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High Performance Fiber Reinforced Cement Composites with Innovative Slip Hardending Twisted Steel Fibers

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Abstract: This paper provides a brief summary of the performance of an innovative slip hardening twisted steel fiber in comparison with other fibers including straight steel smooth fiber, high strength steel hooked fiber, SPECTRA (high molecular weight polyethylene) fiber and PVA fiber. First the pull-out of a single fiber is compared under static loading conditions, and slip rate-sensitivity is evaluated. The unique large slip capacity of T-fiber during pullout is based on its untwisting fiber pullout mechanism, which leads to high equivalent bond strength and composites with high ductility. Due to this large slip capacity a smaller amount of T-fibers is needed to obtain strain hardening tensile behavior of fiber reinforced cementitious composites. Second, the performance of different composites using T-fibers and other fibers subjected to tensile and flexural loadings is described and compared. Third, strain rate effect on the behavior of composites reinforced with different types and amounts of fibers is presented to clarify the potential application of HPFRCC for seismic, impact and blast loadings.

Keywords : strain hardening, slip hardening, pullout mechanism, strain rate sensitivity, twisted fiber.

1. Introduction

In order to meet the demands for future civil infrastructure systems as well as help rehabilitate existing ones, there is an increasing need for robust, tough and durable construction materials. Among these are, for instance, ultra high performance concrete (UHPC), high performance steel, advanced fiber reinforced polymer (FRP) composites, smart materials and high performance fiber reinforced cementitious composites (HPFRCC),[1] HPFRCCs are addressed in this paper.

HPFRCC belongs to a class of discontinuous short fiber reinforced cement based composites characterized by a strain-hardening and multiple cracking response under direct tensile loading as illustrated in Fig. 1. In comparison with normal concrete and conventional fiber reinforced concrete (FRC), the advantage of HPFRCC includes higher load carrying capacity, ductility, durability and energy absorption capacity,[2,3] These benefits are particularly attractive for structures subjected to extreme loading conditions such as impact, earthquake and blast.

Two approaches have been followed to set the conditions for strain-hardening and multiple cracking behavior of brittle matrix composites, including cementitious composites. Their sources, evolution over five decades, and final similarity have been discussed in details by Naaman.[4,5] One condition, initially developed by Marshall, Cox and Evans[6,7] is based on fracture mechanics, and states that the "*complementary energy from the tensile stress-strain curve of the composite must exceed the matrix critical crack tip toughness, in order to develop a steady-state crack*." They defined a steady state crack as follows: "*... a steady state crack can be made to extend indefinitely in the matrix without ligaments (fibers) rupturing in the wake*." The analytical equation formulating steady state cracking based on the complementary energy, is the same as adopted by Li et al. in their various publications such as Li and Wu[8] and Li and Leung.[9] However, Naaman[4,5] showed that while the complimentary energy condition is necessary to generate a steady state crack (that is, a percolation crack with parallel surfaces) it is not sufficient to guarantee multiple cracking. For multiple cracking to occur, the stress condition is needed. Such a condition, initially used by Naaman[10], is also confirmed by the work of Cox, Marshall and Thouless[11] which demonstrated that, "*for non-catastrophic multiple cracking mechanism to occur, the bridging stress must exceed the matrix cracking stress.*" By writing that the post-cracking strength of the composite must exceed its cracking strength (instead of that of the matrix alone), Naaman uses in fact a slightly more conservative approach.

Referring to Fig. 1, in order to obtain strain hardening behavior, it is necessary that the post cracking strength σ_{pc} be higher than the first cracking strength σ_{cc}.

$$\sigma_{pc} \geq \sigma_{cc} \quad (1)$$

Naaman[10,12] using composite mechanics suggested the following equations, to predict the first cracking strength and the post cracking strength:

First cracking strength: $\sigma_{cc} = \sigma_{mu}(1 - V_f) + \alpha\tau V_f(L_f/d_f)$ (2)

Post cracking strength: $\sigma_{pc} = \lambda\tau V_f(L_f/d_f)$ (3)

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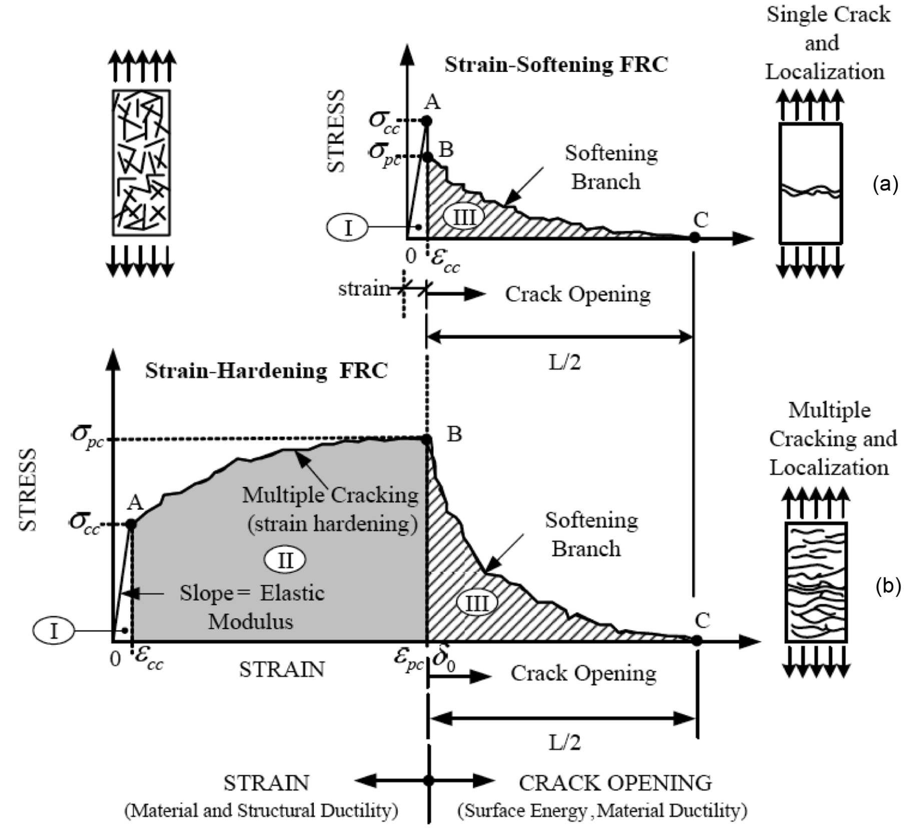


Fig. 1 Typical stress-strain or elongation curve in tension up to complete separation: (a) Conventional strain-softening FRC composites; (b) Strain-hardening FRC composite or HPFRCC[2,3,30]

where, V_f = fiber volume fraction, L_f = fiber length, d_f = fiber diameter, L_f/d_f = fiber aspect ratio, σ_{mu} = tensile strength of matrix, τ = bond strength, α = factor equal to the product of several coefficient for considering average stress, random distribution, fiber orientation, λ = factor equal to the product of several coefficients for considering average pullout length, group reduction, orientation effect. The bond strength τ between fiber and matrix is assumed constant along the entire fiber length.

Note that the post cracking strength σ_{pc} (Eq. 3) contains the contribution of the fibers only, while the first cracking strength σ_{cc} contains contributions from both the fiber and the matrix and the matrix contribution is generally dominant. In summary, the post-cracking strength of HPFRCC is a function of fiber volume fraction V_f, fiber aspect ratio L_f/d_f and bond strength τ.

In order to obtain strain hardening behavior, i.e., a post cracking strength σ_{pc} higher than first cracking strength σ_{cc}, various approaches have been followed.

One simple method is to increase the fiber volume fraction as per Eq. (2),[13] Naaman and Homrich,[14] Rossi et al..[15] For smooth steel fibers, 5 to 8% fiber content by volume were required to obtain strain hardening behavior. However, the method using high fiber volume contents increases the cost of HPFRCC and causes difficulties during mixing and casting. Another approach to satisfy Eq. (1) is to reduce the first cracking strength of the composite by using large amount of fly ash in the matrix.[16] A third approach, used in this investigation is to increase the equivalent bond strength by using fibers with high mechanical bond achieved through their geometry. In this approach, a higher post-cracking strength is obtained while maintaining relatively low volume fractions of fibers.

To improve the bond strength, an innovative Twisted (T-) fiber was developed by Naaman[17,18] polygonal in cross section and twisted along its axis, it shows large slip capacity during pullout which generates much higher pullout energy and equivalent bond strength. In single fiber pull-out tests, T- fiber showed slip hardening behavior up to 76% of the fiber embedment length of 15 mm[19]. The high pullout resistance and slip-capacity of T-fiber originates from the untwisting moment resistance of the fiber which is distributed along the entire length of fiber.[20]

This article provides a brief summary of recent research on the performance of HPFRCC using T- fiber and other fibers for comparison. Pull-out tests on single fiber, and tensile and bending tests on composite specimens are described. The effect of loading rate on pull-out and tensile properties are also briefly presented.

2. Research significance

This paper synthesizes the results of several investigations allowing the reader to get key information otherwise scattered in several publications which may be difficult to access. It emphasizes the role of fiber pullout mechanism in governing the mechanical performance of fiber reinforced composites. For same fiber length, fiber diameter, and matrix composition, different fiber pullout mechanisms produce considerable differences in the tensile, flexural and cracking behavior of HPFRCCs. In addition, different rate sensitive tensile behavior is observed. Such information is useful for the design of HPFRCC in structural applications under both static and dynamic loading such as earthquakes and impact.

3. Slip hardening pullout behavior

Fig. 2 compares typical pullout behavior of three high strength steel fibers, Twisted (T-), Hooked (H-) and Smooth fibers embedded in an identical mortar matrix. Entire pullout behavior up to complete fiber pullout ($L_f/2 = 15$ mm) is shown in Fig. 2(a), while the detail of pullout stress – slip curves up to 2.54 mm is shown in Fig. 2(b) in order to highlight different slip-hardening and slip-softening pullout behavior. In all tests, the embedded length of fiber is half of fiber length ($L_f/2 = 15$ mm), and the diameter of Smooth and T-fibers is 0.3 mm while the diameter of H- fiber is 0.38 mm. Since the three fibers have different diameters, pullout stress–slip curves are shown for comparison instead of pullout load-slip curves; the pull-out stress is the tensile stress induced in the fiber under the applied pull-out load. Note that, although the three fibers have same fiber embedment length in an identical matrix, they show totally different pullout behavior. Deformed steel fibers, H-and T-fibers show slip hardening behavior during fiber pullout while smooth steel fiber shows slip softening behavior right after complete debonding at the interface between fiber and matrix. (Fig. 2(b)) Although both H-and T-fiber generate slip hardening behavior, there is also a noticeable difference in the extent of slip prior to bond decay (slip capacity) between H- and T- fibers. One measure to compare them would be the pullout stress energy which is the amount of pullout energy normalized with the section area of fiber. The pullout stress energy of Smooth, H-, and T- fibers are 3.7 MPa-m, 5.3 MPa-m, and 21.7 MPa-m, respectively. Based on the amount of pullout stress energy, the equivalent bond strength of Smooth, H-, T- fibers can be calculated using the following equation, assuming the embedded length is half the fiber length:

Equivalent bond strength:

$$\tau_{eq} = \frac{2 \times PulloutStressEnergy \times d_f}{(L_f)^2} \qquad (4)$$

where d_f is the fiber diameter and L_f is its length. Using Eq. (4), the equivalent bond strength of Smooth, H-, and T- fiber is equal to 2.44 MPa, 4.50 MPa and 14.46 MPa, respectively.

The unique pullout mechanism of T- fiber creates a much higher slip capacity, pullout energy and eventually equivalent bond strength than Smooth and H- fiber.

Differences between these fibers can also be observed when matrices with different compressive strengths are used. The effect of matrix strength (or composition) on the pullout behavior was reported in an earlier publication.[21] H-and T-fiber are used in three different cement matrices with three different compositions generating a low (28 MPa), medium (56 MPa) and high (84 MPa) compressive strength. Both fibers produced a higher pull-out load with a higher compressive strength, while T- fiber was found to be more efficient in a higher strength matrix than in a lower strength matrix.

4. Influence of slip hardening on tensile behavior of HPFRCC

Kim et al.[19] reported that the pullout behavior of steel fibers with different slip capacities highly influences the strain hardening and multiple cracking behavior of HPFRCC under tension. Even though both the H- and T- fibers were high strength steel fibers (> 2,100 MPa) and were embedded in an identical mortar matrix (56 MPa), the two fibers generated different slip capacity according to their pullout mechanisms. T- fiber utilizes for mechanical bond its untwisting moment, distributed along the entire fiber length, to generate mechanical pullout resistance, while H- fiber utilizes the plastic deformation energy of its hook, concentrated in a localized area of fiber embedded length. The different pullout mechanisms of these two fibers generated different slip capacity, whereas the larger slip capacity of T- fiber produced much higher pullout energy, equivalent bond strength, and eventually generated more multiple cracking in tension with smaller average crack opening, implying higher ductility and durability.

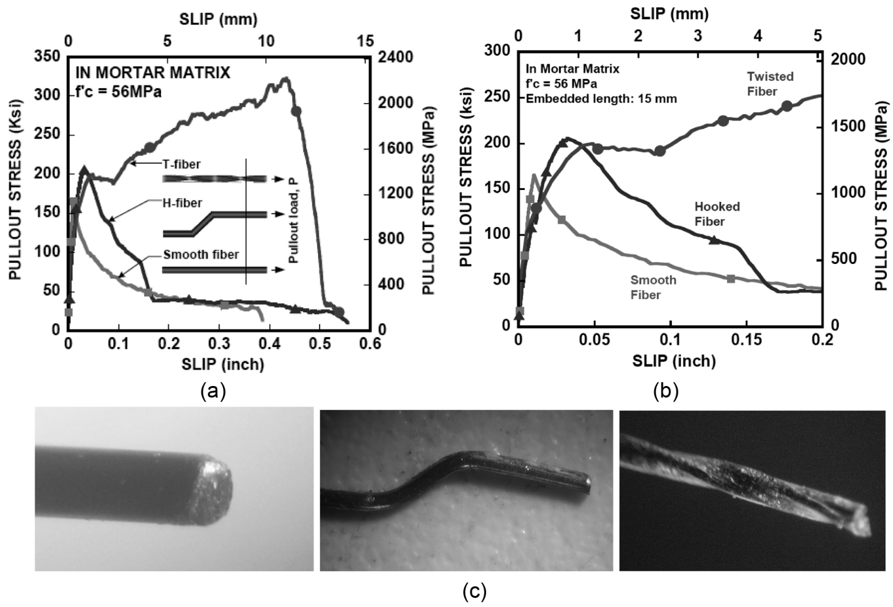


Fig. 2 Slip hardening and slip softening pullout behavior: (a) Entire pullout stress-slip curves; (b) Detail of initial portion of slip hardening and slip softening curves[21]; and (c) Photos for Smooth, Hooked and Twisted fibers.

The different multiple-cracking pattern observed for the two types of fiber (T- and H- fibers) is shown in Fig. 3. The specimen reinforced with 2% T-fiber by volume produced 60 multiple cracks leading to an average crack width of 14 μm, while the specimen with 2% H- fiber generated 15 multiple cracks with an average crack width of 39 μm.

Detail analytical calculations on the correlation between the equivalent bond strength, crack spacing and crack opening under tension are provided by Kim et al.[19] It was concluded that because T- fiber creates larger pullout energy due to its high slip capacity, it is more effective than H-Fiber in developing HPFRCC with strain hardening behavior and multiple micro-cracking.

5. Influence of slip hardening on flexural behavior of HPFRCC

The flexural behavior of fiber reinforced cementitious composites (FRCC) with high strength steel T- and H- fibers in high strength mortar (84 MPa) with two volume fraction contents (1.0% and 2.0%) was investigated by Kim et al.[22] The tests were carried out according to ASTM standards [C1018-97 and C 1609/C 1609M – 05]. As anticipated from both pullout and tensile test results, the T-fiber reinforced specimens showed a much better performance than the H- fiber reinforced specimens in all aspects of flexural behavior including load carrying capacity, energy absorption capacity and multiple cracking behavior, as illustrated in Fig. 4. The equivalent elastic bending stress was estimated using the following equation recommended in ASTM C 1609 and C 1609M-05:

$$\text{Equivalent bending strength: } f = \frac{PL}{bd^2} \tag{5}$$

where f is the strength, P is the load, L is the span length, b is the average width of the specimen and d is its average depth.

The higher equivalent bond strength of T- fiber during pullout generated higher tensile performance than H-fiber as shown in Fig. 3, and the better tensile performance of T- fiber reinforced specimens translated into superior flexural properties, i.e., equivalent bending strength, toughness and cracking behavior (Fig. 4). The equivalent bending strength (f) of beams reinforced with either 2% T- fiber or 2% H- fiber was 29.42 MPa and 22.21 MPa, respectively. For specimens reinforced with 1% T-fiber and H-fiber, the equivalent bending strength was 16.78 MPa and 6.58 MPa, respectively.

Additional experiments were carried out by the authors[22] in order to compare the flexural performance of four different types of fibers within an identical matrix (56 MPa mortar). Typical results are shown in Fig. 5. The four fibers used were T-, H-, SPECTRA and PVA fiber. It is observed from Fig. 5 that the T-fiber reinforced specimens led to the highest load carrying capacity, equivalent bending strength, energy absorption capacity, and toughness at large deflection value of L/150, where L is the span length. The order of performance in both equivalent bending strength and toughness was: T- > H- > SPECTRA > PVA fibers. In addition, different cracking behavior was observed according to the type of fiber as shown in Fig. 5. The order of cracking performance was: T- > SPECTRA > H- > PVA fibers.

T- fiber with large slip capacity during pullout was also found to be more efficient to obtain deflection hardening behavior of HPFRCC with multiple micro-cracking. In addition, in comparing Figs. 4 and 5, it can be implied that T-fibers take better advantage of the higher strength matrix than H- fiber.

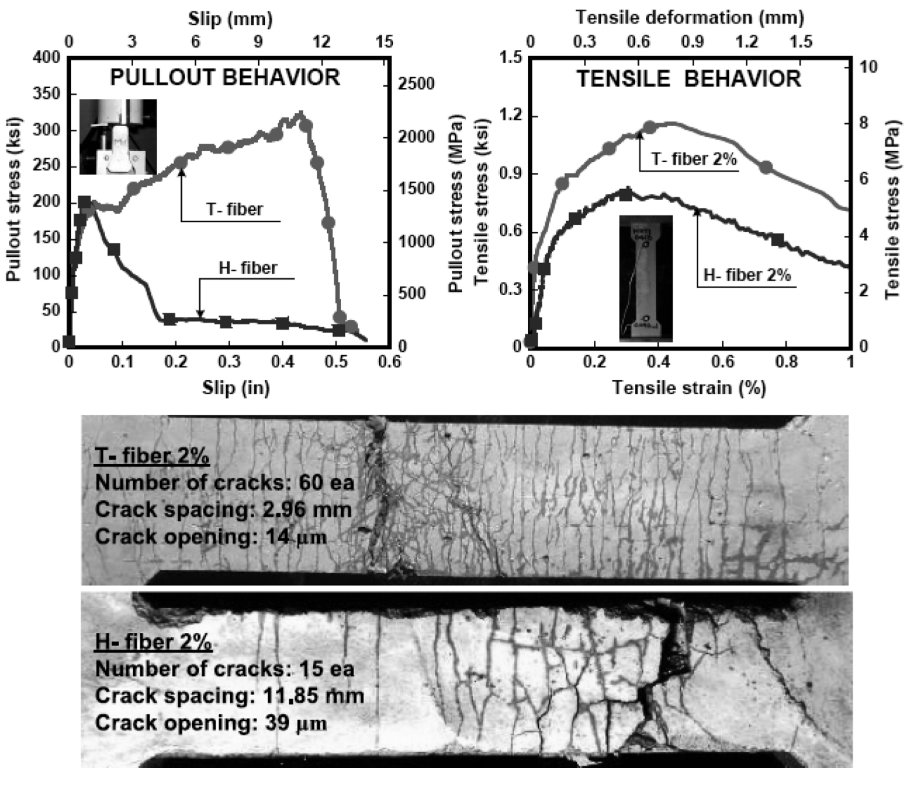


Fig. 3 Influence of different slip capacity on tensile properties of HPFRCC with 56 MPa mortar compressive strength.[19]

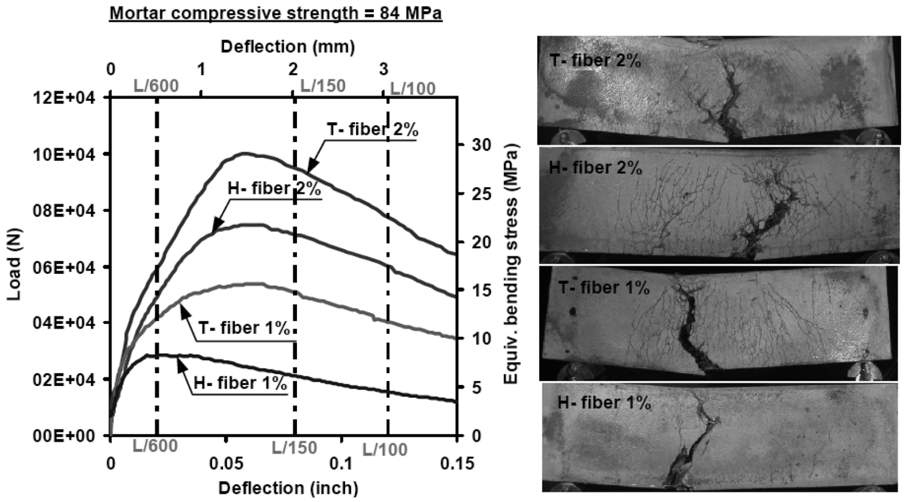


Fig. 4 Influence of different slip capacity on flexural behavior of HPFRCC with 84 MPa mortar compressive strength.[22]

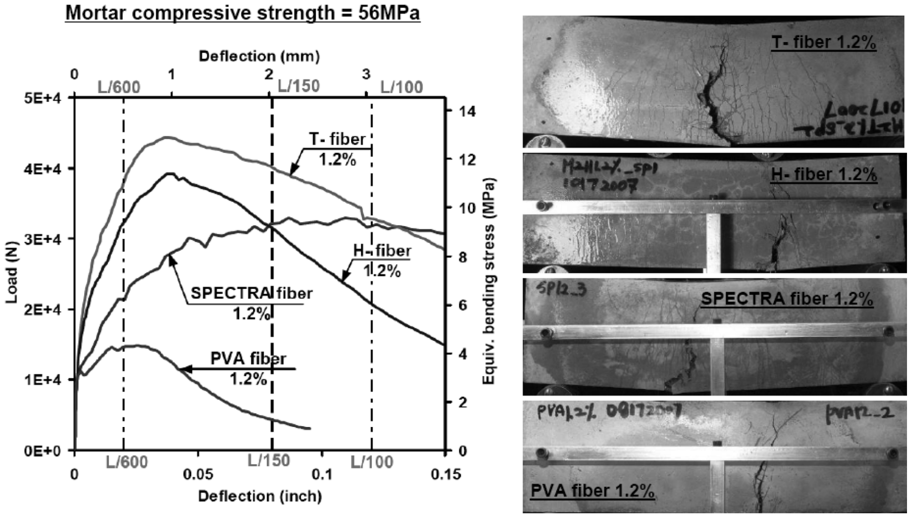


Fig. 5 Comparative flexural performance of four FRC composites.[22]

6. Strain rate effect on HPFRCC

The overall superior performance of HPFRCC under static loading, including high ductility, high energy absorption capacity and high durability is anticipated to remain favorable under seismic, impact, and blast loading conditions. Several investigations dealing with structural applications have already uncovered their many advantages.[23-25] However, the tensile strain hardening behavior of HPFRCC has been proven for static loading conditions ($\dot{\varepsilon}$ = 10^{-6}~10^{-4}) but there is little information about the effect of loading rate on their tensile response (Fig. 6).

Yang and Li[26] reported a strong rate sensitive tensile behavior of engineering cementitious composites (ECC) containing 2% PVA fibers by volume. They investigated tensile response of PVA-ECC under various strain rates ranging from static ($\dot{\varepsilon}$ = 10^{-4}) to seismic ($\dot{\varepsilon}$ = 10^{-1}) by using a hydraulic testing machine and observed a significant reduction in their tensile strain capacity, that is, the strain at peak stress. Douglas and Billington[27] also reported on the

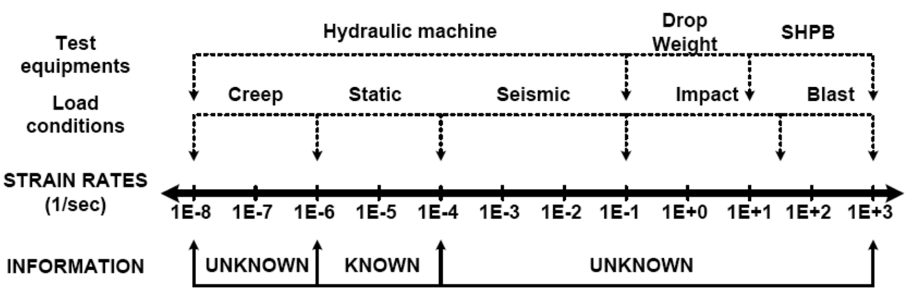


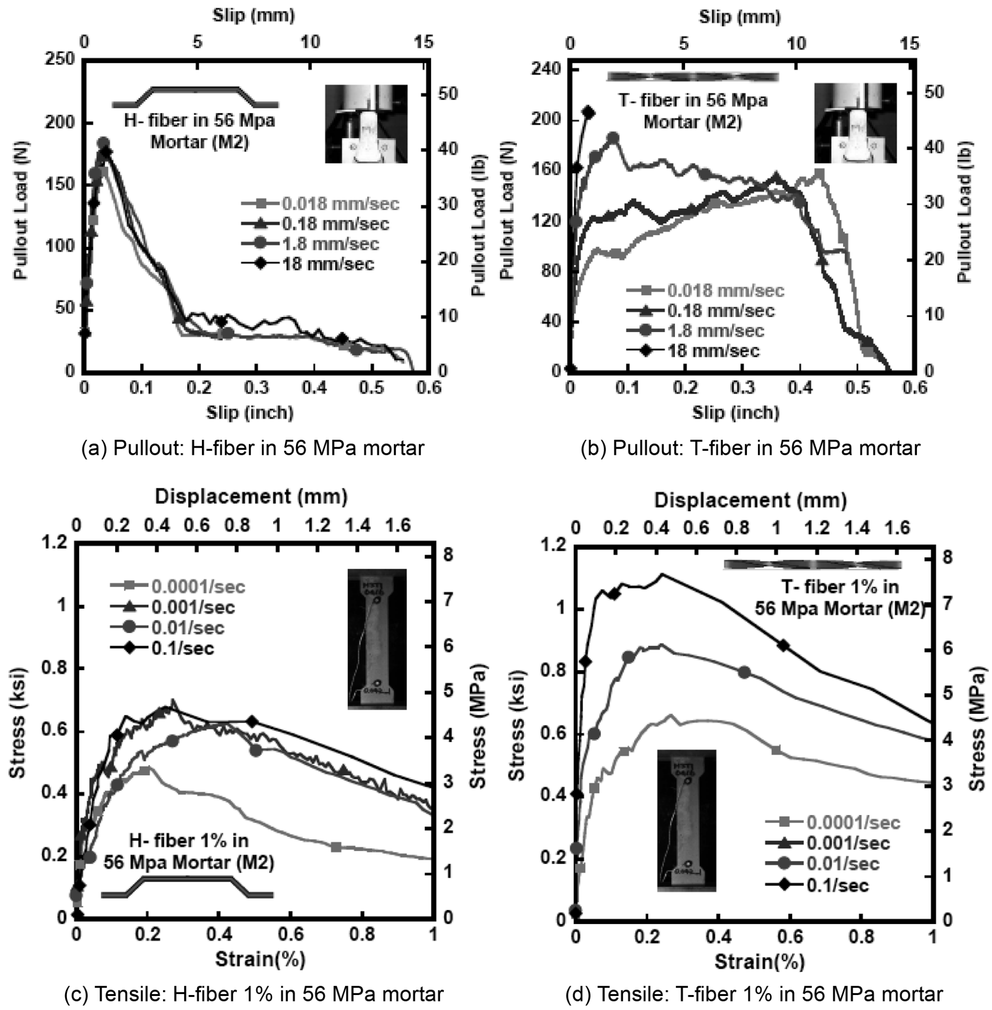
Fig. 6 Available test equipments and information for HPFRCC under various strain rates.

rate dependence of PVA-ECC under seismic loading rate, namely, the tensile strength increases while the strain capacity decreases with strain rate. The authors have carried out an extensive experimental program designed to investigate strain rate effects on the tensile behavior of HPFRCC using T- and H- fiber.[28,29] The experimental program included both single fiber pullout tests and tensile tests on double dog-bone shaped specimens; it investigated the response of HPFRCC under four different loading rates ranging from static to seismic, and for three matrix compositions (M1, M2, and M3) with increasing compressive strength (28 MPa , 56 MPa, and 84 MPa).

Both single fiber pullout and tensile test results showed consistently different rate sensitivities according to the type of fiber. Figure 7(a) and (b) illustrate the pullout test results while Fig. 7(c) and (d) describe the tensile response of HPFRCC as the strain rate (pullout speed) increases one thousand times, from static (0.0001/s = 0.018 mm/s) to seismic rate (0.1/s = 18 mm/s). All tensile specimens practically maintained their strain hardening behavior with no reduction in strain capacity until the seismic strain rate, while T- and H- fiber exhibited different rate sensitivity in an identical matrix. Indeed, the T- fiber generated strong rate sensitivities while the H- fiber showed no clear rate sensitivity. Tensile specimens reinforced with 1% T- fiber in a 56 MPa mortar matrix reveal enhanced tensile strength under seismic rate (Fig. 7(d)). No clear rate sensitivity on strain capacity and multiple micro-cracking were observed, although the first cracking strength and the post cracking strength were found to be strongly sensitive to the strain rate.

Figure 7 also suggests that the rate sensitive tensile behavior of HPFRCC at the composite level can be correlated to the fiber pullout behavior under different pullout speeds. For example, the no-rate sensitivity of H- fibers under pullout (Fig. 7(a)) directly translates into the no-rate sensitive tensile behavior of the corresponding composites (Fig. 7(c)). On the contrary, the strong rate sensitive pullout behavior of T- fiber (Fig. 7(b)) generates strong rate sensitivity in tensile specimens with 1% fibers (Fig. 7(d)).

The different rate sensitivities of the two fibers (T- and H- fibers) originate from their different pullout mechanisms. Optimized T- fibers are likely to un-twist during pullout; they create a torsion moment along the longitudinal axis of the fiber during untwisting and radial stresses at the interface between fiber and matrix. Consequently, T- fibers are likely to create radial and longitudinal interface micro-cracking, which are distributed along the entire embedded fiber length.[28,29] On the other hand, H- fibers generate micro-cracking only in a localized zone during fiber pullout, since they utilize a single end hook for mechanical bond. The strong correlation between the rate sensitive behavior of HPFRCC composites and that of a single fiber pullout response could be ascertained from Fig. 7.



(a) Pullout: H-fiber in 56 MPa mortar

(b) Pullout: T-fiber in 56 MPa mortar

(c) Tensile: H-fiber 1% in 56 MPa mortar

(d) Tensile: T-fiber 1% in 56 MPa mortar

Fig. 7 Influence of fiber type on rate sensitive behavior of HPFRCC.[29]

In a separate study, Kim et al.[28,29] have observed that specimens reinforced with T-fibers show different rate sensitivity depending on the volume fraction of fibers. Tensile specimens reinforced with the lower fiber volume fraction ($V_f = 1\%$) showed higher rate sensitivity than specimens reinforced with the higher fiber volume fraction ($V_f = 2\%$). Moreover, the higher the matrix strength, the more rate sensitive is the composite up to a certain level. First cracking and post cracking strength are sensitive to the strain rate, while no clear trend could be identified for the strain capacity at post cracking strength.

In summary, it can be stated that the unique un-twisting behavior of T-fiber during pullout creates favorable conditions for structural elements subjected not only to static loading but also to dynamic loading as well. When the fiber and matrix parameters are properly designed twisted fibers tend to untwist during pull-out maintaining very high stresses up to large pull-out slips. If the tunnel of matrix surrounding the fiber does not damage significantly, this pull-out mechanism generates a very high energy absorption capacity under both static and dynamic loading. Moreover, such composites at 2% fiber content, maintain very fine crack widths at saturated micro-cracking, and are expected to achieve excellent durability during service life.

7. Conclusions

This paper provides a brief summary of several studies dealing with the performance of an innovative slip hardening Twisted (T-) fiber for use in cement and concrete composites. Single fiber pullout behavior of T- fiber and the tensile and flexural behavior of T- fiber reinforced HPFRCC are discussed and compared to the most commonly used high strength steel smooth and hooked fibers. Moreover, the strain rate sensitivity of both single fiber pull-out and composite tensile response is reported, and the influence of key parameters described. The following conclusions can be drawn.

1) Although T- and H- fibers show slip hardening behavior during pullout, T- fiber generates much higher slip capacity, pullout energy and equivalent bond strength due to its unique untwisting pullout mechanism.

2) There is a strong correlation between single fiber pullout behavior and tensile behavior of fiber reinforced composites. The different slip capacity of T- and H- fibers is responsible for the different strain capacity and multiple cracking behavior at the composites level, in HPFRCCs.

3) T- fibers take better advantage of a higher strength matrix than H- fibers.

4) In both tensile and flexural tests, T- fiber is much more effective than H- fiber in terms of load carrying capacity, energy absorption capacity and multiple cracking behavior.

5) T- fibers show favorable strain rate sensitive behavior in all three matrices, while H- fibers show no noticeable rate sensitivity in both single fiber pullout and composite tensile behavior. T-fibers exhibited higher first and post cracking strength, but no clear trend for the strain capacity and multiple cracking behavior under higher strain rates.

6) Different rate sensitive behavior of T- fiber is observed according to the matrix composition (strength) and fiber volume contents.

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