

# FIBER REINFORCED CONCRETE: FIVE DECADES OF PROGRESS

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#### Abstract

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. The past five decades mark the modern development and broad expansion of fiber reinforced concrete (FRC), which leads to today extensive applications and increased market penetration. Such a success is due in part to significant advances in the fiber reinforcement, the cementitious matrix, the interface bond between fiber and matrix, and fundamental understanding of the mechanics of the composite. Following a brief summary of: 1) the history of fibers in concrete, 3) the reasons why FRC failed during its first 100 years, 3) the underlying principles of fiber reinforcement in cement based composites, 4) the key causal parameters, and 5) related technical as well as practical limitations, this paper-presentation describes the rationale behind the modern developments of FRC composites leading to today's ultra-high performance fiber reinforced concretes, which exhibit tensile strengths of the same order as the compressive strength of normal concretes. It stresses in particular the importance of the transition in composite response from a strainsoftening to a strain-hardening behavior in tension, and the resulting transition of the composite function from an engineering material to a structural material with potential stand-alone usage. Relevant examples of applications will be described in the presentation only.

# **1. INTRODUCTION**

The content of this paper is essentially taken from a recently published book on FRC by the author [1]. While the oral presentation (as suggested by the title) offers a more detailed overall perspective, next only two important milestones leading to today classification of all FRC composites as either strain-softening or strain-hardening are documented.

# 1.1 Fiber Reinforced Cement and Concrete (FRC) Composites

For practical purposes and mechanical modeling, as defined in [1], fiber reinforced cement and/or concrete (FRC) composites are defined as composites with two main constituents, the fiber and the matrix (Fig.1). Generally the fiber is assumed to be discontinuous and, unless otherwise stated, randomly oriented and distributed within the volume of the composite. Both the fiber and the matrix are assumed to work together through bond, thus providing the synergism needed to make an effective composite. The matrix, whether it is a paste (cement mixed with water), mortar (paste with sand), or concrete (mortar with coarse aggregates) is assumed to contain all the aggregates and additives specified. A *concrete* matrix is supposed to contain large size aggregates, say with an equivalent diameter in excess of 8 mm (3/8 in). A *mortar* matrix generally contains sand (of mostly less than 3 mm (1/8 in)) but no large size aggregates. A cement *paste* may contain very fine sand, silica powder, fly ash, silica fume, and other fine additives. Air voids entrapped in the matrix during mixing are assumed to be also part of the matrix (Fig. 1). For simplicity, unless otherwise specifically noted, the term "concrete" will be generally used to represent a cementitious matrix whether it is a paste, a mortar or a concrete.



Figure 1 Composite model considered as a two-constituent system, namely fiber and matrix, as applied to fiber reinforced cements and concretes.

Thus from the broadest perspective, fiber reinforced concrete can be defined as follows:

Fiber reinforced concrete (FRC) is concrete with suitable discontinuous fibers added to it for the purpose of achieving a desired level of performance in a particular property (or properties).

If the fibers are continuous, a different terminology is used to describe the composite such as ferrocement, textile reinforced concrete (TRC), or laminate cementitious composites which use continuous reinforcements made out of continuous wires, textiles, or meshes. Reinforced and prestressed concrete (RC and PC) are also considered composites with continuous reinforcements mostly made out of steel rebars or prestressing strands, but other reinforcing materials (such as fiber reinforced polymer (FRP) reinforcements) are also used.

Figure 2 illustrates how the combination of a concrete matrix with reinforcement, be it continuous or discontinuous, leads to various structural composites developed since the mid nineteenth century; these include the most broadly used structural materials worldwide, namely reinforced and prestressed concrete.



Figure 2 Common cement- and concrete-based composites and possible hybrid combinations.

As described in Section 3.2, modern fiber reinforced concrete started in the early 1960s; here, modern implies the use of a scientific approach to better understand the fundamental properties of the composite. At time of this writing, fiber reinforced concrete has gained a place

of its own in the family of structural concrete materials. Figure 2 illustrates its position within that group. It can be observed that fiber reinforced concrete can be used on its own or in combination with reinforced concrete (RC), prestressed concrete (PC), or ferrocement, thus leading to a hybrid composite containing both discontinuous fibers and continuous reinforcements. Hybrid composites also include the use of fibers of different materials and/or different geometric and mechanical properties (not addressed in this paper).

#### 2. FRC COMPOSITES: HISTORICAL BRIEF

The concept of using fibers to improve the behavior of building materials is old and intuitive. Examples include adding straw fibers to sun-dried mud bricks primarily made out of clay (adobe), horse hair to mud clay, and asbestos fibers to ceramic pottery, thus creating a composite with a better performance.

In the case of adobe for instance, as used in Mesopotamia in the Middle East, straw fibers may not have led to an increase in tensile strength. However, their real benefits (as we understand them today) were to limit fragmentation after cracking, keep cracks from opening wider, decrease the rate of degradation with repetitive cycles of temperature and humidity, and improve toughness. Thus, it is no surprise that when Portland cement concrete started evolving as a building material during the 19<sup>th</sup> century, attempts were made to add fibers to it to improve its behavior.

In 1855, the French patent of *Joseph Louis Lambot* advocated the combination of "iron wires (forming a continuous grid) and cement" leading to a material called in French "ferciment", known today as ferrocement [2]. Shortly thereafter reinforced concrete was born. Prestressed concrete followed in the first third of the 20<sup>th</sup> century (Fig. 2).

However, the use of continuous reinforcement, as in reinforced concrete, requires careful placement and higher technical labor skills, hence higher cost. It also leads to an anisotropic building material with which the average layman is not very comfortable.

The idea of using strong discontinuous fibers as reinforcement for concrete seems to have been both a seduction and a challenge to many practitioner and civil engineers. Adding the reinforcement to the concrete mixer in the form of fibers, simply like adding sand or admixtures, to create a homogeneous, isotropic, strong, tough, durable and moldable structural material is a dream that started toward the end of the 19<sup>th</sup> century and is still in the making today.

# **3. DEVELOPMENT OF FIBERS FOR CONCRETE AND FIBER REINFORCED CONCRETE**

Two distinct time periods seem to characterize the pace of development of fibers specifically intended for concrete (Fig. 3). The first period, prior to the 1960's, corresponds to a slow pioneering phase with many ideas but almost no applications, while the second period, since the early 1960's corresponds to a phase of more rapid and modern developments paralleled by increasing applications.

The first period (1874-1960) can be considered a dormant period during which many patents were submitted on the subject but were not technically convincing since they claimed an increase in tensile or bending resistance by addition of fibers, but only deflection softening

behavior was observed from limited experimental tests (Fig. 3). The second time period termed modern development started with a scientifically based study by Romualdi et al. [3, 4] in the early 1960's; while it also claimed the increase in tensile strength of the composite by fiber addition, it mainly brought awareness of the increase in fracture resistance of the composite. This became a starting point for an intense number of fundamental analytical and experimental studies on the mechanics and behavior of the composite. This second phase was accompanied by the increasing use of modern scientific methods to better understand the reinforcing mechanisms of the fibers, the role of bond, and the contribution of the two main constituent materials. Eventually not only the significant increase in fracture toughness was discovered as the most important benefit of fiber addition, but also researchers were able to develop composites with tensile and bending strengths way higher than those of the matrix alone; thus in effect satisfying what early patents have claimed but could not achieve due to lack of fundamental research. The right side of Fig. 3 is to be correlated with Fig. 14 below where additional details (SS, SH, DS, DS) are explained.



Figure 3 Milestones in the development of fiber reinforced concrete illustrating two distinct time periods.

Numerous patents on fiber reinforced concrete have been granted. They generally address one or a combination of the following: the fiber itself, the fiber reinforced concrete mix, the production process, and the application. A selective number [5 to 12] is reviewed in [1] and summarized next to illustrate the underlying idea behind each patent and the evolution of new ideas with time.

### 3.1 Pioneering Developments: 1874 – 1960

The first patent (1874) on fiber reinforced concrete seems to be due to *A. Berard* from California who suggested the use of granular waste iron in a concrete mix to create an artificial stone. A similar idea suggesting the use of steel shavings and metal scraps was patented by *J.C. Seailles* in France, in 1920. In 1911, *G.M. Graham* (US) suggested the use of steel fibers (short cut steel wires) in addition to conventional reinforcement to increase the strength and stability of reinforced concrete.



A French patent dated 1918 by *H. Alfsen* describes a process to improve the tensile strength of concrete by uniformly mixing small longitudinal bodies (fibers) of iron, wood or other materials. It also suggests that the surface of these fiber elements must be rough or roughened and, if possible, their ends bent in order to provide better adherence to the concrete.

*R. Weakly* (Missouri) obtained a patent in 1912 for using steel fibers made out of two wires and containing loops to secure a durable bond with concrete (Fig. 4). *Weakly*'s fibers were two-dimensional; a tridimensional steel fiber is described farther below.



In 1920, *A. Kleinlogel* from Germany filed a patent for mixing a relatively large volume of iron particles (up to 50% of 2 mm long steel fibers) with concrete in order to produce a moldable mass capable of being chilled, turned, sawed, and filed similarly to an iron mass.

Two relevant patents were granted in California in the 1920's. *Meischke-Smith*'s patent (Fig. 5) describes the use of flat twisted pieces of wires as fiber reinforcement for concrete mixtures. *Martin*'s patent (Fig. 6) describes the use of plain or crimped pieces of steel wires mixed with concrete to strengthen concrete pipes.

The idea of improving the shape of the fiber to increase its contribution was pushed one step further by *H. Etheridge* (New Jersey, 1933) who proposed adding "annuli" fibers (Fig. 7) of different sizes and diameters to improve the crack resistance and fatigue of concrete for use in railway ties. He wrote: "*The object that I have in view is the prevention of local cracks and fractures and I accomplish such object by mixing with the plastic concrete a mass of metal annuli in sufficient quantity to effect coupling of what I may term the 'stitching' together of the adjacent masses of concrete...*".



Numerous patents were granted in different countries in the following years. That of *G. Constantinesco* (England 1943, United States 1954) deserves a special mention since the fiber reinforcing parameters he recommended are quite similar to those of steel fiber reinforced concrete of today. The patent (Fig. 8) describes the use of coiled or helical type steel fibers in order to increase the crack resistance and energy absorption of concrete masses. Suggested applications included army tanks, air raid shelters, machinery foundations, and the like. For comparison, Figure 9 illustrates examples of modern steel fibers marketed since the 1960's.

A tridimensional steel fiber made with four wires forming a frame like two successive footballs was patented by *A.E. Naaman* [11] in 1974 (Fig. 10). It was shown experimentally to provide higher composite strength through an efficient anchorage, and higher toughness through extensive fiber elongation and matrix crushing inside the balls. However, it is not commercially available. The patent stated that the fibers could be premixed or placed in a mold and penetrated by the matrix. Later, *Lankard* [13, 14] developed the SIFCON process whereas straight steel fibers were placed in a mold and infiltrated by a cement-based slurry.

Another patent by A.E. Naaman [12] was granted in 1999 for straight steel fibers with optimized geometries (Fig. 11); the fiber cross-section is primarily square or triangular (offering a lateral

surface for bond higher than that of a circular fiber of same cross-section) and by nature of its shape can be twisted along its length offering a higher mechanical bond than a smooth fiber.

#### 3.2 Modern Developments: 1960 to Date

The modern developments of fiber reinforced concrete started in the early 1960's following the research work of *J.P. Romualdi, J.A. Mandel and G.P. Batson* in the US [3, 4], and *H. Krenchel*, in Denmark [15]. The US researchers hypothesized that the cracking tensile strength of concrete can be significantly increased by adding fibers, and that, in correlation with *Griffith*'s theory of fracture, the strength can be inversely proportional to the square root of the fiber spacing (for details, see [1]). They assumed that fibers play a critical role in arresting cracks and that fiber spacing is thus equal to the maximum crack size. This hypothesis generated considerable attention (and controversy) among researchers and practitioners because it offered a solution for increasing the tensile strength of concrete; indeed, the relatively weak tensile strength of concrete is considered its main drawback and is generally neglected in design. While several studies by different researchers including *S.P. Shah* [16], *A.E. Naaman* [17 to 19], *and N. Swamy* [20, 21] reported experimental observations significantly less optimistic than predicted by *Romualdi's* hypothesis, the spark has been lighted and the impetus to arrive at realistic models continued.

Since the 1960's, a multitude of fibers and fiber materials were introduced and are being continuously introduced in the market as new discoveries and new applications are identified. Many patents have been filed worldwide and can be best accessed through web searches and the US Patent and Trademark Office. The introduction of new fibers or fiber material is invariably preceded and accompanied by research studies providing experimental support and a better understanding of the mechanics of fiber reinforcement (mechanics of composite materials, fracture mechanics, damage mechanics). In turn, such studies point toward a better understanding and identification of desirable fiber and matrix characteristics for any particular application.

At the time of this writing, tens of thousands of technical papers, hundreds of symposia proceedings, numerous guidelines, reports, thesis, standards and books have been written to address fiber reinforced cements and concrete composites, and of course innumerable applications using these composites have been implemented. Several technical societies (ACI, ASTM, JCI, PCI, RILEM, ASCE, etc...) have committees addressing fiber reinforced concrete and have published many related documents on the subject. Several technical journals frequently publish technical papers on FRC composites.

No reference list, no matter how extensive, can be complete and give sufficient credit to all those individuals and organizations responsible for advancing the knowledge base on fiber reinforced concrete. In **[1]** the author lists in order: 1) books on fiber reinforced concrete known to the author at time of this writing; 2) special symposia proceedings series dealing with fiber reinforced concrete; 3) the address of some web sites where technical information can be obtained; 4) some US Patents on fiber reinforced concrete; and 5) a large number of technical references which served as sources for figures and cited results.

#### 4. WHY THE INITIAL LACK OF SUCCESS FOR ALMOST ONE CENTURY

It is important to understand why the pioneers, as described in Section 3.1, did not succeed in getting fiber reinforced concrete adopted enthusiastically by the profession early on. Most of the patents on fibers for concrete developed prior to the 1960's have claimed that the fibers play

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a role similar to reinforcing bars in reinforced concrete thus providing a reinforcing effect, namely by increasing the tensile strength of concrete (mixing-in the reinforcement).

Figure 12 Bending test: (a) Load-type test. (b) Deflection- or deformation-type test.





The proof was to carry out a typical bending test of a simply supported concrete beam and observe if the presence of fibers increased its bending resistance. Loading was carried out by piling up sand bags on top of the beam until failure (Fig. 12a). Such a test, called a load-controlled test, does not capture the resistance of the beam after its maximum load is attained. It is likely that fibers used at the time were not efficient and did not increase the tensile resistance of concrete (after cracking); however, their key hidden benefit (improved toughness) could not be identified by this type of test. The fiber reinforcing parameters and the mechanics of the composite were little understood at the time, and deformation-controlled testing was not available; in such testing, a slowly increasing deflection is applied to the beam and the resistance to the deflection is measured, thus, even after maximum load, the beam resistance, if any, up to very large deflections could be recorded (Fig. 12b). And this is exactly where the

most important benefit of the fibers lies. The post peak response is indicative of toughness, energy absorption capacity, and ductility.

Figure 13a illustrates a "load" type test where only the load, up to its maximum value is recorded; while Fig. 13b illustrates a "deformation" or deflection type test. In the deflection type test, an incremental mid-span deflection is imposed while recording the resistance of the beam to that deflection through a load cell (Fig. 12b); the load (or beam resistance here) for each imposed deflection can thus be recorded throughout, even after the maximum or peak load, up to complete failure.

Consider Fig. 13b where four load-deflection curves are plotted for four different materials; these could be, for instance, concretes with different volume fractions of same fibers or concretes with different fibers. Assume all beams have the same initial response up to the maximum load at point A.

If one uses a load type test (Fig. 13a), the four beams would be considered to fail at A and their possible resistance after A is not recorded (Fig. 12a). One can conclude that the four materials are equivalent. Such was the conclusion in numerous early attempts to demonstrate the potential benefits of fiber reinforcement, leading to little interest from the users. However, a deformation type test would uncover the entire curves of Fig. 13b including the descending branch after point A. The area under each curve is a measure of toughness or energy absorption capacity. While the load type test with same maximum load A cannot differentiate between the four beams, the deflection type test clearly suggests that material C4 is better that C3 which is better than C2 which is better than C1. Figure 13c illustrates another example where deflection hardening is observed; here also, while the load-type test would suggest that B1 is equivalent to B2, the deflection-type test provides more information which can be important in design, such as B2 has a higher energy absorption capacity (area under the load-deflection curve) and higher deflection to failure (i.e.  $\Delta 2 > \Delta 1$ ) but its material has a smaller elastic modulus.

#### 4.1 Summary and Key Observation

During the first period of development of fiber reinforced concrete (Fig. 3), that is until about 1960, the civil engineering profession did not yet fully understand the importance of energy absorption or toughness as compared to strength. Thus two test beams leading to the same bending resistance, but with one exhibiting a toughness ten times larger than the other, would be considered equal (Fig. 13b). A more in-depth scientific and engineering knowledge was needed to better understand the role of the fiber, the matrix, the bond, the production process, and what type of testing and measurements may identify different properties. This has become the norm starting in the 1960's.

We can simply conclude that while the first patents on fibers for concrete contained excellent ideas at the time they were submitted, some not too different from today's fibers, scientific knowledge was insufficient to identify the most important benefit of fiber reinforcement, that is, an increase in toughness translated into increases in energy absorption capacity, ductility and impact resistance. At the time and with the parameters tested, increases in tensile strength were not possible. The lack of initial success in experimental and field tests, and the added cost of fibers, did not encourage usage.

We know today that the paramount advantage of fiber reinforcement in concrete is the substantial increase in the toughness or energy absorption capacity of the composite. However, continuous efforts are being devoted and continuous progress is being achieved to increase the composite's tensile strength through improved fibers, fiber efficiency, fiber content, additives, and the like.

Another important benefit of fibers, being increasingly recognized today, is the improved performance of conventional reinforced and prestressed concrete structures using matrices with fibers. Benefits include increases in bond strength of reinforcing bars and prestressing strands, increases in resistance to shear, increases in resistance to seismic excitation under cyclic loading, reduced spalling, improvement in structural ductility and impact resistance, and an overall increase in damage tolerance and resilience of the structure [1].

#### 5. EVOLUTION SUMMARY OF PARAMOUNT MECHANICAL RESPONSE

During the modern period of development (Fig. 3), and after about fifty years of research and progress, what was achieved is a simple classification of FRC composites that allows us to immediately anticipate what type of application can be used. That is, to distinguish an FRC composite strictly based on its tensile or bending behavior without prior knowledge of the hundreds of parameters (fiber, matrix, bond, etc.) which can affect such behavior.



Figure 14 Evolution of terminology to describe strain-hardening behavior in tension, since modern theory of fiber reinforced concrete.

Without going into innumerable details, Fig. 14 summarizes the evolution of terminology and related progress over about four decades, of fiber reinforced cement composites in relation to their fundamental behavior in tension, that is, either strain softening or strain hardening [1, 22]. The current terminology while very simple encompasses all possible behaviors. It allows a unifying platform and suggests a better discipline for reporting future research and developments. Some clarifications are given next.

# 5.1 General Classification: Strain-Softening and Strain-Hardening FRC Composites

Assuming a failure mode where pull-out (full or partial) prevails, practically all fiber reinforced cement composites currently available are covered by a simple and general classification according to their tensile behavior, as illustrated in Fig. 15, namely, either "strain-softening" or "strain-hardening" [1, 23 to 27]; of course the limit case of "elastic perfectly plastic" (curve 4 of Fig. 13b) is theoretically possible but should be mostly viewed as a conceptual boundary.



Figure 15 Simple classification of all FRC composites based on their tensile response.

Figure 15 shows for each case (strain-softening or strain hardening) a couple of representative curves. The inset in each figure shows one crack for the strain-softening case and multiple cracks for the strain-hardening case. The units of the x axis are also different. For a plain cement matrix, it is assumed that the stress-strain response is linear elastic brittle such as curve C1 in Fig. 13b, although special closed-loop testing could identify some strain-softening behavior (after point A) especially when aggregates are used. However, here the matrix will be assumed simply elastic brittle. Figure 16 compares a tensile strain-softening versus a strain-hardening curve using the same vertical axis that separates strain from crack opening after localization of the failure crack.



Figure 16 Typical stress-strain or stress-elongation curve in tension up to complete separation. (a) Conventional strain-softening FRC composite. (b) Strain-hardening FRC composite (also often termed HPFRC composite).

Typically the stress-strain (or stress-elongation) curve of a strain-softening FRC composite (Fig. 16*a*) starts with a steep initial ascending portion up to first percolation cracking (part I), which also corresponds to the maximum stress point as characterized by its stress and strain coordinates ( $\sigma_{cc}, \varepsilon_{cc}$ ). Here the crack becomes immediately critical (failure crack) defining the onset of crack localization. The resistance drops thereafter. No more cracks can develop, and only the critical crack will open under increased deformation. There is generally a descending branch which corresponds mainly to the load versus opening of the critical crack (part III of Fig. 16*a*). The stress is always smaller than the stress at first percolation cracking (here the peak stress). Along that branch fibers can pull-out, fail, or a combination of these phenomena may occur. Also, the cement matrix may contribute some resistance along that part of the curve up to a certain crack opening, but its contribution is generally assumed negligible.

In a strain-softening composite after first cracking (part III of Fig. 16a), the maximum postcracking stress resistance of the composite,  $\sigma_{pc}$ , is lower than that recorded at first cracking,  $\sigma_{cc}$ . The elongation corresponding to  $\sigma_{pc}$  can be either about equal to that at  $\sigma_{cc}$  or substantially larger depending on the fiber reinforcing parameters such as bond strength, elastic modulus of the fiber, and the fiber content. Because only one crack develops, the elongation of the composite is mainly dictated by the opening of that crack. This elongation cannot be translated into strain for the entire prism, but only describes the opening or width of that crack.

Typically the stress-strain curve of a strain-hardening FRC composite (Fig. 15 and 16b) starts the same way as for a strain-softening composite (part I); however, unlike for the strain-softening case, it is immediately followed by a strain-hardening branch where multiple cracking develops and significant energy is absorbed (part II). Here the fibers bridging the first percolation crack resist the tensile load sufficiently, allowing multiple cracks to develop in the matrix at stresses equal or higher than the cracking strength of the composite. This process continues until multiple-cracking stabilizes (at a certain level of average crack spacing and width); with a further increase in elongation (or strain), one crack becomes critical (localization at maximum post-cracking strength, ( $\sigma_{pc}, \varepsilon_{pc}$ )), and the fibers bridging that crack start pulling out, or fail, or a combination of both leading to a decrease in composite resistance (Part III of Fib. 16b). After  $\sigma_{pc}$  the resistance drops continually and the width of the failure crack increases significantly while the widths of the other cracks decrease. The descending branch is similar in nature to that of a strain-softening composite (part III of Fig. 16a). The elongation of the composite up to critical crack localization (at  $\sigma_{pc}$ ) can be translated into strain, while thereafter it translates into crack opening, crack width, or member elongation.

Whether strain-softening or a strain-hardening behavior occurs, the elongation of the composite before crack localization can be translated into tensile strain. However, after localization, the elongation is controlled by the opening of the critical crack. Note that the critical failure crack may not look like a single crack but could be a smeared crack with several branches and micro-cracks surrounding its main path.

In summary, for strain-hardening composites,  $\sigma_{pc} \ge \sigma_{cc}$ , while for strain-softening composites  $\sigma_{pc} < \sigma_{cc}$  (Figs. 15 and 16). The analytical condition to achieve strain-hardening is covered in detail in [1, 24].

**5.5.1 Important Summary:** As observed from the above discussion, the addition of fibers to concrete fundamentally changes the nature of its tensile response. In particular, whether the response is described as strain-softening or strain-hardening, the stress-elongation curves contain elements (Part II and Part III) that, for all practical purposes, either do not exist (Part II), or are considered negligible (Part III) in conventional concretes without fibers. Moreover, in comparing with plain concrete, there is a paramount element that now emerges as a material characteristic, that is some level of ductility or toughness or energy absorption capacity in contrast to extreme brittleness. Note finally that changes in tensile response significantly influence changes in other properties at the material and structural level (Section 2.10).

#### 5.2 Correlation Between Bending and Tensile Response

Figure **17a** describes schematically the bending response of all FRC composites. Numerous possible load-deflection curves are shown. The terminology "deflection-softening" and "deflection-hardening" describing the behavior under bending correlates with the description of the tensile response as shown in Figs. 15 and 16. The general relationship that ties tensile and bending behavior together is illustrated in Fig. 17b. Note that while the tensile response represents a fundamental property of the composite, the bending response (while not fundamental in nature) is related to the most common applications of fiber reinforced cement

and concrete composites. Such a description can provide the basis for a performance specification for the composite and related structural applications. Details on the mechanical conditions leading to either state can be found in [1, 25]. Practically all fiber reinforced cement composites currently available are covered by the simple classification of Fig. 17.b (an extension of Fig. 15) [1, 22 to 27].



Figure 17 (a) Schematic bending response of all FRC composites [1]. (b) Classification of all FRC composites based on their tensile response and implication for bending response of structural elements [*Naaman* and *Reinhardt* [25, 26].

The terminology used in Fig. 17 clearly reflects the very similar qualitative behavior of FRC composites in tension and bending. The shapes of the stress deformation curves and the wording to describe them are very similar. Analytical modeling of bending response from the tensile response also suggests that all strain-hardening FRC composites in tension should lead to deflection-hardening behavior in bending, while strain-softening FRC composites in tension will lead to either deflection-hardening or deflection-softening behavior depending on the fiber reinforcing parameters. The mechanical condition for a tension strain-softening material to lead to a deflection-hardening behavior is expanded upon in [1]. In short, the bending resistance (MOR) after first cracking (LOP) can be shown to be in the range of 2.5 to 3 times the post-cracking strength in tension,  $\sigma_{pc}$  (Fig. 16); equivalently for deflection hardening to start occurring,  $\sigma_{pc}$  needs only to be in the range of 0.33  $\sigma_{cc}$  to 0.4  $\sigma_{cc}$ . As a first approximation, one can thus estimate MOR from a tensile test, or vice-versa,  $\sigma_{pc}$  from a bending test using the following relation:

$$2.5\sigma_{pc} \le MOR \le 3\sigma_{pc}$$
(1)

Deflection-hardening behavior is useful in structural applications where bending prevails, while deflection-softening composites cover a wide range of practical applications starting at the lower end by the control of plastic shrinkage cracking of concrete, to the higher end where they are used in concrete pavements and slabs on grade. Note that, as with other materials, scale and

size effects can be significant, and therefore, the response of very small specimens may not be indicative of the response of real scale structural elements in either tension or bending.

# 6. FIBER-MATRIX REINFORCING EFFECTIVENESS: BASIC APPROACH

In order to better understand the use of fibers in cement based matrices, it is important to keep in mind the key mechanical properties needed from the fibers. Some of the recommendations summarized next will become more easily understood once models to predict the tensile properties of the composite are explained [1].



Figure 18 Desirable fiber versus matrix properties for successful cementitious composites.

By its very definition a reinforcement (i.e., the fiber) is supposed to induce an increase in strength in the material to be reinforced (i.e., the matrix). Both analysis and experimental test results suggest that, in order to be effective in concrete matrices, fibers must preferably have the following qualitative properties (Fig. 18): 1) a tensile strength significantly higher than 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 the matrix; and 3) unless self-stressing is used through fiber reinforcement, an elastic modulus in tension significantly higher than that of the concrete matrix. Moreover, everything else being equal, a ductile fiber under tension is preferable to a brittle fiber, and a ductile or slip-hardening bond-stress versus slip response is preferable to a brittle or slip-softening one. 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.

Figure 18 assumes that the fiber and matrix are chemically compatible (compatibility issues need to be evaluated for each fiber material); steel fibers are likely to corrode due to environmental exposure should they be crossed by a crack in concrete; and glass fibers, unless properly treated, will react with the alkali of the cement matrix. Similar evaluation should be carried out if the FRC structure is to be operating under high temperatures in service.

Given that a normal weight concrete matrix has an elastic modulus in the range of 15 to 50 GPa depending on its compressive strength and numerous other parameters, synthetic fiber materials intended to act as reinforcement for concrete should have not only a high tensile strength but also a relatively high tensile elastic modulus. Thus high end synthetic fibers are more suitable for use in normal weight cement and concrete matrices. Low end fibers, with relatively low elastic modulus, are likely to be more effective in lightweight and very lightweight cement matrices which themselves are characterized by very low values of elastic modulus. Although many synthetic fibers have been used in numerous small scale applications, their large scale adoption (except for the case of plastic shrinkage cracking control) did not materialize so far. Mixing and dispersion difficulties, fire rating resistance, observed performance, and cost are the commonly cited drawbacks.

#### 7. SIMPLE FRC MECHANICS FOR INITIAL DESIGN

In plain concrete a correlation exists between compressive strength ( $f'_c$ ) and tensile, bending, and shear strength, {such as  $3\sqrt{f'_c}$ ,  $7.5\sqrt{f'_c}$ , and  $2\sqrt{f'_c}$  in psi units}, respectively; even the elastic modulus can be related to the compressive strength,  $f'_c$ .

The most evident observation to the addition of fiber to concrete subjected to tensile loading is the appearance of some ductility or post-cracking resistance after initial cracking.

It is shown in [1] that the tensile, compression, bending and shear response of an FRC composite are strongly correlated; in effect the tensile response sets the tone for the rest A key equation which predicts the post-cracking tensile strength of an FRC composite is reproduced in Fig. 19.



Figure 19 Simple relationship to consider when optimizing the performance of FRC in tension, bending, shear and compression.

The parameters of Fig. 19 allow for the pre-selection of a suitable fiber for a given concrete matrix, with the objective to improve the chances of success of the composite. These parameters are paramount in controlling the mechanical properties of the composite. They are the fiber aspect ratio, L/d, that is, the length of the fiber over its diameter or equivalent diameter; the fiber volume fraction,  $V_f$ , that is, the volume of fiber per unit volume of composite; the bond at the fiber matrix interface,  $\tau$ ; and their product. The aspect ratio is particularly useful for fibers of circular cross-section or substantially circular ones for which an equivalent diameter can be derived by setting the area of the actual fiber equal to that of an equivalent circular fiber. If the fiber is of significantly different shape, its lateral surface area is critical since it represents the bonded area between fiber and matrix; a shown in Fig. 19 the aspect ratio is then replaced by the quantity  $0.25 \times \psi L / A_f$ , where  $\psi$  is the perimeter and  $A_f$ is the cross-sectional area of the fiber. The bond is a very complex property covered in more details in Chapter 13 of Ref. [1], and encompasses the effects of adhesion, friction, mechanical anchorage and fiber to fiber interlock. The product of the three parameters,  $\tau \times V_f \times \frac{L}{d}$ , is present in predicting the post-cracking tensile strength of the composite, its bending resistance, and its surface energy; and since both shear and compression response strongly correlate with

tensile response, it can be easily said that most mechanical properties are likely to improve with an increase in the product  $\tau \times V_f \times \frac{L}{d}$ . In Fig. 19,  $\Lambda$  is a coefficient which is the product of several other coefficients detailed in [1].

Some other parameters also influence the key mechanical properties and relate to the number of fibers per unit volume of composite, the number of fibers crossing a unit area, and the specific surface of fiber reinforcement, but are related to the parameters of Fig. 19.

Since fibers are assumed to be randomly oriented and distributed, their contribution to the composite is also significantly influenced by the statistical nature of the variables involved and the size of the specimen. While all prediction equations are derived assuming deterministic models, real life situations involve random variables, and thus the designer must expect and account for the increased variability inherent in these systems.

# 8. FRC VERSUS OTHER FIBER REINFORCED COMPOSITES: FUNDAMENTAL DIFFERENCE

Fiber reinforced composites occupy a very important role in the field of engineering materials encompassing all areas of applications such as civil, mechanical, manufacturing, naval, aeronautics and aerospace engineering. Most widely used fiber reinforced composites are identified according to the matrix they use: polymer or plastic composites, metal composites, ceramic composites, and cementitious composites. Figure 2 illustrates how fiber reinforced concrete fits within the general family of reinforced cement-based composites. Figure 20 offers a visual flow chart of how FRC composites fit within the general family of fiber reinforced composites can be grouped according to their matrix's ductility, namely: 1) brittle matrix composites, or 2) ductile matrix composites. This last category is addressed broadly in the technical literature and its treatment can serve as an excellent background to, and extension for the treatment of brittle matrix composites.



Figure 20 The two major classes of fiber reinforced composites for modeling purposes based on their matrices: brittle or ductile.

Fiber reinforced polymer and metallic composites typically use matrices with a tensile strain at failure much larger than that of the fiber and a tensile strength significantly smaller than that of the fiber. Examples of matrices include epoxy resins, bismaleimides (BMI), and polyesters; they are generally identified as either thermo-set or thermo-plastic polymers. Fibers used in industrial and aerospace applications are primarily made of manufactured fibers embedded in various polymeric matrices of epoxy, vinyl-ester and the like. The fibers are generally characterized by high tensile strength and a relatively high stiffness such as glass, carbon, aramid (Kevlar), or ultra-high molecular weight polyethylene (Spectra). Hence, failure of the composite implies either failure of the fibers, or their complete debonding while the matrix may be in a yielding state.

Metallic matrix composites include aluminum, magnesium and titanium matrices with carbon, silicon-carbide, boron, and alumina whiskers. They are considered ductile matrix composites. Ceramic composites which are particularly designed for high temperature applications are considered to belong to brittle matrix composites; they often use the same basic material for fiber and matrix but in different forms, such as carbon and graphene or graphite whiskers.

# 9. CONCLUDING REMARK

Two time periods mark the history of fiber reinforced concrete. The pioneering period started in 1874 and claimed strengthening of concrete (in tension or bending) by addition of fibers; but that claim could not be confirmed by test results. Thus the first period saw little progress for almost a century and can be described as technically dormant. The modern period started in the 1960's whereas initial attention focused on the claim that fibers increase the fracture energy of the composite. This drew enormous interest from the technical profession. Fundamental studies and research led to a better understanding of the effect of fibers on energy absorption capacity and all other properties, eventually leading to the development of FRC composites with tensile and bending resistance higher than those of the matrix. It also led to a simple classification of all FRC composites based on their tensile response leading to the qualifiers: "strain-softening"

or "strain-hardening", and consequently "deflection-softening" or "deflection-hardening." With the increasing penetration of ultra-high performance concrete (UHPC) and fiber reinforced concrete (UHP-FRC) and the introduction of enhanced fiber materials, progress will continue. "The engineering dream and challenge that started in the 1870's, that is, to mix fibers into concrete like sand or aggregates to create an isotropic, homogeneous, moldable, strong, ductile and durable composite for construction applications with comparable strength and ductility as reinforced concrete, is today closer than ever" [1].

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