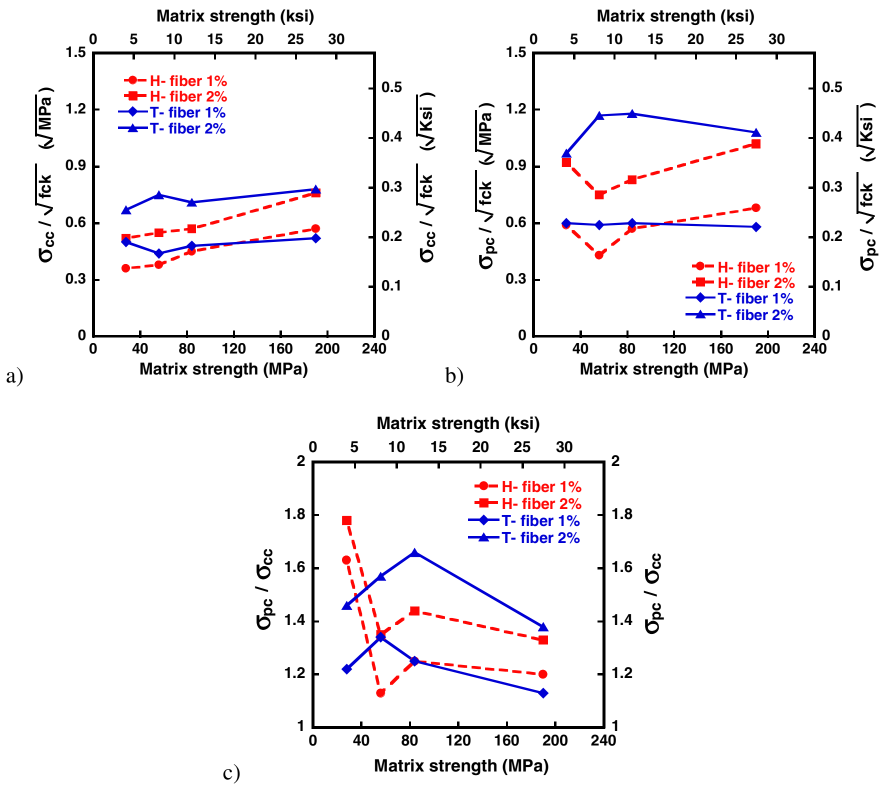


Fig. 5. Influence of matrix strength on load carrying capacity:(a) $\sigma_{cc}/\sqrt{f_{ck}}$, (b) $\sigma_{pc}/\sqrt{f_{ck}}$, (c) σ_{pc}/σ_{cc}

4 Evaluation of Experimental Results

Figs. 2, 4 and 5 clearly show the influence of matrix strength on the tensile behavior of HPFRCC. While an increase in matrix strength leads to increases in both first and maximum post cracking strength there is no clear influence on the strain capacity and cracking behavior. To quantify the effect of matrix strength, both first and post cracking strength are normalized by the square root of compressive strength ($\sqrt{f_{ck}}$) and their values are plotted versus the compressive strength in Fig. 5a and 5b, respectively. In addition, the ratio between the post cracking strength and the first cracking strength is illustrated in Fig. 5c.

As shown in Fig. 5a, the ratio $\sigma_{cc}/\sqrt{f_{ck}}$ slightly increases as the compressive strength of the matrix increases, e.g., composites with M1 generate a ratio $\sigma_{cc}/\sqrt{f_{ck}}$ ranging from 0.36 to 0.67, while composites with M4 produce higher ratios of $\sigma_{cc}/\sqrt{f_{ck}}$ ranging from 0.52 to 0.78. The influence of matrix strength on the ratio $\sigma_{pc}/\sqrt{f_{ck}}$ is graphically shown in Fig. 5b. There is no noticeable effect on the ratio $\sigma_{pc}/\sqrt{f_{ck}}$, whereas the ratio σ_{pc}/σ_{cc} is dependent upon the type of fiber and volume contents of fiber as shown in Fig. 5c.

5 Conclusions

This study investigated the influence of matrix strength on the tensile behavior of HPFRCC using two deformed high strength steel fibers, namely Hooked (H-) fibers and Twisted (T-) fibers. The strengths of the four matrices employed are 28 MPa (4 ksi), 56 MPa (8 ksi), 84 MPa (12 ksi), and 190 MPa (28 ksi), respectively. One of the key results of the experimental program is that composites using high strength deformed steel fibers are sensitive to the strength of the matrix and that T-fibers take better advantage of higher strength matrices than H- fibers due to their unique un-twisting pullout mechanism. For example, a post-cracking tensile strength exceeding 15 MPa at a peak strain of 0.61% was achieved by using 2% T-fibers with the ultra-high strength matrix (M4), whereas only 14 MPa tensile capacity at 0.45% strain could be achieved with H-fibers. The results also showed that, as the compressive strength of the matrix increases, the first and post cracking strength of the composite correspondingly increase. However, the increase in matrix compressive strength does not lead to clear trends in either the maximum strain capacity or cracking behavior. In fact, the maximum strain capacity remains almost independent of matrix strength while energy absorption at peak load increases.

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