Invited Paper

Engineered Steel Fibers with Optimal Properties for Reinforcement of Cement Composites

Antoine E. Naaman[1]

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Abstract

Although steel fibers have been used in cement and concrete composites for more than four decades, most of the steel fibers on the market today have been introduced prior to 1980. This is in sharp contract to the continuous progress and development in the cement matrix itself. Following a brief summary of the main properties and limitations of steel fibers used in cement based composites, this paper describes the rationale and technical background behind the development and design of a new generation of steel fibers for use in cement, ceramic and polymeric matrices. These fibers are engineered to achieve optimal properties in terms of shape, size, and mechanical properties, as well as compatibility with a given matrix. They are identified as Torex fibers. Typical tests results are provided and illustrate without any doubt the superior performance (2 to 3 times) of Torex fibers in comparison to other steel fibers on the market. The new fibers will advance the broader use of high performance fiber reinforced cement composites in structural applications such as in blast and seismic resistant structures, as well as in stand-alone applications such as in thin cement sheet products.

1. Introduction

Cementitious matrices such as concrete have low tensile strength and fail in a brittle manner. Adding short needle-like fibers to such matrices enhances their mechanical properties, particularly their toughness, ductility and energy absorbing capacity under impact.

The last four decades have seen a large number of research studies on fiber reinforced concrete, most of which devoted to the use of steel fibers. In contrast, few studies dealt with the design and development of the fibers themselves. Indeed most steel fibers on the market today have been conceived and introduced over thirty years ago.

Recent research at the University of Michigan (Naaman, 1998, and Naaman, 1999, 2000a) led to the development of a new steel fiber of optimized geometry, here called Torex fiber. It is made of very high strength steel wire, polygonal in cross section (primarily triangular or square), possibly having indented sides, and twisted along its length. The key feature of this fiber is that when pulled-out from a cement matrix, its resistance increases with increase in slip (the more it pulls out, the harder it resists). The fiber can be tailored to achieve a level of desirable performance, depending on the type of matrix. Its design is applicable to other brittle matrices such as ceramics.

The main purpose of this paper is to explain the rationale and technical background behind the design of these new fibers and show typical results illustrating their superior performance in comparison to other steel fibers on the market. The reader is referred to the list of references at the end of the paper for additional details.

[1]Professor, Department of Civil and Environmental Engineering, University of Michigan, Ann Arbor, USA.
E-mail: naaman@engin.umich.edu

2. Background and current status

2.1 Classification of discontinuous fibers

Short fibers used in concrete can be characterized in different ways (**Fig. 1**). First according to the fiber material: natural organic (such as cellulose, sisal, jute, bamboo, etc.); natural mineral (such as asbestos, rock-wool, etc.); man-made (such as steel, titanium, glass, carbon, polymers or synthetic, etc). Second, according to their physical/chemical properties: density, surface roughness, chemical stability, non-reactivity with the cement matrix, fire resistance or flammability, etc. Third according to their mechanical properties such as tensile strength, elastic modulus, stiffness, ductility,

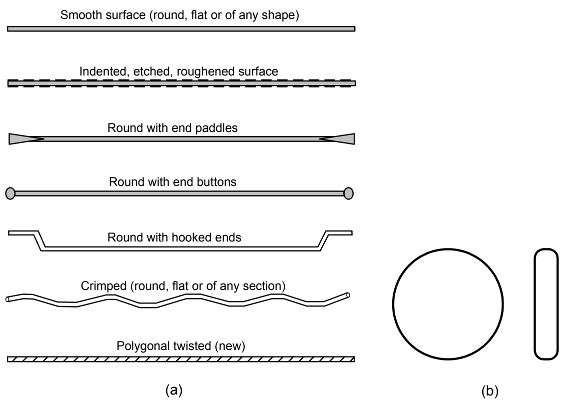


Fig. 1 (a) Typical profiles of steel fibers commonly used in concrete (twisted fiber is new). (b) Closed loop fibers tried in some research studies.

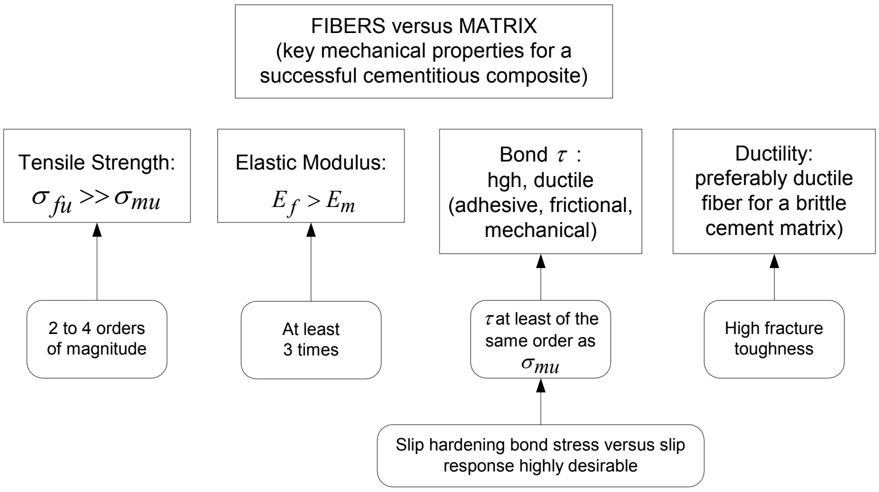


Fig. 2 Desirable fiber versus matrix properties.

elongation to failure, surface adhesion property, etc.

Moreover, once a fiber has been selected, an infinite combination of geometric properties related to its cross sectional shape, length, diameter or equivalent diameter, and surface deformation can be selected. The cross section of the fiber can be circular, rectangular, diamond, square, triangular, flat, polygonal, or any substantially polygonal shape. To develop better bond between the fiber and the matrix the fiber can be modified along its length by roughening its surface or by inducing mechanical deformations. Thus fibers can be smooth, indented, deformed, crimped, coiled, twisted, with end hooks, paddles, buttons, or other anchorage. Typical examples of steel fibers are shown in **Fig. 1a**. In some fibers the surface is etched or plasma treated to improve bond at the microscopic level. Some other types of closed-loop steel fibers such as ring, annulus, or clip type fibers (**Fig. 1b**) have also been used and shown to significantly enhance the toughness of concrete in compression; however, work on these fibers did not advance beyond the research level.

2.2 Current range of fiber geometric properties

Most common steel fibers are round in cross-section, have a diameter ranging from 0.4 to 0.8 mm, and a length ranging from 25 to 60 mm. Their aspect ratio, that is, the ratio of length over diameter or equivalent diameter, is generally less that 100, with a common range from 40 to 80. The length and diameter of synthetic fibers vary greatly. Single filament fibers can be as little as 10 micrometers in diameter such as for Kevlar or carbon fibers, and as large as 0.8 mm such as with some polypropylene or poly-vinyl-alcohol (PVA) fibers. Generally in concrete applications, the aspect ratio of very fine fibers exceeds 100 while that of courser fibers is less than 100. Most synthetic fibers (glass, carbon, kevlar) are round in cross section; flat synthetic fibers cut from plastic sheets and fibrillated are suitable when very low volume content is used such as for the control of plastic shrinkage cracking.

2.3 Fiber content and volume fraction of fibers

Due to the formulation of the mechanics of the composite (see Section 2 below), the fiber content in cement matrices is specified by volume fraction of the total composite. The fiber volume content in typical fiber reinforced concrete applications is shown in **Table 1**. Because of fiber materials of different densities, the same volume fraction of fibers of different materials leads to different weight fractions of fibers. Fibers are purchased by weight, but mechanical properties of composites are based on volume fraction, not weight fraction of fibers. Typically a 1% volume fraction of steel fibers in normal-weight concrete amounts to about 80 kg/m^3 of concrete; however, a 1% volume fraction of polypropylene fibers amounts to about only 9.2 kg/ m^3.

2.4 Fiber-matrix reinforcing effectiveness

By its very definition a reinforcement (i.e., the fiber) is supposed to induce an increase in strength in the reinforced material (i.e., the matrix). Both analysis and experimental test results suggest that, in order to be effective in concrete matrices, fibers must have the following properties (**Fig. 2**): 1) a tensile strength significantly higher that that of concrete (two to three orders of magnitude); 2) a bond strength with the concrete matrix preferably of the same order as or higher than the tensile strength of matrix; and 3) unless self-stressing is used through fiber reinforcement, an elastic modulus in tension significantly higher than that of the concrete matrix. The Poisson's ratio and the coefficient of thermal expansion should preferably be of the same order for both the fiber and the matrix. Indeed if the Poisson's ratio of the fiber is significantly larger than that of the matrix, detrimental debonding will occur under tensile load. However, these drawbacks can be overcome by various methods such as inducing surface deformation to create mechanical anchorage.

Table 1 Range of volume fraction of fibers for typical fiber reinforced cement composites.

Material	Range of V_f	Remark
FRC – Fiber Reinforced Concrete	$V_f \leq 2\%$	Fibers are premixed with the concrete matrix. Finer aggregates may be needed.
HPFRCC – High Performance Fiber Reinforced Cement Composites	$V_f \begin{cases} \geq (V_f)_{critical} \\ \geq 1\% \end{cases}$	Strain hardening and multiple cracking characteristics in tension. With proper design, critical V_f can be less than 2%.
Shotcrete (steel fibers)	$V_f \leq 3\%$	Applications in tunnel lining and repair.
Spray Technique (glass fibers)	$4\% \leq V_f \leq 7\%$	Applications is cladding and panels.
SIMCON (steel fibers)	$4\% \leq V_f \leq 6\%$	Slurry Infiltrated Mat Concrete. A prefabricated fiber mat is needed.
SIMCON (PVA fibers)	$V_f \approx 1\%$	Recently available.
SIFCON (steel fibers)	$4\% \leq V_f \leq 15\%$	Slurry Infiltrated Fiber Concrete. Fibers are preplaced in a mold and infiltrated by a fine cementitious slurry matrix.

3. Simplified mechanics of fiber reinforcement

The mechanics of fiber reinforcement of concrete and other information on the applications of fiber reinforced concrete can be found in several books and symposia proceedings some of which are listed in the references such as Reinhardt and Naaman (1992, 1996, 1999, 2003). Next only a simplified approach is presented to provide a background to the key points of the discussion.

The typical stress-elongation response of a fiber reinforced cement composite indicate two properties of interest, the stress at cracking, σ_{cc}, and the maximum post-cracking stress σ_{pc} (**Fig. 3**). Extensive discussion of the meaning of these two properties and their relationship is given elsewhere (Naaman and Reinhardt, 1996, and Naaman, 2002). While the cracking strength of the composite, σ_{cc}, is primarily influenced by the strength of the matrix, the post-cracking strength is solely dependent on the fiber reinforcing parameters and the bond at the fiber-matrix interface. Thus, improving the post-cracking strength is key to the success of the composite.

3.1 Assumptions

In the following derivations, the following assumptions are made: 1) a critical crack exists across the entire section of the tensile member (**Fig. 3**), 2) the crack is normal to the tensile stress field, 3) the contribution of the matrix is negligible, and 4) the fibers crossing the crack are in a general state of pull-out. This is typically the case when steel fibers are used in concrete.

3.2 Classical approach

In the most general way the post cracking strength of the composite, assuming general fiber pull-out, can be estimated from the following equation:

$$\sigma_{pc} = \Lambda \tau V_f \frac{L}{d} \tag{1}$$

in which τ is the bond strength at the fiber-matrix interface, V_f is the volume fraction of fibers, L is the fiber length, d is the fiber diameter, L/d is the aspect ratio, and Λ is the product of several coefficients dealing with expected pull-out length, efficiency factor of orientation, group reduction factor associated with number of fibers pulling out per unit area, snubbing coefficient, etc. To simplify the presentation and the discussion, these coefficients have been combined together in the product, Λ, and will not be discussed in any detail.

3.3 New approach

Equation (1) assumes that the fiber is circular in cross section, with a diameter d. For non circular fibers, d is generally considered to be the equivalent diameter, d_e, for simplification. However, using L/d as a main variable can be misleading for non-circular fibers.

In order to accommodate in the most general way fibers that are not circular in cross section, Eq. (1) should be written as follows:

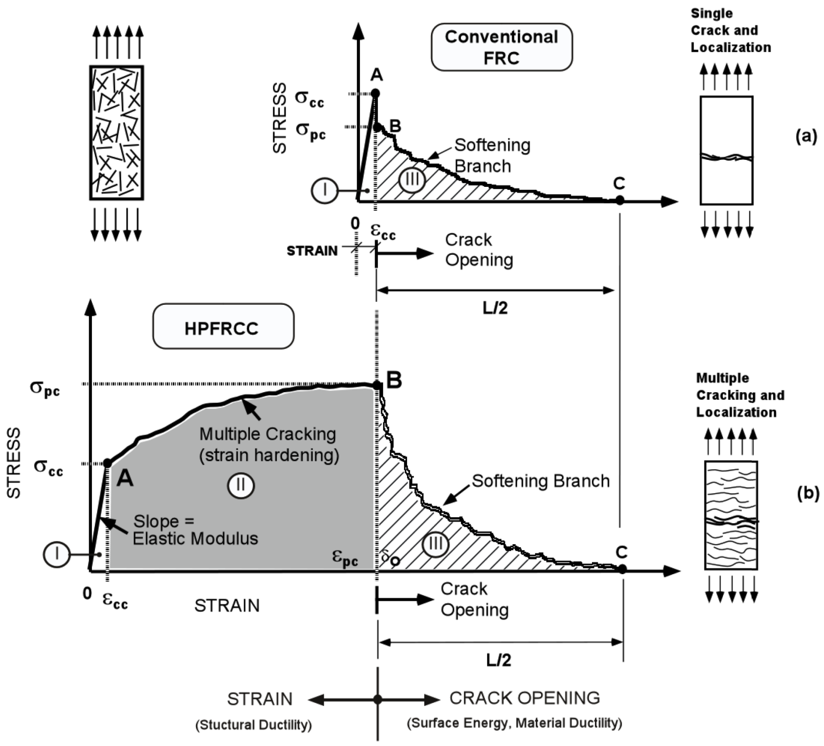


Fig. 3 Typical stress elongation response of fiber reinforced cement composites illustrating the cracking and maximum post-cracking stress.

$$\sigma_{pc} = \frac{\Lambda}{4} \tau V_f \frac{\psi L}{A} \tag{2}$$

in which ψ is the perimeter of the fiber and A is its cross sectional area. Thus for a given fiber length, L, increasing the bond strengths, τ, or the volume fraction of reinforcement, V_f, or the ratio of perimeter to cross sectional area, ψ/A, leads to a direct increase in the post-cracking strength of the composite.

In comparing Eq. (1) with Eq. (2), one can observe that for a given circular fiber of length, L, and cross section A, there is only one equivalent diameter d, thus one value of L/d; however, for the same L and A values, there is theoretically an infinite number of non-circular sections with different perimeters, ψ, thus different values of ψ/A. Equation (2) is more general than Eq. (1) and illustrates the influence of the ratio ψ/A, that is, the shape of the fiber cross section.

3.4 Fiber intrinsic efficiency ratio (*FIER*)

One way to characterize the influence of the ratio ψ/A is through a variable defined as the fiber intrinsic efficiency ratio (*FIER*). It has been defined in a previous study as the ratio of bonded lateral surface area of fiber, to its cross sectional area; the ratio can be calculated either per unit length of fiber, or for the total length, L, of a given fiber. This last definition is used here:

$$FIER = \frac{\psi L}{A} \tag{3}$$

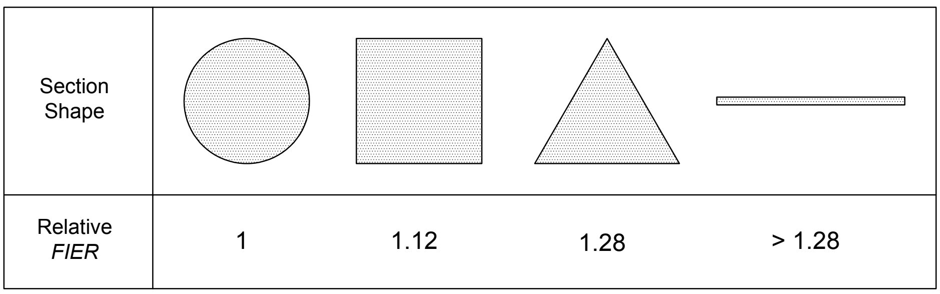


Fig. 4 Possible fiber sections and corresponding values of their fiber intrinsic efficiency ratio (*FIER*) compared to that of a circular fiber.

Figure 4 illustrate the relative value of the *FIER* for a circular, square, triangular and flat rectangular fiber. It can be observed that for the same cross sectional area, a triangular fiber is 28% more effective than a circular fiber, while a square fiber is 12% more effective.

For a circular fiber it can be shown that:

$$FIER = \frac{1}{4}\frac{L}{d} \quad (4)$$

Replacing the FIER from Eq. 3 into in Eq. 2 leads to:

$$\sigma_{pc} = \frac{\Lambda}{4}\tau V_f FIER \quad (5)$$

Equation (5) suggests that the higher the *FIER* of a fiber the higher the expected post-cracking strength of the composite. It is more general than Eq. (1), since it accommodates fibers of any cross-sectional shape, whether circular or not. Equation (5) indicates that there are four main independent variables or parameters we may consider in order to increase the post-cracking strength of the composite: Λ, τ, V_f, and *FIER*. Their influence is discussed in Section 4.

Finally, note that the maximum pull-out load of a fiber embedded in a cement matrix can be written in the following way (**Fig. 5**):

$$P_{max} = \begin{cases} \pi d \tau L_e & \text{for a circular fiber} \\ \psi \tau L_e & \text{for a fiber of any cross-sectional shape} \end{cases} \quad (6)$$

where L_e is the embedded length and the average bond strength, τ, is assumed constant. It should be noted that between Eq. (5) is derived from Eq. (6) where a large number of fibers are considered in a state of pull-out.

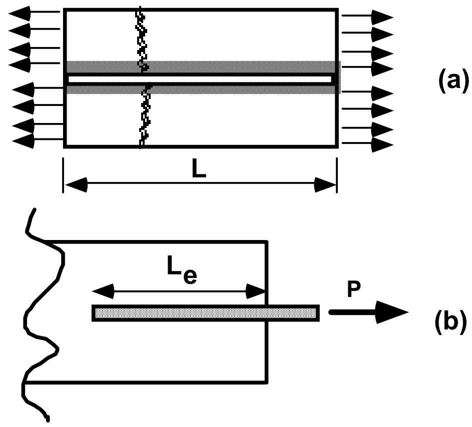


Fig. 5 (a) Unit cell model of composite with a crack, and (b) correlation with fiber pull-out.

4. Effect of independent variables: composite design

Whether Eq. (1, 2 or 5) is considered, it is clear that a number of independent variables can be controlled by the material designer to achieve a better composite post-cracking response. These variables or parameters are shown in **Fig. 6**. Increasing one or a combination of the independent variables V_f or τ or *L/d* or $\psi L/A$ should lead to an increase in the post-cracking strength of the composite. However there is a practical limit to how much each variable can be increased or controlled.

For instance, if normal steel fibers are to be premixed with a concrete matrix, using more than about 2% fibers by volume becomes difficult from a practical viewpoint; it may lead to balling, segregation, harsh mix, etc. To further increase V_f, other processes are used such as in SIFCON or SIMCON where a fiber network or a fiber mat is preplaced in a mold and is infiltrated by a cement matrix. Note that increasing the volume fraction of fi-

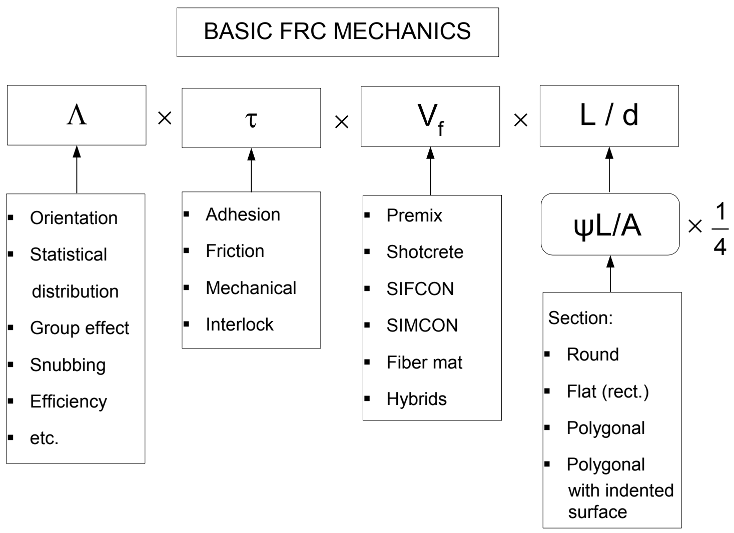


Fig. 6 Independent variables, components, constraints and solutions in FRC design.

bers, invariably leads to a matrix made with only fine grain particles, that is, a concrete matrix without course aggregate or even without normal sand, generally leading to a decrease in the elastic modulus of the composite.

Similarly, with rigid fibers such as steel fibers, increasing the aspect ratio beyond about 100, leads to increased segregation, balling and difficulty in mixing. Theoretically this correlates with the topography of a fiber network and how randomly oriented and distributed rigid fibers fill a given volume. The aspect ratio limitation, can also be overcome by using other processes such as by shotcreting, or in SIFCON or SIMCON where the fibers do not need to be premixed.

The coefficient Λ in **Fig. 6** is the product of a number of other coefficients and depends on several statistics such as fiber orientation and distribution. While we can influence the orientation of the fibers (1D, 2D, or 3D), little can be done to change the other coefficients. Thus Λ can only marginally be controlled.

The last and most difficult parameter to control composite performance is the bond strength, τ, which is often assumed in composite design to be a constant. Increasing the average bond strength, τ, leads to a direct increase in the post-cracking strength of the composite and other important properties as well such as toughness and energy absorption capacity. A comprehensive discussion of the various bond components listed in **Fig. 6** (adhesion, friction, mechanical, interlock) is given in Naaman (1999 and 2000b). It is argued that in order for bond to be truly effective, its value must be maintained over relatively large slips, leading to what is described as a ductile bond stress versus slip response. It should be noted that in the current state of the art, all four components of bond have been explored. Friction is considered an essential part of bond and is practically always counted on. Adding for instance latex or an epoxy resin to the cement matrix will increase the adhesive (or chemical) bond at the fiber matrix interface; however, prior tests have shown that because of the brittle nature of adhesion, the bond increase observed in a single fiber pull-out test, does not translate in an equal improvement at the composite level. Practically all steel fibers have their bond improved through mechanical deformations: examples include crimping or indenting the fibers along their length or adding hooks or buttons or paddles at their ends. Fiber-to-fiber interlock exists in SIFCON and SIMCON composites where the fibers are in contact with each other but cannot be generally counted on when fibers are premixed with the matrix.

In summary to **Fig. 6** and the above discussion, it seems at first that no additional improvement can be thought off to improve composite performance. However, as shown in the following section, bond offers some interesting and hidden opportunities that have been recently uncovered and have led to a new type steel fiber, here identified as Torex fiber, for use in composite applications.

5. How to optimize bond by changing fiber cross-sectional shape and geometry?

Three of the bond components shown in **Fig. 6** (friction, adhesion, and mechanical bond) can be optimized beyond what has been done so far in current practice. This is achieved through optimizing the fiber cross-sectional shape and its geometry.

5.1 Improving adhesion and frictional components of bond

In **Fig. 7**, a fiber of round section (a) is shown in the

The primarily square fiber (b) has the same perimeter as the circumscribing circular fiber (a), but only 28% of its cross sectional area.

However, everything else being equal, under fiber pull-out conditions, fiber (b) will carry the same pull-out load as fiber (a). Thus it will be subjected to a tensile stress 3.66 times that of the circular fiber (a).

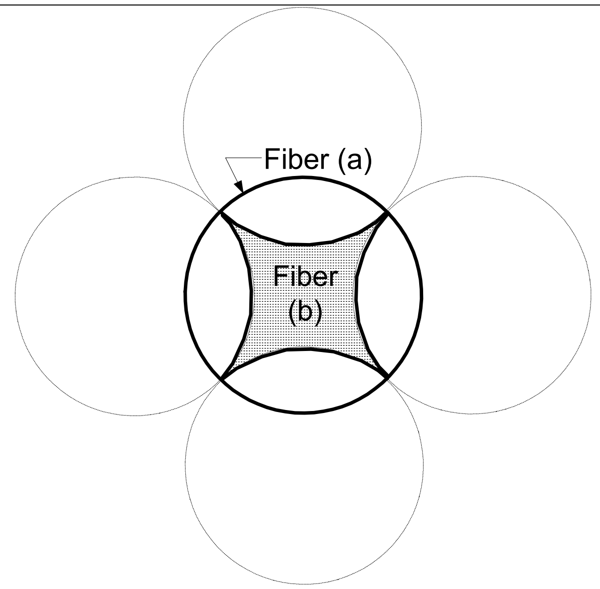


Fig. 7 Effect of improved ratio of lateral surface or perimeter to cross section.

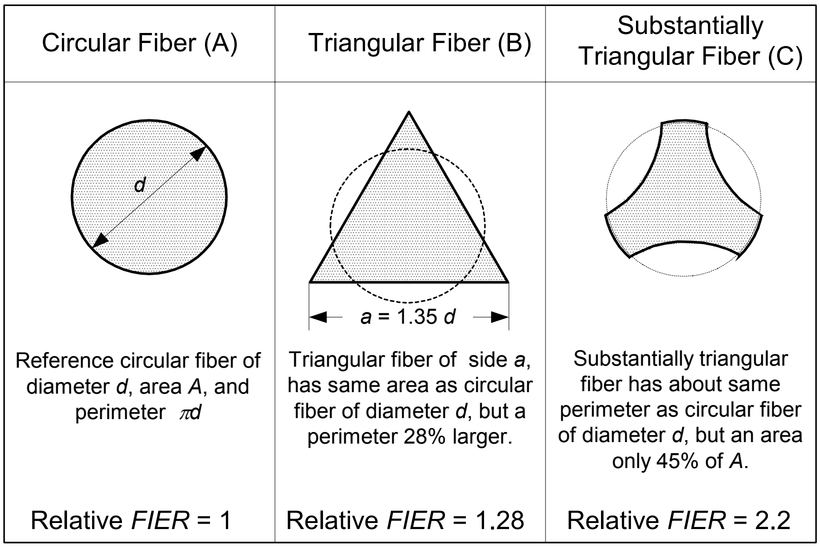


Fig. 8 Example of generating an optimum fiber shape.

center of the figure; several sectors can be cut from fiber (a) leading to the dashed fiber section (b). Assume the fibers have same length and mechanical properties. From geometry, it is observed that both fiber (a) and (b) have the same perimeter. Yet the cross-sectional area of fiber (b) is only 28% that of fiber (a). In theory, for the same embedded length, if the two fibers are pulled-out from a concrete matrix, they will both carry the same pull-out load (Eq. 6). The stress in fiber (b) will be 3.66 (or 1/0.28) times the stress in fiber (a) making it much more efficient provided fiber pull-out prevails. Thus, everything else being equal, if the same volume fraction of fibers is used, the composite with fiber (b) should have a post-cracking strength 3.66 times that of composite with fiber (a) (Eq. 5). This example illustrates the influence of fiber cross section which can be controlled to a certain extent by the designer.

Fibers similar to fiber (b) can be generated with triangular or other polygonal shapes. However, fiber (b) in **Fig. 7** has sharp vertices and is not very practical to manufacture. Nevertheless, the idea can be applied to achieve significant increase in performance. **Figure 8** shows three fiber cross sections. Fiber (A) is circular with a diameter d and a perimeter πd ; fiber (B) is triangular and has the same cross section as fiber (A). However, its perimeter is 1.28 times that of (A). Thus, everything else being equal, using fiber (B) should in theory lead to a 28% increase in σ_{pc} (Eq. 2). Fiber (C) has about the same perimeter as the circular fiber (A) but a cross section only 45% of it. Everything else being equal, its use should lead to a 220% increase in σ_{pc} (Eq. 2). This example illustrates the influence of the ratio ψ/A, and the importance of the cross-sectional shape of the fiber. Typical polygonal shapes such as fiber (B) and primarily polygonal shapes, such as fiber (C) of **Fig. 8**, are more effective than circular fibers in contributing to the post-cracking response of the composite.

Additional examples of primarily square and primarily triangular fibers and their relative efficiency in comparison to circular fibers are given in **Fig. 9**. Such fibers, whether made out of steel or polymers, can be manufactured with current technology.

5.2 Improving mechanical component of bond

As mentioned earlier, mechanical deformations are added to steel fibers to improve their mechanical anchorage (or bond) to concrete. These include crimping or indenting the fiber along its length, or adding hooks or buttons at its ends. However, one very effective way to develop mechanical bond is by twisting the fibers to achieve a profile similar to that of a screw. Most steel fibers are either round or flat (circular or rectangular) in cross section. To be amenable to twisting, fibers must be polygonal in cross section in order to develop ribs along their length. Round fibers cannot develop ribs when twisted and flat fibers, when twisted, form tube-like tunnels which can be sites to stress concentrations and may be later difficult to penetrate by the matrix. Not only polygonal or primarily polygonal fibers have a higher value of surface to area ratio (**Figs.7** to **9**) which improves the frictional and adhesive components of bond, but also they can be twisted leading to a very effective mechanical anchorage or mechanical bond.

Indeed when twisted along their longitudinal axis, polygonal fibers form ribs along their surface that improve their gripping (pull-out resistance) to a similar extent that a screw grips better than a nail. However, the mechanism of twisted fibers is different from that of a conventional screw.

Extensive tests on the pull-out load versus slip response of steel fibers of different shapes indicated that twisting is the most effective way to improve the me-

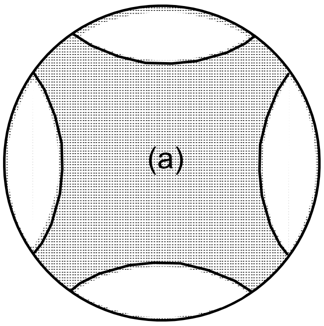
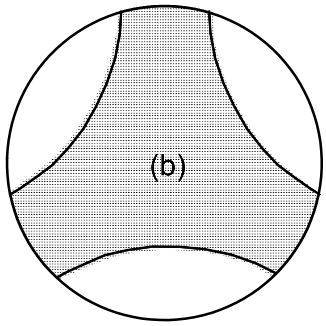
Primarily Square Fiber: Actual Example	Primarily Triangular Fiber: Actual Example
	
FIER = 1.6 For about the same perimeter, the cross section of primarily square fiber *(a)* is only 62% that of the circumscribing round fiber. This implies that (all other parameters being equal), the same pull-out load and composite strength can be achieved; however, the needed volume fraction of square fibers *(a)* can be only 62% that of the round fibers.	*FIER* = 2 For about the same perimeter, the cross section of primarily triangular fiber (*b)* is only 50% that of the circumscribing round fiber. This implies that (all other parameters being equal) the same pull-out load and composite strength can be achieved. However, the needed volume fraction of triangular fibers (*b)* can be only 50% that of round fibers.

Fig. 9 Actual examples of primarily square and primarily triangular fibers with improved surface area and suitable for twisting.

chanical component of bond of the fiber. This is further supported in Section.6.

How Much to Twist? In order to answer the question “to what extent should a polygonal fiber be twisted?” to improve its mechanical bond, an extensive analytical and experimental program was carried out. **Figure 10** illustrates the mechanisms involved. **Figure 10a** shows how a smooth fiber with a week adhesive and frictional bond pulls out from its tunnel of matrix. It essentially slips out, with little damage to the surrounding matrix. If the fiber is replaced by a “screw” (**Fig. 10b**) the grip (or mechanical anchorage) may be too strong; indeed, upon increased pull-out load, the tunnel of matrix around the fiber may break in one of two possible ways: either along the length of the fiber, or along a cone emanating at an angle to the fiber axis. Such failures are typical of anchorages to concrete. With a properly twisted polygonal fiber such as triangular or square (**Fig. 10c**), the fiber, under increasing pull-out load, tends to untwist while slipping out from the matrix, thus providing a constant or increasing resistance to pull-out. To properly twist a fiber to achieve such behavior, the number of ribs or twists must be engineered in terms of the fiber and matrix properties. Assuming this is achieved, there is a final beneficial mechanism that arises from twisting the fibers; it is difficult to explain but observed nevertheless. It will be simply described as a “repetitive stick-slip mechanism” and is generated by the untwisting wave that travels along the embedded length of the fiber when pulled out. The stick-slip

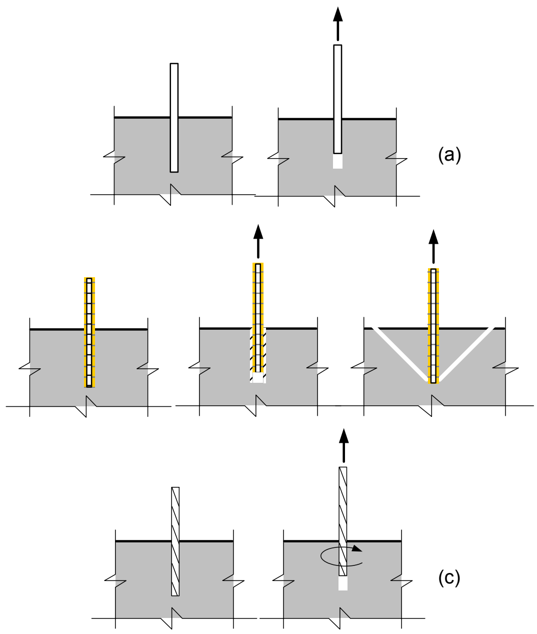


Fig. 10 Typical pull-out behavior of steel fibers embedded in concrete: (a) Smooth fiber. (b) Screw type fiber or anchor. (c) Twisted polygonal fiber.

mechanism is believed responsible for the apparent hardening of the bond stress versus slip relationship of the fiber up to relatively large slips, and is unique to the new Torex steel fibers described here.

6. Typical test results

Estensive tests have been carried out at the University of Michigan to evaluate the new Torex fibers and compare their performance to that of other steel fibers on the market today. Practically all the references listed contain some information on the Torex fibers and can be consulted for additional details. In particular, abundant test results are given by Chandrangsu and Naaman, (2003), Guerrero and Naaman, (2000), Naaman, (1999), Naaman and Sujivorakul, (2001), and Sujivorakul and Naaman (2002, 2003a, 2003b, 2004). Typical results are shown in **Figs. 11** to **15. Figure 11** compares the pull-out load versus slip response of smooth, hooked,

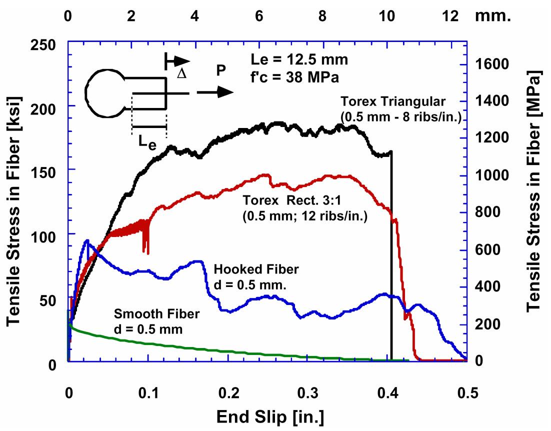


Fig. 11 Comparison of typical tensile stress versus slip response of smooth, hooked, and twisted steel fibers under pull-out.

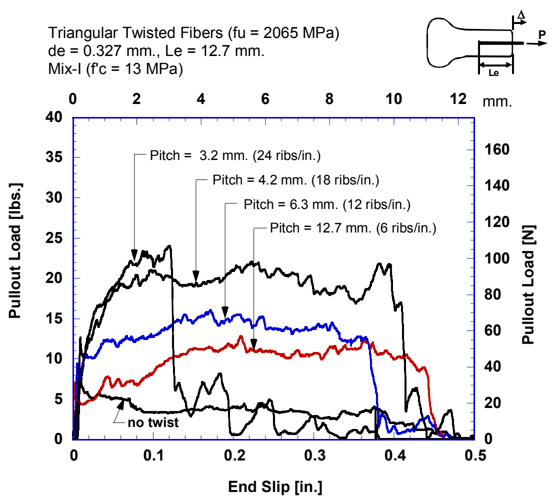


Fig. 12 Typical tensile stress versus slip response of twisted Torex steel fibers under pull-out illustrating the effect of twisting.

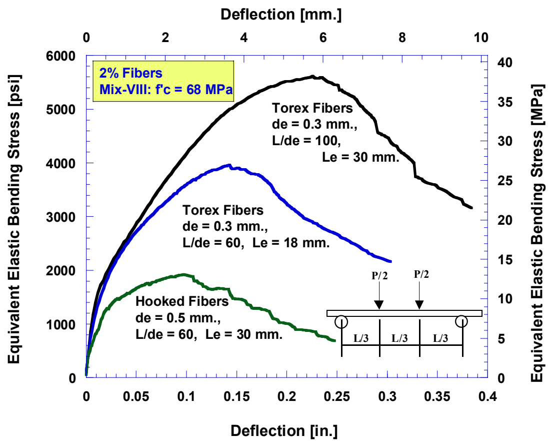


Fig. 13 Typical response in bending of thin (12.5 mm) specimens reinforced with Torex and hooked fibers.

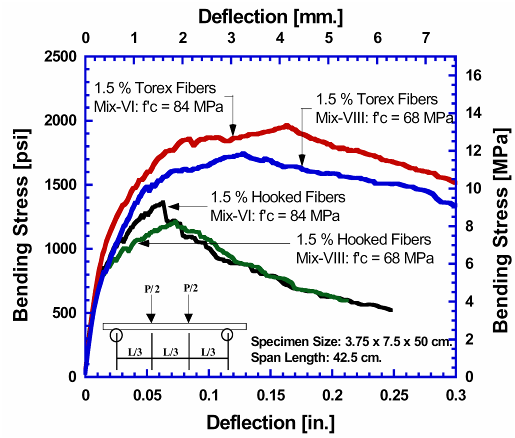


Fig. 14 Typical response in bending of thick specimens (37.5 mm) reinforced with Torex and hooked fibers.

and twisted Torex fibers. The pull-out load is transformed into the tensile stress generated in the fiber. What is most surprising about the Torex fibers is that they maintain a relatively high pull-out load up to very large slips, which corresponds to about 70%-80% of embedded length. This has significant implications at the composite level where cracks can be constrained by the fibers up to very large crack widths. Also very high stresses are induced in the Torex fiber under pull-out suggesting its high level performance. **Figure 12** illustrates the influence of one variable (number of ribs or extent of twisting) on the pull-out response of Torex fibers and remind the material designer that many parameters can be modified to arrive at the desired behavior. A low strength concrete is used in **Fig. 12** because, at low strength, the effect of number of ribs is very significant. **Figure 13** compares the response of thin (12.5 mm) fiber reinforced concrete bending specimens with Torex fibers and commercially available hooked steel fibers on the market; **Figure 14** shows a similar comparison with thicker (37.5 mm) bending specimens.

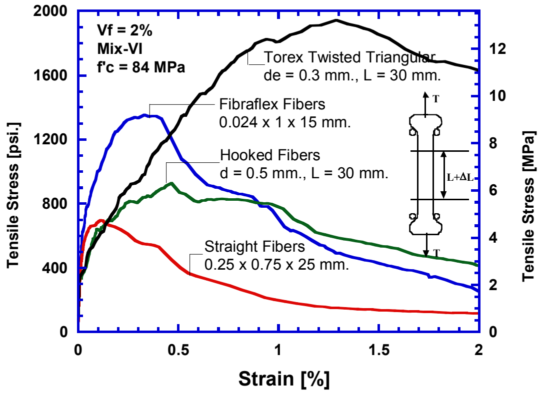


Fig. 15 Typical response in tension of dog-bone specimens reinforced with different steel fibers.

These figures clearly illustrate the superior performance of the Torex fibers. **Figure 15** compares the response mortar specimens reinforced with different steel fibers. Here again the superior performance of the Torex fiber does not need to be stressed. Details of these tests can be found in the references listed at the end of the paper.

It should be observed that while extensive tests with Torex fibers have been carried out at the material level on small size specimens, a number of larger scale tests at the structural level are underway at the University of Michigan and will be described in future publications.

6.1 Conclusions on optimum fiber design

From the above discussion and observations two conclusions can be drawn:

Conclusion 1: Increasing the lateral surface area of a fiber, for the same cross-section, increases frictional and adhesive bond forces along the fiber and leads to an increase in pull-out resistance and thus in fiber efficiency.

Conclusion 2: In existing art, twisting is the best way to improve the mechanical component of bond of fibers. It preserves the elastic response of the fiber (i.e. elastic modulus) and, with proper design, leads to a pull-out load versus slip response with unique slip hardening characteristics (Naaman, 1999).

Note that round fibers cannot be twisted; and flat fibers, if twisted will form tunnel like sections that may not be penetrated by the cement matrix and are undesirable sites of stress concentration. Crimping, i.e. leading to a sinusoidal wave form, while effective in improving bond, leads to a significant reduction in the equivalent elastic modulus of the fiber. A hook at the end of a straight fiber is equivalent to a half amplitude wave.

The new fibers with optimized section geometry developed by the author at the University of Michigan (here identified as Torex fibers) are designed according to the above principles and observations. That is they provide a larger surface area for adhesion and frictional bond and they are twisted to achieve the most effective mechanical bond; moreover, by designing the twist parameters, these fibers can provide a slip-hardening bond stress versus slip relationship which is unique to date among existing steel fibers. The new fibers are covered by US patents (Naaman, 1999, 2000). Examples of Torex fibers are shown in the photos of **Fig. 16**.

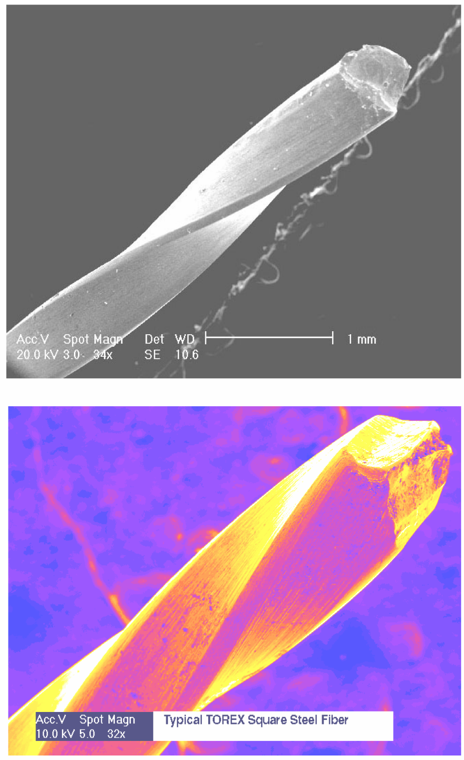


Fig. 16 Typical examples of Torex twisted triangular and square steel fibers.

7. Extension of concept to composite fibers, reinforcing bars and prestressing tendons

The concepts and ideas illustrated above for improving the bond of discontinuous fibers, are generic in nature. They apply to discontinuous composite fiber bundles made out of multiple fibers, as well as to continuous reinforcing bars and prestressing tendons.

Typical examples of cross-section of fiber bundles are shown in **Fig. 17**. Their shape can be further optimized to increase the stress transfer between fibers that are near the surface and fibers that are close to the main axis of the section (**Fig. 17a**). In the case of continuous bars or tendons, an application of particular interest is in non-metallic fiber reinforced polymeric (FRP) reinforcements. In such cases the use of straight bars of optimized shape (**Fig. 17a**) will lead to significantly lower transfer lengths and development lengths. Additional efficiency in the transfer of stresses within the section of an FRP bar can be achieved by using a hollow cored

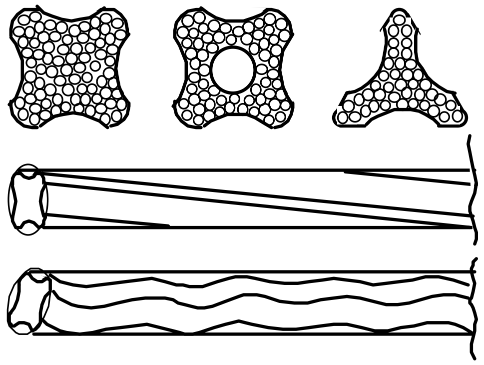


Fig. 17 Examples of sections of: a) composite fiber bundles, bars, or tendons, using multiple fibers with, b) continuous twisting or, c) alternate twisting.

section, or a section with a filler core material of much lower strength and stiffness. Furthermore, should there be need, twisting can be applied either continuously or alternately, as shown in **Figs. 17b** and **17c**, allowing for improved mechanical bond characteristics with even smaller development and transfer lengths.

8. Summary: Advantages of optimized Torex fibers

1. **Section Efficiency Advantage.** Using simply geometric configurations and a smooth lateral surface, the newly engineered fibers can be up to 300% more efficient than round fibers. A 200% efficiency seems attainable immediately with primarily triangular fibers such as fiber (b) of **Fig. 9.** That is, for the same required composite post-cracking strength and toughness, the volume fraction of triangular fibers (b) will be half that required with round fibers.
2. **Twisting Advantage.** The bond strength of smooth steel fibers embedded in concrete is generally small and mostly frictional in nature. Most fibers used as reinforcement in cementitious composites, generally are mechanically deformed to improve their bond and thus lead to improving other mechanical properties of the composite such as strength and toughness. Mechanical deformations include: hooked ends, buttoned ends, indenting the surface, and crimping. Because of the polygonal nature of their optimized fiber section, Torex fibers can be twisted, thus improving their mechanical bond significantly. In extensive experimental tests, the improvement of bond due to twisting is found to be far superior to any other form of mechanical deformation process used to date.
3. **Mixing Advantage.** Because significantly less amount of fibers (by volume or weight) is needed to achieve a given composite performance, difficulties encountered in practice in pre-mixing a large amount of fibers are minimized.
4. **Compatibility with Prior Art.** Plain or twisted polygonal fibers with improved geometry, can also be crimped or have hooks at their ends, similarly to other fibers on the market, should there be need for additional mechanical bond. So far, from observed tests, this does not seem necessary.
5. **Extension of concept.** The concepts and ideas developed for discontinuous fibers are generic in nature and accommodate metallic and non-metallic materials. They also apply to continuous reinforcing bars as well, and are particularly suitable for fiber reinforced polymeric (FRP) reinforcements used in reinforced and prestressed concrete, because they offer better bond properties, i.e. larger fiber intrinsic efficiency ratio (*FIER*), which translates in better development lengths or transfer lengths.
6. **Superior performance.** From extensive tests, it seems now possible to develop fiber reinforced cement composites with about half the fiber content and a performance about equal to that obtained with currently available fibers. On the other hand, for the same fiber content, performance with the new Torex fibers is expected to be far superior.

The new fibers will advance the broader use of high performance fiber reinforced cement composites which are characterized by a strain hardening behavior in tension [Reinhardt and Naaman, 1992, 1999, and Naaman and Reinhardt, 1996, 2003]; these composites offer a combination of high tensile strength, ductility and toughness. They are suitable in structural applications such as in blast and seismic resistant structures, as well as in stand-alone applications such as in thin sheet products for housing, claddings for buildings, shells, pipes, and the like. With Torex fibers, the engineering dream that started more than a century ago, to mix fibers with concrete, like sand or gravel, to achieve a self-sufficient structural material, without reinforcing bars, is closer than ever.

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