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Fiber-reinforced Concrete: an Overview after 30 Years of Development

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Abstract

This paper presents a rhetorical discussion on the subject of fiber-reinforced concrete, FRC. It is intended as an overview of the types of commercially available FRCs and how they work. It discusses commonly applied terminology and models of mechanical behavior that form a basis for understanding material performance without presenting mathematical details. Historical review is intended to help build a background for what is currently understood about FRC rather than as historical reporting. References from both early and contemporary authors are included as a means of tying the subject together along a time line. © 1997 Elsevier Science Ltd.

Keywords: Fiber reinforced concrete, fibers for, mechanics of, concrete mechanics, fiber concrete testing, strength, toughness, energy absorption.

INTRODUCTION

The term fiber-reinforced concrete (FRC) is defined by ACI 116R, Cement and Concrete Terminology, as concrete containing dispersed randomly oriented fibers. Over 30 years have passed since the initiation of the modern era of research and development on fiber-reinforced concrete. In the early 1960s Romualdi, Batson, and Mandel published the papers[1,2] that brought FRC to the attention of academic and industry research scientists around the world. The writer can report that at that time there was a strong sense of discovery and an air of excitement regarding the promise that FRC held for the future development of composite materials based on Portland cement concrete. However, few if any of that era accurately envisioned the magnitude of the impact that FRC would have on research and commercial development communities world-wide.

In the ensuing three decades, thousands of scientific papers have been published on the subject. Large numbers of individuals have worked their way through academic degree requirements at all levels, Bachelors, Masters and Doctoral, conducting research and contributing to the development of FRC. Assessment of the number of local seminars, regional symposia and international conferences still held each year and throughout the world provides evidence that there remains a high level of interest in FRC development. Such educational programs serve the dual purpose of fostering understanding of FRC as a material of construction and transferring the fruits of research into commercial enterprise.

SCOPE OF DISCUSSION

Intending to be as brief as is consistent with the goals of the presentation, the discussion is divided into four parts: Fiber-reinforced Portland cement concrete composite technology, Mechanics of behavior, Testing and performance evaluation, and Value-added applications.

The breadth of FRC formulations and applications makes clear the fact that consideration of either the mechanics of behavior or the performance of FRC in a strictly generic sense, ie. fibers in concrete, is an unproductive over-simplification. Instead it is necessary to establish subcategories within the generic concept of FRC and to establish associated terminologies. A discussion of the diverse formulations of

FRC and associated terminology constitutes the section 3 of this presentation.

Even while stressing the differences among types of FRC, both contemporary and historical thinking on the subject point to a somewhat unified, if not singular, notion as to how fibers act to improve the performance of brittle-matrix Portland cement concrete. Accordingly, the discussion seeks to integrate seemingly diverse FRC historical developments as a basis for understanding the mechanical behavior.

Much of the discussion incorporates what has been reported in published state-of-the-art reports,[3,4] books,[5–7] and special publications which are available world-wide. However, the discussion also contains concepts and a point of view based on experience through long association with the subject, especially on the matter of performance testing and evaluation.

Finally, the section on applications is not intended to be exhaustive but selected applications are included as a means of demonstrating the utility of applying the energy concepts of the previous discussion. A complete compilation of potential applications is left to the imagination of the reader.

FIBER-REINFORCED PORTLAND CEMENT CONCRETE COMPOSITE TECHNOLOGY

Terminology

The character and performance of FRC changes with varying concrete *binder* formulation as well as the fiber *material* type, fiber *geometry*, fiber *distribution*, fiber *orientation* and fiber *concentration*. Correspondingly, it is expected that more than one mechanical behavior theory could aptly model the performance of a particular FRC formulation. Likewise, while the phrase FRC is useful generic terminology, most often these materials do not permit simple generic descriptions when seeking to determine material properties needed for engineering analysis and design.

The following terminology has been widely accepted as being useful when describing the great variety of FRC composites.

Fiber materials

According to terminology adopted by the American Concrete Institute (ACI) Committee 544, Fiber Reinforced Concrete, there are four categories of FRC based on fiber material type. These are SFRC, for steel fiber FRC; GFRC, for glass fiber FRC; SNFRC, for synthetic fiber FRC including carbon fibers; and NFRC, for natural fiber FRC.

Table 1 lists the materials and properties of fibers which are currently commercially available to FRC production.

Fiber geometry

Individual fibers are produced in an almost limitless variety of geometric forms including

Table 1. Selected fiber types and properties

*Fiber type**	*Equivalent diameter ($in \times 10^{-3}$)*	*Specific gravity*	*Tensile strength (ksi)*	*Elastic modulus (ksi)*
Acrylic	0.5–4.1	1.16–1.18	39–145	2000–2800
Aramid I	0.47	1.44	425	9000
Aramid II	0.40	1.44	340	17000
Carbon I	0.30	1.9	250	55100
Carbon II	0.35	1.9	380	33400
Nylon	0.90	1.14	140	750
Polyester	0.78	1.34–1.39	33–160	2500
Polyethylene	1.0–40.0	0.92–0.96	11–85	725–17000
Polypropylene	—	0.90–0.91	20–100	500–700
Alkali-resistant	—	2.7–2.74	355–360	11400–11600
Non alkali-resistant	—	2.46–2.54	450–500	9400–10400
Coconut	4–16	1.12–1.15	17.4–29.0	2750–3770
Sisal	—	—	40–82.4	1880–3770
Bagasse	8–16	1.2–1.3	26.65–42.0	2175–2750

*Listed fiber types include synthetic, glass and natural fiber varieties. Steel fiber types and properties are governed by ASTM A820. Not all types of synthetic fibers are currently used for commercial production of FRC.
1 in = 25.4 mm; 1 ksi = 6.895 MPa.

Prismatic: rounded or polygon cross-section with smooth surface or deformed throughout or only at the ends.

Irregular cross-section: cross-section varies along the length of the fiber.

Collated: multifilament (alternatively termed branching or fibrillated) or monofilament networks (or bundles) that are usually designed to separate during FRC production (mixing).

Present concrete mixing and placing technologies include:

batch mixing and placing,
pneumatic placement,
slip forming (moving-form extrusion),
extrusion (through a stationary die),
slurry infiltration, and
sheet production with or without vacuum or pressure forming.

Specific production techniques allow almost any fiber geometry and a wide range of fiber amount, usually specified as a volume percent of the total composite, to be placed.

Equivalent diameter

For fibers that are not circular and prismatic in cross-section, it is useful to determine what would be the diameter of an individual fiber if its actual cross-section were formed as a prismatic circular cross- section. The equivalent diameter of a fiber is the diameter of the circle having the same area as that of the average cross-sectional area of an actual fiber.

Relatively small equivalent diameter fibers have correspondingly low flexural stiffness and thus have a certain ability to conform to the shape of the space they occupy in the paste phase of the concrete mixture in between aggregate particles. Relatively large equivalent diameter fibers have greater flexural stiffness and will have a correspondingly greater effect on consolidation of aggregates during the process of mixing and placement.

Fiber aspect ratio

The fiber aspect ratio is a measure of the slenderness of individual fibers. It is computed as fiber length divided by the equivalent fiber diameter for an individual fiber. Fibers for FRC can have an aspect ratio varying from approximately 40 to 1000 but typically less than 300. This parameter is also a measure of fiber stiffness and will affect mixing and placing.

Fiber denier

Principally when discussing SNFRC, the term fiber denier (or just denier) is often used. This is terminology that evolved from the textiles industry. The denier of a fiber is defined as the weight, in grams, of 9000 metres of fiber. Fiber denier is mathematically related to equivalent diameter for individual fibers if the specific gravity of the fiber material is known. This is presented in the following equation:

$$d = f\left(\frac{D}{SG}\right)^{1/2}$$

where:

d equivalent diameter
f 0.0120 for d in millimetres,
f 0.0005 for d in inches,
D fiber denier, and
SG fiber specific gravity.

The nomograph of Fig. 1 is a useful graphical tool for conversion between fiber denier and equivalent diameter.

Pre- and post-mix denier

The terms pre-mix denier and post-mix denier are sometimes necessary in material specifications to reflect the fact that the form of the fiber may change from the time that the fibers are added to a particular concrete mixture until the time that they become dispersed within the mixture. This applies to collated or bundled fiber products of all material types. For

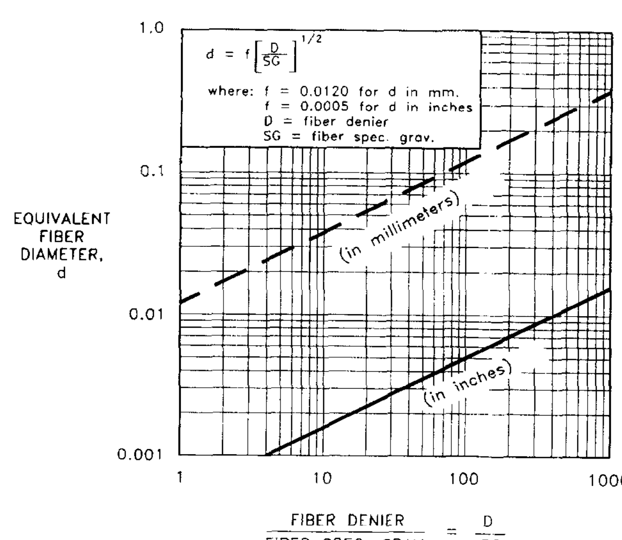

Fig. 1. Fiber diameter vs denier relationship.

example, some synthetic, glass, natural or steel fibers are introduced to concrete mixtures either as rovings (bundles), or as collated (loosely connected) fibers. Thus fiber denier will be different for bundled or collated (pre-mix) fibers than for the individual fibers (post-mix). When the mixing process is sufficient to break up fiber bundles, by mechanical shear action or by dissolution chemistry, then it is the post-mix fiber denier that should be applied to calculations involving the number and distribution of fibers within a particular mixture.

Strength and toughness

Strength and toughness are generic terminology useful only when precisely defined and determined. As regards FRC, no single definition is universally accepted. Furthermore, consensus on a definition does not appear to be forthcoming and in fact may not be necessary. If strength is considered a stress capacity, and toughness an energy capacity, then when and how these are measured must be specified.

Strength and toughness measurements are affected by the particular testing machinery and measurement devices employed, and by the size and shape of test specimens. As it is generally accepted that the principal benefit of fibrous reinforcement relates to tensile stress and strain capacities, cracking and crack propagation are the failure events most often used in strength and toughness definitions. But these events cannot themselves be precisely determined, which makes comparison of test results among testing laboratories problematic. Nevertheless, strength and toughness, both in pre- and post-cracking regimes of performance, are the parameters best suited for establishing design criteria for FRC.

Precise determination of strength and toughness, however specified, generally requires sophisticated and costly testing procedures. Such procedures are thought to be more applicable to R&D efforts than they are to production and quality control testing. Measurements which are generally required for engineering design and specification or for quality control should be obtained with less effort. Test methods which integrate over the imprecisely defined events that make testing problematic, such as cracking, are under development and are discussed later in this text.

The binder (matrix) component

The matrix material applicable to this discussion is ordinary Portland cement concrete. However, other brittle cement types have been used as a host matrix for special applications.

Matrix materials suitable for refractory applications contain high-alumina cement and utilize special mineralogy and mixing processes.[8] FRC refractory precast has enjoyed widespread industrial acceptance.

Early work on extruded FRC,[9] a pressure forming process, as well as more recent research[10] into this production technique, used mineral additives to assist in preventing dewatering and segregation during the pressure forming process. Provided there is ample fiber strength and ductility, FRC performance is generally enhanced by pressure forming production processes thus confirming theories of increased fiber efficiency through enhanced fiber-to-matrix bonding.

Portland cement concrete with only bubble voids and fiber as the aggregate phase is termed fiber-reinforced cellular concrete (FRCC). Cellular concrete is produced in two ways, either by utilizing foaming agents or by a process using chemical and mineral additives to achieve a volume expansion within the matrix. In this form the matrix is relatively weak and brittle. The latter system of FRCC is commercially available utilizing polypropylene synthetic fibers.[11,12] FRCC is a relatively lightweight concrete, about 40 lb/ft^3 (640 kg/m^3), having suitable and reliable strength and toughness properties for many applications.

To summarize as regards the matrix materials currently used for FRC, the composite matrix material is based on Portland cement and is always brittle. Fibers are added to inhibit cracking, control the brittle fracture process, provide reliable post-cracking strength and, by virtue of the post-cracking strength and deformation behavior, provide post-cracking toughness as well.

Regimes of fiber content

The concentration of fiber within a given unit volume of FRC ranges from high to low relative to the total volume of concrete produced. It is useful to classify FRC on the basis of fiber concentration (volume percentage) as this one factor is seen to significantly affect mixing, plac-

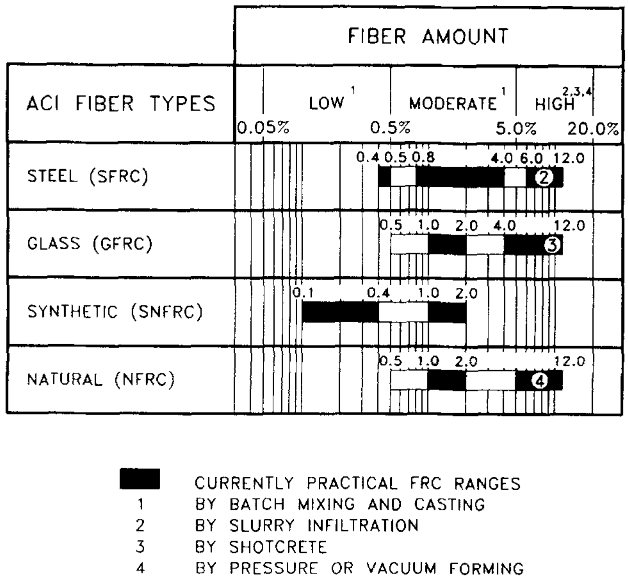

Fig. 2. Fiber types and amount used by volume per cent of matrix.

ing, and hardened concrete performance, as much as any other single factor. Volume percentage may be considered high if in the range 3 to 12%, moderate if in the range 1 to 3%, and low if in the range 0.1 to 1.0%, based on the total volume of the concrete produced.

Fiber concentration affects the choice of FRC production technology. Figure 2 provides a summary of the basic fiber types, their ranges of commercial application, including the low,[13] moderate, and high[14] regimes, and the associated production technologies. Notice that the low range of fiber addition is apparently well suited for batch mix preparation using conventional mixing equipment and drop placement. Higher fiber concentrations often require special mixing or placing techniques.

Fiber parameters relating to geometry

Fiber parameters that relate to fiber geometry can be used[15] in evaluating fiber effectiveness. Specifically, the number of fibers within a unit volume of concrete, the surface area of fibers in a unit volume of concrete, and the cross-sectional area of fibers across a given plane of an FRC volume, appear to be the most relevant.

Assume for the moment that the presence of fibers influences fracture energy requirements during crack propagation. Then, for any cause of damage, the probability that a crack will extend to reach critical size initiating unstable failure will depend in some way on the fiber spacing, which is related to the packing density.

Likewise, the notion that cracks which encounter fibers will consume energy depending upon how the crack progresses through or around fibers is related to both the number of fibers encountered and the surface area of these fibers. Energy-absorbing mechanisms, debonding and pull-out being two examples, depend on the surface area of the affected fibers.

Lastly, the ability of fibers to transfer stress across a crack will depend on the cross-sectional area of fibers within the crack plane as well as on the elastic properties and bond characteristics of the fibers. Therefore, the fiber count (*FC*), fiber specific surface (*FSS*), and reinforcement area are of particular interest.

Fiber count and specific surface

Fiber count (*FC*) and fiber specific surface (*FSS*) are the number of fibers in a unit volume of FRC and the surface area of fiber in a unit volume of FRC, respectively.

Consider the mass of an FRC composite strictly on a volume basis. The total volume of fiber in any given unit of volume of composite, i.e. the volume fraction (or percentage if multiplied by 100), may consist of only one single (large) fiber or it may be any number of smaller individual fibers. Thus, for any given fiber volume, the number of fibers depends on the individual fiber volume. In any case, large or small numbers of fibers, the fibers are necessarily located and distributed within the paste or binder phase of the composite. The actual number of fibers in a unit of volume of the composite, *FC*, may be computed from any one of the following expressions:

$$FC = \left[\frac{7.5 \times DRT \times 10^{-4}}{l \times d^2 \times SG}\right]$$

$$= \left[\frac{1.27 \times V}{l \times d^2}\right] = \left[\frac{3.0 \times DRT \times 10^3}{l \times PoMD}\right]$$

$$= \left[\frac{5.08 \times V \times SG \times 10^6}{l \times PoMD}\right]$$

where:

V	total fiber volume percentage/100,
l	fiber length (in inches),
d	fiber equivalent diameter (in inches),
SG	specific gravity of the fiber material,
DRT	fiber dosage rate (lb/yd^3), and

PoMD post-mix denier.

Multiplying the *FC* by the surface area of a characteristic individual fiber gives the fiber specific surface, *FSS*, in the unit volume of composite. Then:

$$FSS = FC \times \pi \times d \times L$$

Alternatively, *FSS* may be computed directly from any of the following expressions:

$$FSS = \left[\frac{2.36 \times DRT \times 10^{-3}}{d \times SG}\right] = \left[\frac{4 \times V}{d}\right]$$

$$= \left[\frac{4.71 \times DRT}{(PoMD \times SG)^{1/2}}\right]$$

$$= \left[\frac{8 \times V \times (SG)^{1/2} \times 10^3}{(PoMD)^{1/2}}\right]$$

The nomograph of Fig. 3 is useful to determine *FC* and *FSS* for fibers of specific equivalent diameter and fiber volume (diameter and length). To use the chart enter the volume percentage of fiber at the bottom, proceed vertically upwards to a chosen fiber equivalent diameter, turn to the left-hand scale and find

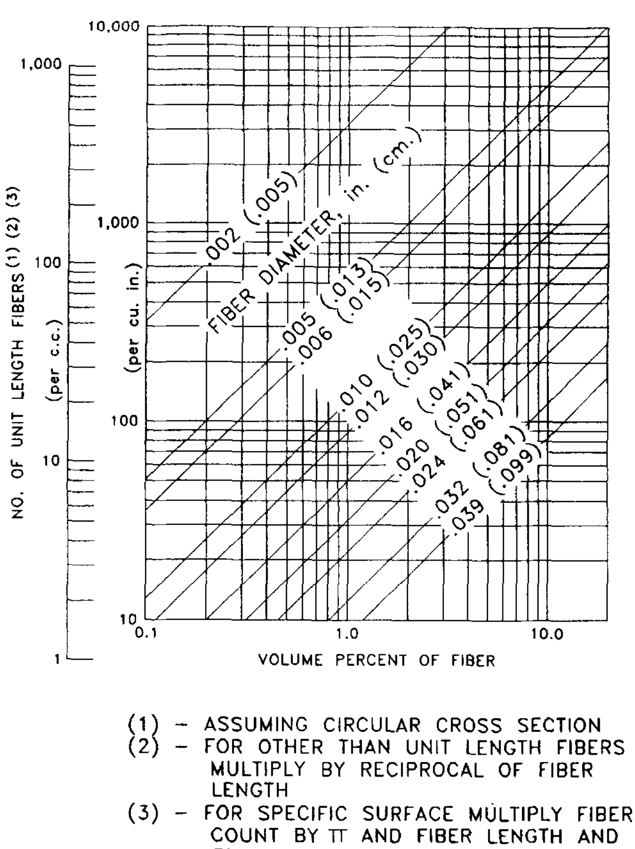

Fig. 3. Fiber count and specific surface as a function of fiber volume and geometry.

FC, and by multiplying *FC* by π, d and L, find *FSS*. The results are for a unit length of fiber. For other than unit-length fibers divide the result by the actual fiber length.

Inasmuch as the fibers must reside in the paste phase of the composite, there are trade-offs that can affect FRC performance in the plastic (mixing and placing) production process as well as in the hardened state. The ability of fibers to either conform to or displace aggregate particles is expected to be greatest in the case of coarse-diameter, relatively stiff and long fibers and less in the case of fine-diameter, flexible and short fibers which are better able to conform to the aggregate packing density and shape.

Reinforcement area

It is often desirable to determine the actual cross-sectional area of fiber that cuts across any plane of an FRC composite containing a random distribution of fibers. This is the reinforcement area, equivalent to A_s in a conventional steel-reinforced concrete beam.

Recognize that the desired cross-sectional area is a planar or two-dimensional concept and that, for uniformly distributed fibers within a unit volume of concrete, many fibers will not penetrate a random single plane. The implication is that the computation of reinforcement area is affected by the length of individual fibers.

For example, for any system of units chosen, if the actual fiber length is one half of the dimension of the side of the unit of volume of concrete which is the depth dimension, and if the fibers are assumed for the moment to be in perfect (most favorable) alignment as reinforcement (perpendicular to an intersecting plane), then exactly two fibers would have to be placed butt end to end to obtain a uniform distribution throughout the volume. Any plane cut through the volume would necessarily intersect only 1/2 the total number of fibers in the volume.

Now add the fact that the fibers are not normally perfectly aligned but can be assumed to be randomly oriented. A number of authors[2,16–20] have proposed factors to be applied when determining the effective cross-section of fibers in a single plane when considering orientation effects. One such recommendation[20] is 54%, indicating that the individual fiber cross-sectional area is only 54%

effective given random orientation in comparison with the most favorable alignment.

Incorporating all of those factors which influence reinforcement area discussed above, the expression that provides the cross-sectional area of a random distribution of fiber depends only upon the orientation factor, the volume fraction of fiber, and the area of the plane of concrete for which the reinforcement area is required. Thus the total cross-sectional area of randomly distributed and oriented fibers intersecting a plane through a volume of FRC, A_{fx}, is given as follows. Letting:

V_f = volume fraction of fibers in the concrete,

FC = fiber count, total number of fibers in the volume,

l_f = characteristic length of the individual fiber,

a_f = cross-sectional area of an individual fiber,

l_c, w_c, h_c = length, width and height of the concrete volume, respectively,

then

$$V_f = (FC \times l_f \times a_f)/(l_c \times w_c \times h_c)$$

Solving for a_f:

$$a_f = (V_f \times l_c \times w_c \times h_c)/(FC \times l_f)$$

But the total area of all fibers in the volume, A_f, is:

$$A_f = FC \times a_f = (V_f \times l_c \times w_c \times h_c/l_f)$$

Now, the total area of fibers in a volume of depth l_c is related to the total area of fibers crossing any single plane through the volume by the relation:

$$A_{fx} = A_f(l_f/l_c)$$

Therefore

$$A_{fx} = V_f \times w_c \times h_c$$

or, including the effects of random orientation,

$$A_{fx} = 0.54 \times V_f \times w_c \times h_c$$

The resulting units for A_{fx} are in the dimensional units of the area of concrete intersected by the plane; the units of $w_c \times h_c$.

For example, for 0.1 vol% of fiber, in a 1 foot width of 4 inch FRC slab, the total area of fiber crossing any single plane is:

$$A_{fx} = 0.54 \times (0.1/100) \times 12 \times 4 = 0.026\ in^2$$

MECHANICAL BEHAVIOR MODELS FOR FRC

Most often energy theories are only indirectly considered by design engineers. This may be due to valid criticism based on mathematical difficulties. However, qualitative application of energy concepts are useful in relation to modeling FRC behavior. By doing so the analyst can relate energy concepts to the more familiar classical methods of mechanics such as are applied in the analysis of conventional reinforced concrete.

Historical analytical development

The development of FRC that began three decades ago was not based on the traditional concept of reinforced concrete. It was based on a fracture mechanics concept whereby the strength of a brittle Portland cement concrete could be improved by reinforcing the matrix with closely spaced continuous wires.[1] The operative term was closely spaced. There was evidence that the improvement in strength of a filament-reinforced composite disappeared as the filament spacing increased. Initial tests were based on closely spaced continuous wire filament but further testing using discrete fibers produced the same result: no strength improvement with increased spacing.[2]

Fibers suitable for testing purposes, first steel and soon after polypropylene, were not readily available in the early stages of research. Sources were identified from diverse industries including the automobile tire manufacturing and textile industries. FRC was produced and laboratory experiments were conducted but there was little that could be done to control or vary the fiber geometry component of the concrete.

The first fibers tested were relatively coarse, 6 to 10 mil (0.15 to 0.25mm) diameter, and were thus relatively stiff. Mixing and casting problems were evident. Coarse, stiff fibers could not conveniently, and sometimes not even inconveniently, be distributed in a batch mix concrete such that there would result a čclose enough spacing' of distributed fiber to produce the desired improvement in composite strength as fracture mechanics would predict. However, when suitable mixtures could be made in the laboratory, a statistically significant improvement in strength was found in both the pre- and post-cracking behavior of the composite.

The inability to conveniently, and thus economically, produce high fiber concentration FRC in field applications diverted the interest of researchers away from attempts to improve the initial cracking strength of FRC. At this time research took a detour towards a concentration on post-cracking behavior. In retrospect this was a turning point that actually delayed the development of FRC.

Since the middle of the 1980s many new fiber types and fiber geometries have been introduced. These have significantly altered FRC production techniques and have affected FRC strength and toughness (crack control) performance measures. Readily available FRC component materials, new admixtures, and new production techniques have each had favorable effect on the fiber concentrations that can be achieved in field applications as well as on fiber bond efficiency; two factors which are known to greatly influence mechanical behavior. As a result of technological development, materials designers and suppliers are now readily able to economically produce and specify a broad range of FRC formulations.

Reinforcing and strain energy dispersion

Just how do fibers affect FRC performance? With early emphasis on post-cracking behavior, which recall resulted from the inability to economically produce FRC with suitable fiber concentrations, the well-known concepts of reinforced concrete based in engineering strength of materials (SOM) were applied. These procedures require cracked sections and a relatively high modular ratio between reinforcing materials and the reinforced matrix. The following discussion is intended to show how SOM and the application of conventional reinforced concrete analytical methods alone is an over-simplification of the behavior of FRC.

SOM does not consider the important contribution of fibrous reinforcement in energy absorption during crack growth. Recall history once again. The earliest fibers tested were coarse steel, glass and synthetic fibers. They were all relatively large diameter, relatively stiff fibers[21] in the flexural sense. This caused mixing and placing problems especially when higher fiber concentrations were used. These problems pre-empted reaching the goal of achieving a desired close fiber spacing. In addition, coarse fibers of synthetic geneses were generally ineffective for other than high load-rate applications and glass fibers had problems associated with durability given the rigors of batch mixing and the effect of chemical alkaline attack.

An example of how much influence historical precedent had in directing FRC development was the attention given to the use of even coarser steel fibers. Precedent required relatively high fiber concentration (volume per cent) in order to obtain useful post-cracking strength and toughness levels but high fiber concentrations presented mixing and placing problems. Conventional wisdom said that relatively high fiber volumes could be maintained by using even larger (coarser) fibers, which of course reduces the fiber count and thus increases even further the fiber spacing. Research was going in exactly the wrong direction.

A fiber geometry similar to that of steel nails of approximately 2 in (50 mm) length were applied. This allowed field production of FRC without significant mixing and placement problems but with significantly fewer fibers within a unit volume of composite, a corresponding reduction of the fiber specific surface, and even greater theoretical average fiber spacing resulted.

The fiber spacing misnomer

The phrase 'close enough' as it refers to the spacing of fibers needs to be examined. The phrase is most naturally understood according to its literal implied spatial reference. While the fiber spacing concept was at the root of early FRC development, strict reference to spacing in its literal meaning is an over-simplification and somewhat misleading.

The term 'close enough spacing' is a misnomer because is does not consider factors affecting fiber efficiency other than fiber spacing. Close enough spacing for FRC in a broader interpretation is that which is required to guarantee that a propagating crack is affected so as to be stopped or at least slowed in its advancement. Close enough spacing includes the probability that further energy input to the composite system will either be absorbed or redirected to areas of lesser fracture toughness.[22] This behavior is truly a form of matrix strengthening. The matrix itself continues to conduct the load (stress) while on the ascending (strain hardening) or the descending (strain softening) portions of the material's load/deflection response.

The crack arrest mechanism for FRC is similar to the manner in which aggregate fillers absorb energy and are known to arrest microcracks in concrete. It appears, however, that benefits attributable to fibers accrue to the brittle matrix in amounts exceeding that which is predicted by the law of mixtures. In addition to a fiber's strength and elastic properties, improved fiber efficiency is related to bond or anchorage and the potential for energy absorption through the accumulated effect of the number of fibers, their specific surface, and their orientation within the matrix.

The number of fibers in a unit volume of matrix material, i.e. the fiber count, *FC*, is directly related to the statistical probability of cracks encountering fibers. The fiber specific surface, *FSS*, is directly related to the amount of energy that is absorbed in encounters between cracks and fibers. In this way weak brittle matrices can be improved, some would say strengthened, to provide a measure of post-cracking toughness. The same is true for strong brittle matrices but in that case the fibers have to achieve even greater fiber efficiency through strength, bond, stiffness, orientation and numbers, in order to counter the effect of increased amounts of stored elastic strain energy that is released and made available to drive cracks at failure.

The schematic diagram of Fig. 4 demonstrates the ways in which fibers act to absorb energy and control crack growth. Starting from the leftmost fiber element in the figure and proceeding along the crack towards the right there is represented fiber rupture, fiber pull-out, fiber bridging by tension through the fiber, and debonding at the fiber/matrix interface, respectively. These mechanisms do not depend on fiber spacing and they are effective, albeit in insignificantly small amounts, even for a single fiber. It is the cumulative effect, however, of large numbers of fibers located in the restricted topography of the brittle paste phase of the typical concrete composite that has been shown to be significant.

Fracture mechanics vs strength of materials

Evidently there are at least two theoretical approaches to modeling FRC mechanics: the conventional reinforcement theory related to

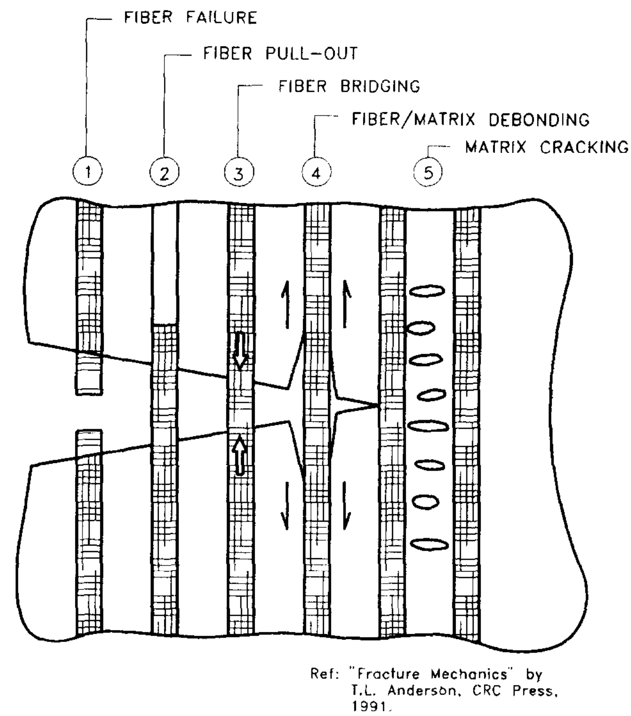

Fig. 4. Energy-absorbing fiber/matrix mechanisms.

strength of materials (SOM), and a crack arrest energy-absorption approach related to fracture mechanics (FM). The relative degree of importance given to either theory may depend on the specific formulation and technique used for the production of the FRC as well as the application. However, experience suggests that too little emphasis is given the energy-absorbing characteristics of FRC and that this performance benefit is under-utilized.

FRC matrix design, maturity and production considerations

In the case of immature concrete the favorable modular ratio required by SOM will exist even for relatively low modulus fiber types. Furthermore, at later ages when cracks appear or extend for whatever reason, the modulus within the crack is effectively zero and crack opening is resisted by the transfer of stress through the fiber for any fiber material used provided that (1) there is adequate bond or anchorage of the fiber reinforcement, and (2) there is adequate opportunity for the fibers to participate in the process, i.e. an adequate concentration of fiber. Attention should also be given to taking care that mixing and placement processes[23] ensure that the particular fiber used will not adversely affect composite fracture toughness by becoming matrix-disruptive. The use of coarse, stiff fiber may require adjustment in the aggregate mix design to minimize this effect.

Qualitative summary of FRC behavioral mechanics

The chart shown in Fig. 5 summarizes the theoretical bases for the two theoretical approaches, i.e. strength of materials and fracture mechanics, as they apply to FRC mechanics.

TESTING AND PERFORMANCE EVALUATION

Standards development

The development of standards as regards FRC has been guided by contributions from individuals and organizations through the professional societies. The American Concrete Institute (ACI) and the American Society for Testing and Materials (ASTM) in North America, and their counterparts on other continents such as the International Union of Testing and Research Laboratories for Materials and Structures (RILEM) or the International Organization for Standardization (ISO), have led in the information exchange process. The influence of standards publishing organizations in shaping model codes and engineering specifications as a means of gaining acceptance in the stream of commerce as a material of construction, is generally readily appreciated. However, it is worthwhile to take another brief look at history to gage the progress of standards development as regards FRC.

The history of the development of FRC through the ACI Committee 544 began in about 1970. This group has been instrumental in reporting the state-of-the-art on the subject and their educational mission is evidenced by the list of publications and symposium sponsorship.

Suited to their function, ASTM has recognized the interest in commercial utilization of FRC and has responded with a number of standards regarding test methods for performance evaluation, primarily through its Committee C09.42.

Progress through consensus organizations such as ACI and ASTM is sometimes made difficult by divergent commercial interests. While delay in the progress of standards development is not always an unwelcome outcome, history demonstrates how research development has been diverted along non-productive paths apparently creating useless delay. As an example consider the historical development of testing standards.

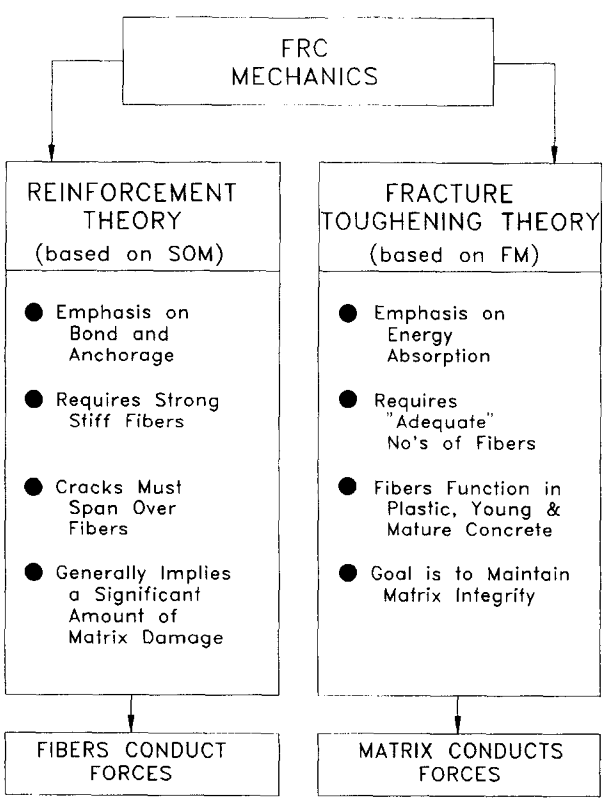

Fig. 5. Summary of mechanical behavior of FRC.

Testing for flexural strength and toughness

Attempts to quantify the toughness of FRC using energy concepts related to the area under a stress/strain diagram have been numerous.[24–26] Criticism of these methods generally comes from one of two directions: relevance in representing material performance and difficulty of application.[27,28] For example, critics have argued that the current ASTM C1018 standard, which discusses measurement and use of strength and toughness performance indicators, suffers from indexing characteristic performance measurements to ill-defined cracking events requiring the use of elaborate test equipment and sophisticated test technicians which are not commonly or economically available within the construction industry.

More recent research demonstrates simpler testing and performance evaluation techniques[29] which seek to avoid the complexities associated with the post-cracking performance evaluation procedures as described in ASTM C1018. These methods are, at present, termed post-peak testing methods and are working their way through the process of review and approval. The reader may wish to become aware of the deliberations of ACI 544 and ASTM C09.42 for more details.

Post-peak testing is concerned only with the post-cracking range of performance of FRC as characterized by measures termed the residual strength of the material. Some high-performance FRC composites exhibit substantial strain hardening, i.e. increase in strength in a strain softening regime of behavior, and these are yet to be considered in relation to post-peak testing. However, for the low and moderate ranges of fiber additions which are most common to current commercial batch cast and pneumatically applied FRC production, the cracking event is usually well exhibited as a single critical crack and reliable post-cracking strength is found beyond that point. Thus for FRC in which macro crack redistribution is not found, reliable post-cracking residual strength is a measure of material performance which is most useful for design and analysis with FRC. Although the concept has thus far only been developed for the flexural testing, similar performance has been demonstrated in other test configurations such as direct tension and shear.

Briefly, post-peak testing recognizes the fact that, with the possible exception of high-performance formulations, FRC most generally produces little influence on strength, when defined as the maximum stress at the time of failure, beyond that of the plain unreinforced matrix. Failure in this context generally occurs after a sample has been caused to exhibit a substantial matrix crack. But the cracking event, sometimes erroneously termed the first crack, is itself difficult to define and associated measurements are sensitive to the specific type of testing equipment and apparatus used. The post-peak test accomplishes the failure event without the need for a corresponding measurement and with some degree of control. Thereafter, measurements of residual strength at post-peak deformations are a demonstration of the effect of the fiber reinforcement.

The test begins by loading the specimen with a parallel loading of a relatively stiff elastic element as a means of controlling the sudden release of elastic strain energy that is available to extend damage to the specimen at the time of failure. In the case of the flexure test, this is accomplished by having a steel plate loaded in parallel with the FRC specimen until such time as the system fails by cracking in the FRC specimen. During cracking of the FRC the load and energy that are shed by the FRC and by the testing machinery and apparatus transfers to the parallel-loaded steel element.

At a predetermined deformation of the parallel-loaded system the load is removed and the steel element which was placed to control the energy transfer during cracking is removed from the system. The flexure test is then restarted with only the FRC test specimen in place in the same test configuration and loading apparatus as had been used to crack the specimen. A load vs deflection record is obtained up to a chosen deformation such as that which is considered to be potentially within the useful range for a chosen material application as measured by average strain or crack width.

The post-peak methodology is consistent with the notion that for most FRC applications the usefulness of the material system is less often related to the ultimate load capacity and more often related to the ability to transfer stress across a crack at a given strain or deformation. As discussed earlier, this is especially appropriate for applications in which there is some degree of confinement of the FRC.

Figure 6 depicts a typical residual strength load vs deflection curve for a particular type of fiber-reinforced cellular concrete (FRCC). For this application, the FRC specimen is a standard 4 in × 4 in × 14 in (100 mm × 100 mm × 350 mm). The steel plate used as the parallel load element is 0.5 in (12.7 mm) in thickness. The material modulus for the FRCC is quite low, approximately 200 ksi (29 kPa). The beam is subject to four-point loading. The initial slope of the load/deflection diagram indicates the stiffness of the combination of steel plate and FRC specimen. This is substantially greater

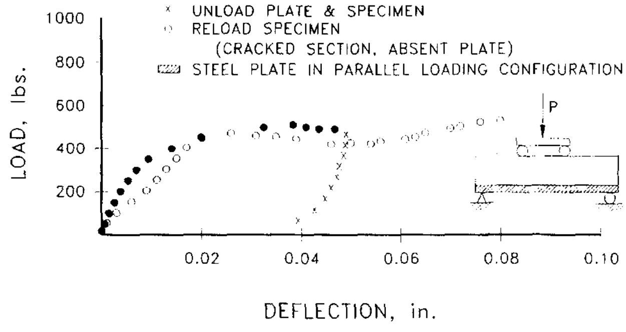

Fig. 6. Post-peak load vs deflection in flexure for FRCC.

than the stiffness of the cracked FRC specimen loaded in the absence of the steel plate.

The post-cracking response demonstrates an essentially elastic-plastic behavior. The residual strength is a reliable tensile stress capacity for a given crack width and can be used for design purposes, as a measure of the post-cracking strength in comparisons among alternative FRC formulations, and as a specification for quality control and acceptance testing.

VALUE-ADDED APPLICATIONS

The most successful applications of FRC are those which result from understanding the mechanical behavior of FRC using the energy concepts of the previous discussion.

There are many applications in which FRC may be required to act as a primary structural load-carrying component, i.e. provide structural integrity. However, there are many more applications in which the fibers are intended principally to augment the integrity of the matrix material and in this way favorably affect the integrity of the structural system. In the latter case, the goal is to affect the non-structural serviceability aspects of the design.

Confinement of an FRC matrix can either be from internal sources, such as conventional reinforcement, or from external structural support. Applications in the low fiber volume regime include slab on grade and composite deck as two examples. In these applications the continued ability to transfer tensile stress, either through the matrix or through fibers which bridge cracks, improves the serviceability aspects of design such as durability and toughness.

Applications of cast in place and precast FRC in new construction and repair include dam, bridge deck, mine, tunnel, canal, and reservoir lining, security and utility vaults, caisson, pile and pile cap foundation elements, slope stabilization, refractory castables and precast, modular panel including tilt up and sheet, breakwaters, mine crib block, machine bases, pipe, and non-structural flatwork such as for highway, airport, composite deck, residential grade slab, and industrial floors. For the wide range of applications listed there is a corresponding wide range of appropriate FRC formulations.

Two categories of applications, one low fiber volume and the other involving high strain or loading rates, each of which emphasize the importance of fracture mechanics over the strength of materials approach to FRC analysis, are chosen for further discussion.

Low fiber volume applications

Low fiber volume applications, using less than 0.5 vol% fiber, have experienced commercial success. Within this category performance criteria will usually include a desire for a high degree of material integrity in the form of crack width and area reduction, i.e. crack control, for both aesthetic and serviceability-related considerations. These are applications in which the stress due to loading is less important than control of the effects of volume change.[3]

The use of relatively low fiber volumes minimizes the effect of fibers in batching, mixing and placing operations. Also, in these applications the energy-absorbing capabilities of fibers and their effect on matrix integrity are realized at all stages of concrete maturity; including from the time the concrete is placed and is still in the plastic state.

FRC performance in field and laboratory research[30,31] at 0.1 to 0.5 vol% percentage for synthetic and steel fiber respectively, makes clear the fact that the effect of the fibers is more in the nature of energy absorption and crack control rather than in increased load-transfer capacity. Although the fiber volume is relatively low the fibers are yet present in large numbers uniformly distributed throughout the concrete mass so that they are affecting crack propagation in both the immature and the mature concrete. For these applications analysis solely by the SOM approach is not well suited.

The genesis of the design as to specification of the amount of fibers is empirically based. Given the previous discussion on how fibers work to absorb and dissipate energy, minimum percentage levels of fiber addition cannot reasonably be determined. However, most field experience and reported research has been at fiber volume loadings of 0.1 vol% for synthetic fiber and 0.5 vol% for steel fiber. In the case of synthetic fiber the 0.1 vol% level can be doubled or tripled, still remaining in the low volume regime, and corresponding improvements in performance can be measured with the post-peak test methodology.

Some purveyors of synthetic and steel fibers recommend specification of even lower fiber volume loadings than the respective 0.1 and 0.5 vol% discussed above for the fiber they market. As reported research involving such applications is generally not available, it appears that such reductions are based solely on economic competitive factors. In view of the earlier discussion one would have to expect a corresponding reduction in effectiveness in comparison with higher minimum fiber loadings.

The diagram of Fig. 7 demonstrates schematically the shrinkage behavior of brittle and ductile materials. An analogy can be drawn between maintenance of matrix integrity in fiber-reinforced brittle composites and the manner in which steel wire lath is manufactured from slit sheet material.

The lath is produced when sheet steel is first slit, so as to provide cracks distributed throughout the steel continuum, and then stretched in-plane to expand the sheet by opening the cracks and thus form the lath. The force required to open the sheet which has been slit is far less than that which would be required to stretch the solid sheet by the same amount. What has changed as a result of the slitting (cracking) process is the effective in-plane stiffness. The slits (cracks) do not propagate as cracks owing to the fracture toughness of the material (steel in the lath analogy) and yet stress, and force, are able to be conducted through the matrix' of the material.

The analogy is shown in Fig. 7(d). The short uniformly distributed lines in the schematic diagram are not fibers but rather are meant to represent fine cracks, as shown in the magnified insert. Prior to coalescence of the distributed cracks into a single through crack, the matrix material continues to conduct the force. The force that is conducted is of magnitude somewhere between zero and the force required to stretch the concrete by an amount δ, reflecting a reduction in the stiffness of the composite.

In relation to the performance of low fiber volume FRC, it is also useful to consider exactly what changes volume and when such volume changes are likely to occur in concrete. For the most part shrinkage is confined to the paste

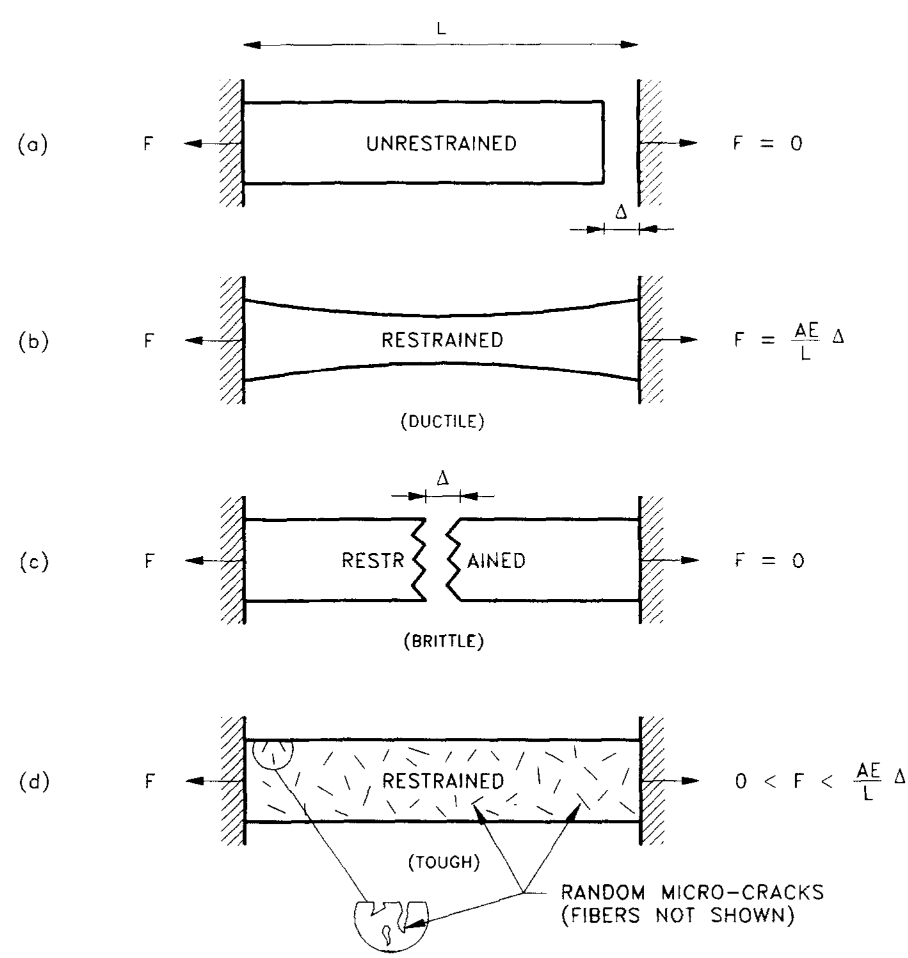

Fig. 7. Shrinkage models for ductile and brittle materials.

phase of Portland cement concrete. Furthermore, much of the volume change takes place within the first few hours after concrete placement, and continues at lesser rate and towards a lesser total amount after the initial chemical reactions in the concrete have taken place and during drying of the concrete.

Figure 8 is a stylized version of the results of research on plastic and drying shrinkage in concrete and mortar.[32] This demonstrates that shrinkage strain is concentrated in the mortar phase and at an early age in the maturation process. Fibers, which recall are found in relatively large number in the paste volume of FRC, are effective from the time of the initial set of the concrete mass. The influence of the fiber in resisting the effects of volume change within the paste phase can best be described using the FM and energy approach to analysis and the analogy discussed using Fig. 7.

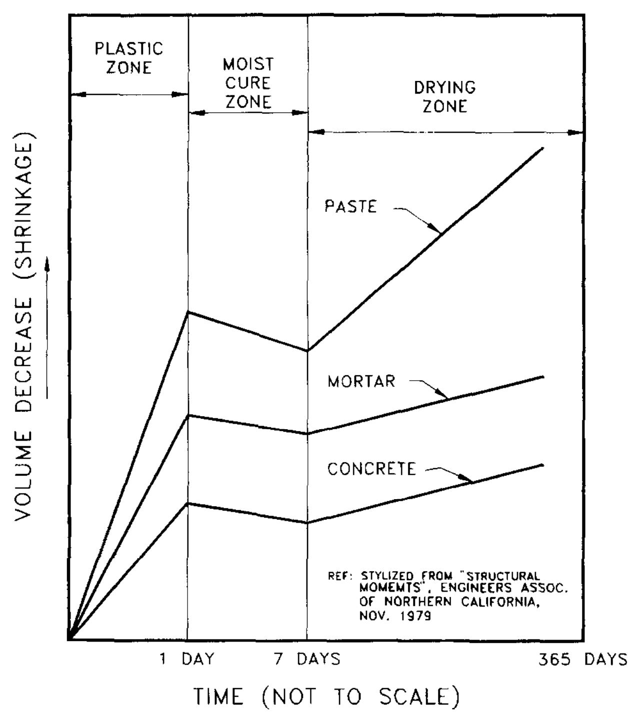

Fig. 8. Where and when concrete shrinks.

Impact energy application

The ability of FRC to absorb energy transmitted by high rates of loading has widely been reported.[33–35] This capability is further demonstrated by the fiber-reinforced cellular composite in the photograph of Fig. 9. The photograph is itself a composite of three photographs showing the ability of an 8 in (20 cm) nominal dimension FRCC wall panel to resist ballistic impact. The photograph shows core samples taken from a test wall which had been split open after firing a handgun at the wall at a range of 20 ft (6.1 m). From the left to the right side of the photograph are, respectively, the trajectory and position of a 44 caliber magnum bullet which penetrated approximately two-thirds of the wall thickness, a close-up of the same 44 caliber magnum bullet after firing, and finally a 9 mm bullet which penetrated less than 3.5 in (90 mm) into the wall.

The same wall panel system was tested in impact according to the Dade County, Florida, Testing Protocol PA 201-94.[36] In the subject test[37] a nominal size 2 in × 4 in (50 mm × 100 mm) #2 surface-dry southern pine dimensional lumber projectile, cut to between 7 and 9 ft (2.13 and 2.74 m) long so as to weigh between 9 and 9.5 lb (4.08 and 4.31 kg), is impacted at 80 ft/s (24 m/s), or 30 ft/s (9 m/s) in excess of the test protocol requirement. The test panel is indented approximately 0.75 in

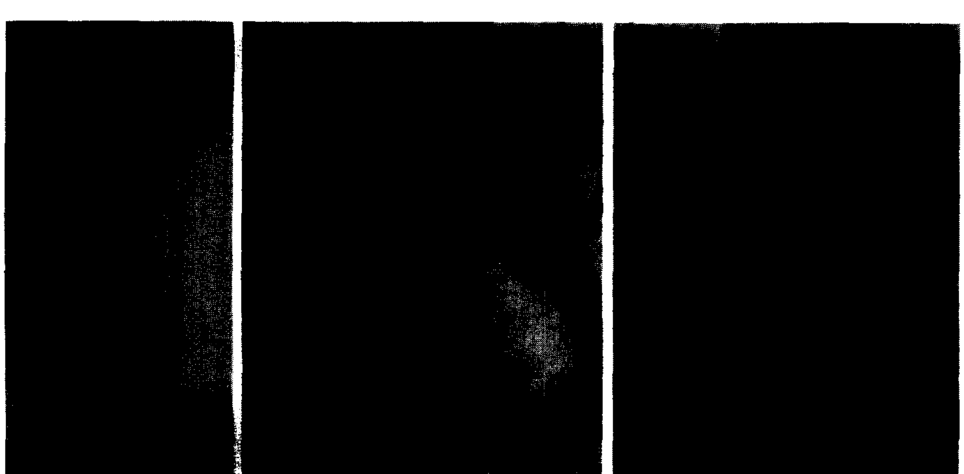

Fig. 9. Ballistic impact resistance of FRCC.

(19 mm) with little or no damage, in the form of tight surface cracks at some test locations, seen on the reverse side. Conventional nominal 8 in (200 mm) concrete block was completely penetrated in a comparative test. The photograph of Fig. 10 shows the indentations made by the standard missile with area dimension of approximately the same size as that of the lumber impact projectile.

SUMMARY AND CONCLUSION

The mechanics of improving the fracture toughness of FRC composites can be summarized as follows.

Existing as paste-phase reinforcement, fibers can, as a practical matter, be disruptive to a brittle concrete composite. This will be true for all fibers but will be especially true for high-modulus, relatively stiff and coarse fibers. Mix designs can be adjusted and mixing and placing precautions taken to minimize this effect. Irregularities in the paste-phase microstructure that are considered disruptive include the formation of voids and aggregate particle segregation. The production process must ensure that the benefits accruing to the composite through the use of fibers outweigh any possible disruptive effects that the fibers may have.

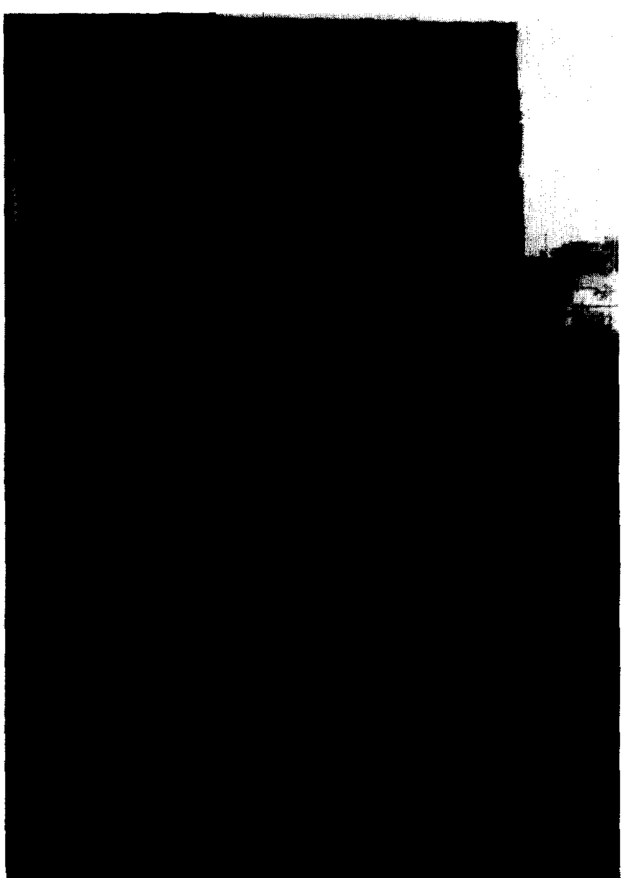

Fig. 10. Large-missile impact test on FRCC panel.

The operative mechanisms that exist for improving crack control and fracture toughness in mature concrete are also available in immature concrete composites containing fibrous reinforcement. It follows that fibers of all types, including relatively low modulus materials, which are capable of being placed in fiber concentrations that ensure a high fiber count and specific surface, will improve composite fracture toughness in both immature and in mature concrete composites.

Fiber efficiency is a notion of fiber effectiveness that considers a combination of factors including fiber material properties, bond or anchorage capability, fiber concentration, and production process. Achieving a desired degree of fiber efficiency provides reliable pre- and post-cracking strength and performance related to toughness, as may be needed for particular applications. The effect of the variety of available fiber types on design parameters needs to be assessed. The development of standards for testing and design are still in progress and are currently limiting the development of FRC.

Many FRC applications are such that the concrete is acting with some degree of confinement; such as in slabs with edge protection or confinement, or in combination with conventional and to some degree confining reinforcement. In these applications improvement in the matrix toughness has particular significance with regard to energy absorption, crack control and durability.

In addition to reports from basic research there has also been noteworthy, if less scientific, field experience gained on the behavior of FRC as a material of construction. The developments stemming from this type of activity have been noteworthy and should not be overlooked by the research community. Indeed, based on the history of FRC, it appears that basic research has progressed largely in response to field experience for applications in which there was a need or desire to use FRC.

Transfer of what has been learned regarding FRC to the design engineering community has suffered from a basic lack of training or interest within the professional ranks in the field of engineering materials science and the application of energy methods in analysis and design. The reader is urged to consult those industry, professional, and trade organizations which are publishers of FRC research and development information in order to explore potential design applications.

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