

Report on Fiber Reinforced Concrete

Reported by ACI Committee 544

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The report prepared by ACI Committee 544 on Fiber Reinforced Concrete (FRC) is a comprehensive review of all types of FRC. It includes fundamental principles of FRC, a glossary of terms, a description of fiber types, manufacturing methods, mix proportioning and mixing methods, installation practices, physical properties, durability, design considerations, applications, and research needs. The report is broken into five chapters: Introduction, Steel FRC, Glass FRC, Synthetic FRC, and Natural FRC.

Fiber reinforced concrete (FRC) is concrete made primarily of hydraulic cements, aggregates, and discrete reinforcing fibers. Fibers suitable for reinforcing concrete have been produced from steel, glass, and organic polymers

(synthetic fibers). Naturally occurring asbestos fibers and vegetable fibers, such as sisal and jute, are also used for reinforcement. The concrete matrices may be mortars, normally proportioned mixes, or mixes specifically formulated for a particular application. Generally, the length and diameter of the fibers used for FRC do not exceed 3 in. (76 mm) and 0.04 in. (1 mm), respectively. The report is written so that the reader may gain an overview of the property enhancements of FRC and the applications for each general category of fiber type (steel, glass, synthetic, and natural fibers).

Brittle materials are considered to have no significant post-cracking ductility. Fibrous composites have been and are being developed to provide improved mechanical properties to otherwise brittle materials. When subjected to tension, these unreinforced brittle matrices initially deform elastically. The elastic response is followed by microcracking, localized macrocracking, and finally fracture. Introduction of fibers into the concrete results in post-elastic property changes that range from subtle to substantial, depending upon a number of factors, including matrix strength, fiber type, fiber modulus, fiber aspect ratio, fiber strength, fiber surface bonding char-

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acteristics, fiber content, fiber orientation, and aggregate size effects. For many practical applications, the matrix first-crack strength is not increased. In these cases, the most significant enhancement from the fibers is the post-cracking composite response. This is most commonly evaluated and controlled through toughness testing (such as measurement of the area under the load-deformation curve).

If properly engineered, one of the greatest benefits to be gained by using fiber reinforcement is improved long-term serviceability of the structure or product. Serviceability is the ability of the specific structure or part to maintain its strength and integrity and to provide its designed function over its intended service life.

One aspect of serviceability that can be enhanced by the use of fibers is control of cracking. Fibers can prevent the occurrence of large crack widths that are either unsightly or permit water and contaminants to enter, causing corrosion of reinforcing steel or potential deterioration of concrete [1.1]. In addition to crack control and serviceability benefits, use of fibers at high volume percentages (5 to 10 percent or higher with special production techniques) can substantially increase the matrix tensile strength [1.1].

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CHAPTER 1—INTRODUCTION

1.1—Historical aspects

Since ancient times, fibers have been used to reinforce brittle materials. Straw was used to reinforce sun-baked bricks, and horsehair was used to reinforce masonry mortar and plaster. A pueblo house built around 1540, believed to be the oldest house in the U.S., is constructed of sun-baked adobe reinforced with straw. In more recent times, large scale commercial use of asbestos fibers in a cement paste matrix began with the invention of the Hatschek process in 1898. Asbestos cement construction products are widely used throughout the world today. However, primarily due to health hazards associated with asbestos fibers, alternate fiber types were introduced throughout the 1960s and 1970s.

In modern times, a wide range of engineering materials (including ceramics, plastics, cement, and gypsum products) incorporate fibers to enhance composite properties. The enhanced properties include tensile strength, compressive strength, elastic modulus, crack resistance, crack control, durability, fatigue life, resistance to impact and abrasion, shrinkage, expansion, thermal characteristics, and fire resistance.

Experimental trials and patents involving the use of discontinuous steel reinforcing elements—such as nails, wire segments, and metal chips—to improve the properties of concrete date from 1910 [1.2]. During the early 1960s in the United States, the first major investigation was made to evaluate the potential of steel fibers as a reinforcement for concrete [1.3]. Since then, a substantial amount of research, development, experimentation, and industrial application of steel fiber reinforced concrete has occurred.

Use of glass fibers in concrete was first attempted in the USSR in the late 1950s [1.4]. It was quickly established that ordinary glass fibers, such as borosilicate E-glass fibers, are attacked and eventually destroyed by the alkali in the cement paste. Considerable development work was directed towards producing a form of alkali-resistant glass fibers containing zirconia [1.5]. This led to a considerable number of commercialized products. The largest use of glass fiber reinforced

concrete in the U.S. is currently for the production of exterior architectural cladding panels.

Initial attempts at using synthetic fibers (nylon, polypropylene) were not as successful as those using glass or steel fibers [1.6, 1.7]. However, better understanding of the concepts behind fiber reinforcement, new methods of fabrication, and new types of organic fibers have led researchers to conclude that both synthetic and natural fibers can successfully reinforce concrete [1.8, 1.9].

Considerable research, development, and applications of FRC are taking place throughout the world. Industry interest and potential business opportunities are evidenced by continued new developments in fiber reinforced construction materials. These new developments are reported in numerous research papers, international symposia, and state-of-the-art reports issued by professional societies. The ACI Committee 544 published a state-of-the-art report in 1973 [1.10]. RILEM's committee on fiber reinforced cement composites has also published a report [1.11]. A Recommended Practice and a Quality Control Manual for manufacture of glass fiber reinforced concrete panels and products have been published by the Precast/Prestressed Concrete Institute [1.12, 1.13]. Three recent symposium proceedings provide a good summary of the recent developments of FRC [1.14, 1.15, 1.16].

Specific discussions of the historical developments of FRC with various fiber types are included in [Chapters 2](#) through [5](#).

1.2—Fiber-reinforced versus conventionally reinforced concrete

Unreinforced concrete has a low tensile strength and a low strain capacity at fracture. These shortcomings are traditionally overcome by adding reinforcing bars or prestressing steel. Reinforcing steel is continuous and is specifically located in the structure to optimize performance. Fibers are discontinuous and are generally distributed randomly throughout the concrete matrix. Although not currently addressed by ACI Committee 318, fibers are being used in structural applications with conventional reinforcement.

Because of the flexibility in methods of fabrication, fiber reinforced concrete can be an economic and useful construction material. For example, thin (1/2 to 3/4 in. [13 to 20 mm] thick), precast glass fiber reinforced concrete architectural cladding panels are economically viable in the U.S. and Europe. In slabs on grade, mining, tunneling, and excavation support applications, steel and synthetic fiber reinforced concrete and shotcrete have been used in lieu of welded wire fabric reinforcement.

1.3—Discussion of fiber types

There are numerous fiber types available for commercial and experimental use. The basic fiber categories are steel, glass, synthetic, and natural fiber materials. Specific descriptions of these fiber types are included in [Chapters 2](#) through [5](#).

1.4—Production aspects

For identical concrete mixtures, addition of fibers will result in a loss of slump as measured by ASTM C 143. This

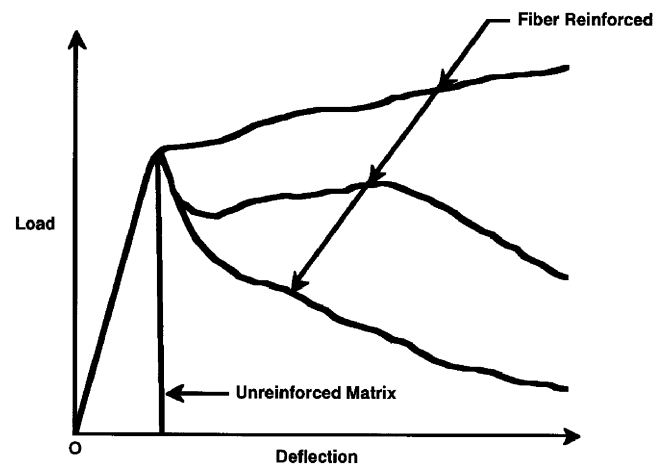


Fig. 1.1—Range of load versus deflection curves for unreinforced matrix and fiber reinforced concrete.

loss is magnified as the aspect ratio of the fiber or the quantity of fibers added increases. However, this slump loss does not necessarily mean that there is a corresponding loss of workability, especially when vibration is used during placement. Since slump is not an appropriate measure of workability, it is recommended that the inverted slump cone test (ASTM C 995) or the Vebe Test (BS 1881) be used to evaluate the workability of fresh FRC mixtures.

For conventionally mixed steel fiber reinforced concrete (SFRC), high aspect ratio fibers are more effective in improving the post-peak performance because of their high resistance to pullout from the matrix. A detrimental effect of using high aspect ratio fibers is the potential for balling of the fibers during mixing. Techniques for retaining high pullout resistance while reducing fiber aspect ratio include enlarging or hooking the ends of the fibers, roughening their surface texture, or crimping to produce a wavy rather than straight fiber profile. Detailed descriptions of production methods for SFRC are found in [Chapter 2](#).

Glass fiber reinforced concretes (GFRC) are produced by either the spray-up process or the premix process. In the spray-up process, glass fibers are chopped and simultaneously deposited with a sprayed cement/sand slurry onto forms producing relatively thin panels ranging from 1/2 to 3/4 in. (13 to 20 mm) thick. In the premix process, a wet-mix cement-aggregate-glass fiber mortar or concrete is cast, press molded, extruded, vibrated, or slip formed. Glass fiber mortar mixes are also produced for surface bonding, spraying, or shotcreting. Specific GFRC production technologies are described in [Chapter 3](#).

Synthetic fiber reinforced concretes (SNFRC) are generally mixed in batch processes. However, some pre-packaged dry mixtures have been used. Flat sheet products that are pressed, extruded, or vacuum dewatered have also been produced. Long fibers are more effective in improving post-peak performance, but balling may become a problem as fiber length is increased. Techniques for increasing pullout resistance while keeping fibers short enough to avoid balling

include surface texturing and splitting to produce branching and mechanical anchorage (fibrillation). [Chapter 4](#) offers a full description of production technologies for SNFRC.

Natural fiber reinforced concretes (NFRC) require special mix proportioning considerations to counteract the retardation effects of the glucose in the fibers. Wet-mix batch processes and wet-compacted mix procedures are used in plant production environments. Details for production methods of NFRC are presented in [Chapter 5](#).

1.5—Developing technologies

SFRC technology has grown over the last three decades into a mature industry. However, improvements are continually being made by industry to optimize fibers to suit applications. A current need is to consolidate the available knowledge for SFRC and to incorporate it into applicable design codes.

A developing technology in SFRC is a material called SIFCON (Slurry Infiltrated Fiber Concrete). It is produced by filling an empty mold with loose steel fibers (about 10 percent by volume) and filling the voids with a high strength cement-based slurry. The resulting composite exhibits high strength and ductility, with the versatility to be shaped by forms or molds [1.17].

GFRC technology is continuing to develop in areas of matrix improvements, glass composition technology, and in manufacturing techniques. New cements and additives have improved composite durability, and new equipment and application techniques have increased the material's versatility.

SNFRC is a rapidly growing FRC technology area due to the availability of a wide spectrum of fiber types and a wide range of obtainable composite enhancements. To date, the largest use of synthetic fibers is in ready-mix applications for flat slab work to control bleeding and plastic shrinkage cracking. This application generally uses 0.1 percent by volume of relatively low modulus synthetic fibers.

Higher volume percentages (0.4 to 0.7 percent) of fibers have been found to offer significant property enhancements to the SNFRC, mainly increased toughness after cracking and better crack distribution with reductions in crack width. [Chapter 4](#) details the current technological advancements in SNFRC in separate sections that discuss each specific fiber material.

As described in [Chapter 5](#), natural fiber reinforced concretes vary enormously in the sophistication by which they are manufactured. Treatment of the fibers also varies considerably. In less developed countries, fibers are used in a minimally treated state. In more advanced countries, wood pulp fibers are used. These fibers have been extracted by an advanced industrial process which significantly alters the character of the fibers and makes them suitable for their end uses.

1.6—Applications

As more experience is gained with SFRC, more applications are accepted by the engineering community. ACI Committee 318 "Building Code Requirements for Reinforced Concrete" does not yet recognize the enhancements that SFRC makes available to structural elements. As more experience is gained and reported, more data will be available to contribute to the recognition of enhanced SFRC prop-

erties in this and other codes. The most significant properties of SFRC are the improved flexural toughness (such as the ability to absorb energy after cracking), impact resistance, and flexural fatigue endurance. For this reason, SFRC has found many applications in flat slabs on grade where it is subject to high loads and impact. SFRC has also been used for numerous shotcrete applications for ground support, rock slope stabilization, tunneling, and repairs. It has also found applications in plant-produced products including concrete masonry crib elements for roof support in mines (to replace wood cribbing). SIFCON is being developed for military applications such as hardened missile silos, and may be promising in many public sector applications such as energy absorbing tanker docks. SFRC applications are further summarized in [Chapter 2](#).

GFRC has been used extensively for architectural cladding panels due to its light weight, economy, and ability to be formed against vertical returns on mold surfaces without back forms. It has also been used for many plant manufactured products. Pre-packaged surface bonding products are used for dry stacked concrete masonry walls in housing applications and for air-stoppage walls in mines. [Chapter 3](#) discusses the full range of GFRC applications.

SNFRC has found its largest commercial uses to date in slabs on grade, floor slabs, and stay-in-place forms in multi-story buildings. Recent research in fibers and composites has opened up new possibilities for the use of synthetic fibers in construction elements. Thin products produced with synthetic fibers can demonstrate high ductility while retaining integrity. [Chapter 4](#) discusses applications of SNFRC for various fiber types.

Applications for NFRC range from the use of relatively low volume amounts of natural fibers in conventionally cast concrete to the complex machine manufacture of high fiber content reinforced cement sheet products, such as roof shingles, siding, planks, utility boards, and pipes. [Chapter 5](#) discusses NFRC in more detail.

1.7—Glossary

The following FRC terms are not already defined in ACI 116R "Definitions of Terms for Concrete."

1.7.1 General terms

aspect ratio—the ratio of length to diameter of the fiber. Diameter may be equivalent diameter.

balling—when fibers entangle into large clumps or balls in a mixture.

bend-over-point (BOP)—The greatest stress that a material is capable of developing without any deviation from proportionality of stress to strain. This term is generally (but not always) used in the context of glass fiber reinforced concrete (GFRC) tensile testing. See "**PEL**" for flexural testing. The term "First Crack Strength" is the same property but often used for fiber concretes other than GFRC.

collated—fibers bundled together either by cross-linking or by chemical or mechanical means.

equivalent diameter—diameter of a circle with an area equal to the cross-sectional area of the fiber. See "**Equivalent Diameter**" for the determination of equivalent diameter.

fiber count—the number of fibers in a unit volume of concrete matrix.

first crack—the point on the flexural load-deflection or tensile load-extension curve at which the form of the curve first becomes nonlinear.

first crack strength—the stress corresponding to the load at “First Crack” (see above) for a fiber reinforced concrete composite in bending or tension.

flexural toughness—the area under the flexural load-deflection curve obtained from a static test of a specimen up to a specified deflection. It is an indication of the energy absorption capability of a material.

impact strength—the total energy required to break a standard test specimen of a specified size under specified impact conditions.

modulus of rupture (MOR)—the greatest bending stress attained in a flexural strength test of a fiber reinforced concrete specimen. Although modulus of rupture is synonymous with matrix cracking for plain concrete specimens, this is not the case for fiber reinforced concrete specimens. See proportional elastic limit (PEL) for definition of cracking in fiber reinforced concrete.

monofilament—single filament fiber typically cylindrical in cross-section.

process fibers—fibers added to the concrete matrix as fillers or to facilitate a production process.

proportional elastic limit (PEL)—the greatest bending stress that a material is capable of developing without significant deviation from proportionality of stress to strain. This term is generally (but not always) used in the context of glass fiber reinforced concrete (GFRC) flexural testing. “Bend Over Point (BOP)” is the term given to the same property measured in a tensile test. The term “First Crack Strength” is the same property, but often used for fiber concretes other than GFRC.

specific surface—the total surface area of fibers in a unit volume of concrete matrix.

toughness indices—the numbers obtained by dividing the area under the load-deflection curve up to a specified deflection by the area under the load-deflection curve up to “First Crack.”

ultimate tensile strength (UTS)—the greatest tensile stress attained in a tensile strength test of a fiber reinforced concrete specimen.

1.7.2 SFRC terms

SFRC—steel fiber reinforced concrete.

1.7.3 GFRC terms

embrittlement—loss of composite ductility after aging caused by the filling of the interstitial spaces surrounding individual glass fibers in a fiber bundle or strand with hydration products, thereby increasing fiber-to-matrix bond and disallowing fiber slip.

AR-GFRC—alkali resistant-glass fiber reinforced concrete.

GFRC—Glass fiber reinforced concrete. Typically, GFRC is AR-GFRC.

P-GFRC—polymer modified-glass fiber reinforced concrete.

polymer addition—less than 10 percent polymer solids by volume of total mix.

Polymer modified—Greater than or equal to 10 percent polymer solids by volume of total mix.

1.7.4 SNFRC terms

denier—weight in grams of 9000 meters of a single fiber.

equivalent diameter—diameter of a circle with an area equal to the cross-sectional area of the fiber. For SNFRC, equivalent fiber diameter, d , is calculated by:

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

where:

$$\begin{aligned} f &= 0.0120 \text{ for } d \text{ in mm} \\ f &= 0.0005 \text{ for } d \text{ in inches} \\ D &= \text{fiber denier} \\ SG &= \text{fiber specific gravity} \end{aligned}$$

fibrillated—a slit film fiber where sections of the fiber peel away, forming branching fibrils.

fibrillated networks—continuous networks of fiber, in which the individual fibers have branching fibrils.

monofilament—any single filament of a manufactured fiber, usually of a denier higher than 14. Instead of a group of filaments being extruded through a spinneret to form a yarn, monofilaments generally are spun individually.

multifilament—a yarn consisting of many continuous filaments or strands, as opposed to monofilament, which is one strand. Most textile filament yarns are multifilament.

post-mix denier—The average denier of fiber as dispersed throughout the concrete mixture (opened fibrils).

pre-mix denier—The average denier of fiber as added to the concrete mixture (unopened fibrils).

staple—cut lengths from filaments. Manufactured staple fibers are cut to a definite length. The term staple (fiber) is used in the textile industry to distinguish natural or cut length manufactured fibers from filament.

SNFRC—synthetic fiber reinforced concrete.

tenacity—having high tensile strength.

tow—A twisted multifilament strand suitable for conversion into staple fibers or sliver, or direct spinning into yarn.

1.7.5 NFRC terms

NFRC—natural fiber reinforced concrete.

PNF—processed natural fibers

PNFRC—processed natural fiber reinforced concrete

UNF—unprocessed natural fibers

1.8—Recommended references

General reference books and documents of the various organizations are listed below with their serial designation. These documents may be obtained from the following organizations:

American Concrete Institute
P. O. Box 9094
Farmington Hills, MI 48333-9094

ASTM International
1916 Barr Harbor Dr.
West Conshohocken, PA 19380



Documents
Document Sharing Hub

British Standards Institute
2 Park Street, London W1A 2B5, England

Japanese Society of Civil Engineers
Mubanchi, Yotsuya 1 - chome, Shinjuku - ku, Tokyo 160,
Japan

RILEM
Pavillon Du Crous, 61 Av. Du President Wilson, 94235
Cachan, France

1.8.1 ACI committee documents

- 116R Cement and Concrete Terminology
- 201.2R Guide to Durable Concrete
- 211.3 Standard Practice for Selecting Proportions for No-Slump Concrete
- 223 Standard Practice for the Use of Shrinkage-Compensating Concrete
- 304R Guide for Measuring, Mixing, Transporting, and Placing Concrete
- 318 Building Code Requirements for Structural Concrete
- 506.1R Report on Fiber Reinforced Shotcrete
- 506.2R Standard Specification for Materials, Proportioning, and Application of Shotcrete
- 544.2R Measurement of Properties of Fiber Reinforced Concrete
- 544.3R Guide for Specifying, Proportioning, Mixing, Placing, and Finishing Steel Fiber Reinforced Concrete
- 544.4R Design Considerations for Steel Fiber Reinforced Concrete
- 549R Report on Ferrocement

1.8.2 ACI Special Publications

- SP-155 Testing of Fiber Reinforced Concrete, edited by D. J. Stevens, N. Banthia, V. S. Gopalratnam, and P. C. Tatnall, (*Proceedings*, March 1995 Symposium, Salt Lake City)
- SP-142 Fiber Reinforced Concrete—Developments and Innovations, edited by J. I. Daniel and S. P. Shah, (*Proceedings*, March 1991 and November 1991 Symposia, Boston and Dallas)
- SP-124 Thin-Section Fiber Reinforced Concrete and Ferrocement, edited by J. I. Daniel and S. P. Shah, (*Proceedings*, February 1989 and November 1989 Symposia, Atlanta and San Diego)
- SP-105 Fiber Reinforced Concrete Properties and Applications, edited by S. P. Shah and G. B. Batson, (*Proceedings*, November 1986 and March 1987 Symposia, Baltimore and San Antonio)
- SP-81 Fiber Reinforced Concrete (*Proceedings*, September 1982 Symposium, Detroit)
- SP-44 Fiber Reinforced Concrete (*Proceedings*, October 1973 Symposium, Ottawa)

1.8.3 RILEM symposia volumes

- 1. *Proceedings 15, High Performance Fiber Reinforced Cement Composites*, edited by H. W. Reinhardt and A. E. Naaman, *Proceedings of the International*

Workshop held jointly by RILEM and ACI, Stuttgart University and the University of Michigan, E&FN Spon, ISBN 0 419 39270 4, June 1991, 584 pp.

2. *Proceedings 17, Fibre Reinforced Cement and Concrete*, edited by R. N. Swamy, *Proceedings of the Fourth RILEM International Symposium on Fibre Reinforced Cement and Concrete*, E & FN Spon, ISBN 0 419 18130 X, 1992, 1376 pp.

3. *Developments in Fibre Reinforced Cement and Concrete*, RILEM Symposium *Proceedings*, RILEM Committee 49-TFR, 1986, 2 volumes.

4. *Testing and Test Methods of Fibre Cement Composites*, RILEM Symposium *Proceedings*, Construction Press Ltd., 1978, 545 pp.

5. *Fibre Reinforced Cement and Concrete*, RILEM Symposium *Proceedings*, Construction Press Ltd., 1975, 650 pp. in 2 volumes.

1.8.4 Books

1. Balaguru, P. N., and Shah, S. P., *Fiber-Reinforced Cement Composites*, McGraw-Hill, Inc., 1992.

2. Daniel, J. I.; Roller, J. J.; Litvin, A.; Azizinamini, A.; and Anderson, E. D., "Fiber Reinforced Concrete," SP 39.01T, Portland Cement Association, Skokie, 1991.

3. Majumdar, A. J., and Laws, V., *Glass Fibre Reinforced Cement*, Building Research Establishment (U.K.), BPS Professional Books Division of Blackwell Scientific Publications Ltd., 1991, 192 pp.

4. Bentur, A., and Mindess, S., *Fibre Reinforced Cementitious Composites*, Elsevier Applied Science, 1990.

5. Swamy, R. N., and Barr, B., *Fibre Reinforced Cement and Concrete: Recent Developments*, Elsevier Applied Science Publishers Ltd., 1989.

6. *Steel Fiber Concrete*, US-Sweden Joint Seminar, Elsevier Applied Science Publishers Ltd., 1986, 520 pp.

7. Hannant, D. J., *Fibre Cements and Fibre Concretes*, John Wiley and Sons, 1978.

1.8.5 ASTM standards

- A 820 Specification for Steel Fibers for Fiber Reinforced Concrete
- C 31 Practice for Making and Curing Concrete Test Specimens in the Field
- C 39 Test Method for Compressive Strength of Cylindrical Concrete Specimens
- C 78 Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)
- C 94 Specification for Ready-Mixed Concrete
- C 143 Test Method for Slump of Hydraulic Cement Concrete
- C 157 Test Method for Length Change of Hardened Hydraulic Cement Mortar and Concrete
- C 172 Procedure for Sampling Freshly Mixed Concrete
- C 173 Test Method for Air Content of Freshly Mixed Concrete by the Volumetric Method
- C 231 Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method
- C 360 Test Method for Ball Penetration in Freshly Mixed Hydraulic Cement Concrete
- C 469 Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression
- C 597 Test Method for Pulse Velocity through Concrete
- C 685 Specification for Concrete Made by Volumetric Batching and Continuous Mixing
- C 779 Test Method for Abrasion Resistance of Horizontal Concrete Surfaces
- C 827 Test Method for Early Volume Change of Cementitious Mixtures

- C 947 Test Method for Flexural Properties of Thin-Section Glass-Fiber Reinforced Concrete (Using Simple Beam with Third-Point Loading)
- C 948 Test Method for Dry and Wet Bulk Density, Water Absorption, and Apparent Porosity of Thin-Section Glass-Fiber Reinforced Concrete
- C 995 Test Method for Time of Flow of Fiber Reinforced Concrete Through Inverted Slump Cone
- C 1018 Test Method for Flexural Toughness and First Crack Strength of Fiber Reinforced Concrete (Using Beam with Third-Point Loading)
- C 1116 Specification for Fiber Reinforced Concrete and Shotcrete
- C 1170 Test Methods for Consistency and Density of Roller-Compacted Concrete Using a Vibrating Table
- C1228 Practice for Preparing Coupons for Flexural and Washout Tests on Glass-Fiber Reinforced Concrete
- C 1229 Test Method for Determination of Glass-Fiber Content in Glass-Fiber Reinforced Concrete (GFRC)
- C 1230 Test Method for Performing Tension Tests on Glass-Fiber Reinforced Concrete (GFRC) Bonding Pads
- E 84 Test Method for Surface Burning Characteristics of Building Materials
- E 119 Fire Tests of Building Construction and Materials
- E 136 Test Method for Behavior of Materials in a Vertical Tube Furnace at 750 C

1.8.6 British Standards Institute

- BS 476: Part 4 Non-Combustibility Test for Materials
- BS 1881: Part 2 Methods of Testing Concrete

1.8.7 Japanese Society of Civil Engineers

- JSCE Standard III-1 Specification of Steel Fibers for Concrete, Concrete Library No. 50, March, 1983

1.8.8 Indian standards

- IS 5913: 1970 Acid Resistance Test for Materials

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CHAPTER 2—STEEL FIBER REINFORCED CONCRETE (SFRC)

2.1—Introduction

Steel fiber reinforced concrete (SFRC) is concrete made of hydraulic cements containing fine or fine and coarse aggregate and discontinuous discrete steel fibers. In tension, SFRC fails only after the steel fiber breaks or is pulled out of the cement matrix. Fig. 2.1 shows a typical fractured surface of SFRC.

Properties of SFRC in both the freshly mixed and hardened state, including durability, are a consequence of its composite nature. The mechanics of how the fiber reinforcement strengthens concrete or mortar, extending from the elastic precrack state to the partially plastic post-cracked state, is a continuing research topic. One approach to the mechanics of SFRC is to consider it a composite material whose properties can be related to the fiber properties (volume percentage, strength, elastic modulus, and a fiber bonding parameter of the fibers), the concrete properties (strength, volume percentage, and elastic modulus), and the properties of the interface between the fiber and the matrix. A more general and current approach to the mechanics of fiber reinforcing assumes a crack arrest mechanism based on fracture mechanics. In this model, the energy to extend a crack and debond the fibers in the matrix relates to the properties of the composite.

Application design procedures for SFRC should follow the strength design methodology described in ACI 544.4R.

Good quality and economic construction with SFRC requires that approved mixing, placing, finishing, and quality control procedures be followed. Some training of the construction trades may be necessary to obtain satisfactory results with SFRC. Generally, equipment currently used for conventional concrete construction does not need to be modified for mixing, placing, and finishing SFRC.

SFRC has advantages over conventional reinforced concrete for several end uses in construction. One example is the use of steel fiber reinforced concrete for tunnel lining, rock slope stabilization, and as lagging for

Table 2.1— Recommended combined aggregate gradations for steel fiber reinforced concrete

U. S. standard sieve size	Percent passing for maximum size of				
	3/8 in. (10 mm)	1/2 in. (13 mm)	3/4 in. (19 mm)	1 in. (25 mm)	1-1/2 in. (38 mm)
2 (51 mm)	100	100	100	100	100
1-1/2 (38 mm)	100	100	100	100	85-100
1 (25 mm)	100	100	100	94-100	65-85
3/4 (19 mm)	100	100	94-100	76-82	58-77
1/2 (13 mm)	100	93-100	70-88	65-76	50-68
3/8 (10 mm)	96-100	85-96	61-73	56-66	46-58
#4 (5 mm)	72-84	58-78	48-56	45-53	38-50
#8 (2.4 mm)	46-57	41-53	40-47	36-44	29-43
#16 (1.1 mm)	34-44	32-42	32-40	29-38	21-34
#30 (600 μ m)	22-33	19-30	20-32	19-28	13-27
#50 (300 μ m)	10-18	8-15	10-20	8-20	7-19
#100 (150 μ m)	2-7	1-5	3-9	2-8	2-8
#200 (75 μ m)	0-2	0-2	0-2	0-2	0-2

*Fig. 2.1—Fracture surface of SFRC.*

the support of excavation. Labor normally used in placing mesh or reinforcing bars in these applications may be eliminated. Other applications are presented in this report.

2.1.1 Definition of fiber types—Steel fibers intended for reinforcing concrete are defined as short, discrete lengths of steel having an aspect ratio (ratio of length to diameter) from about 20 to 100, with any of several cross-sections, and that are sufficiently small to be randomly dispersed in an unhardened concrete mixture using usual mixing procedures.

ASTM A 820 provides a classification for four general types of steel fibers based upon the product used in their manufacture:

- Type I—Cold-drawn wire.
- Type II—Cut sheet.

Type III—Melt-extracted.

Type IV—Other fibers.

The Japanese Society of Civil Engineers (JSCE) has classified steel fibers based on the shape of their cross-section:

Type 1—Square section.

Type 2—Circular section.

Type 3—Crescent section.

The composition of steel fibers generally includes carbon steel (or low carbon steel, sometimes with alloying constituents), or stainless steel. Different applications may require different fiber compositions.

2.1.2 Manufacturing methods for steel fibers—Round, straight steel fibers are produced by cutting or chopping wire, typically wire having a diameter between 0.010 and

0.039 in. (0.25 to 1.00 mm). Flat, straight steel fibers having typical cross sections ranging from 0.006 to 0.025 in. (0.15 to 0.64 mm) thickness by 0.010 to 0.080 in. (0.25 to 2.03 mm) width are produced by shearing sheet or flattening wire (Fig. 2.2a). Crimped and deformed steel fibers have been produced with both full-length crimping (Fig. 2.2b), or bent or enlarged at the ends only (Fig. 2.2c,d). Some fibers have been deformed by bending or flattening to increase mechanical bonding. Some fibers have been collated into bundles to facilitate handling and mixing. During mixing, the bundles separate into individual fibers (Fig. 2.2c). Fibers are also produced from cold drawn wire that has been shaved down in order to make steel wool. The remaining wires have a circular segment cross-section and may be crimped to produce deformed fibers. Also available are steel fibers made by a machining process that produces elongated chips. These fibers have a rough, irregular surface and a crescent-shaped cross section (Fig. 2.2e). Steel fibers are also produced by the melt-extraction process. This method uses a rotating wheel that contacts a molten metal surface, lifts off liquid metal, and rapidly solidifies it into fibers. These fibers have an irregular surface, and crescent shaped cross-section (Fig. 2.2f).

Steel fibers are also produced by the melt-extraction process. This method uses a rotating wheel that contacts a molten metal surface, lifts off liquid metal, and rapidly solidifies it into fibers. These fibers have an irregular surface, and crescent shaped cross-section (Fig. 2.2f).

2.1.3 History—Research on closely-spaced wires and random metallic fibers in the late 1950s and early 1960s was the basis for a patent on SFRC based on fiber spacing [2.1-2.3]. The Portland Cement Association (PCA) investigated fiber reinforcement in the late 1950s [2.4]. Principles of composite materials were applied to analyze fiber reinforced concrete [2.5, 2.6]. The addition of fibers was shown to increase toughness much more than the first crack strength in these tests [2.6]. Another patent based on bond and the aspect ratio of the fibers was granted in 1972 [2.3]. Additional data on patents are documented in [Reference 2.7](#). Since the time of these original fibers, many new steel fibers have been produced.

Applications of SFRC since the mid-1960s have included road and floor slabs, refractory materials and concrete products. The first commercial SFRC pavement in the United States was placed in August 1971 at a truck weighing station near Ashland, Ohio [2.8].

The usefulness of SFRC has been aided by other new developments in the concrete field. High-range water-reducing admixtures increase the workability of some harsh SFRC mixtures [2.9] and have reduced supplier and contractor resistance to the use of SFRC. Silica fume and accelerators have enabled steel fiber reinforced shotcrete to be placed in thicker layers. Silica fume also reduces the permeability of the shotcrete material [2.10].

2.2—Physical properties

2.2.1 Fiber properties—The fiber strength, stiffness, and the ability of the fibers to bond with the concrete are important fiber reinforcement properties. Bond is dependent on the aspect ratio of the fiber. Typical aspect ratios range from about 20 to 100, while length dimensions range from 0.25 to 3 in. (6.4 to 76 mm).

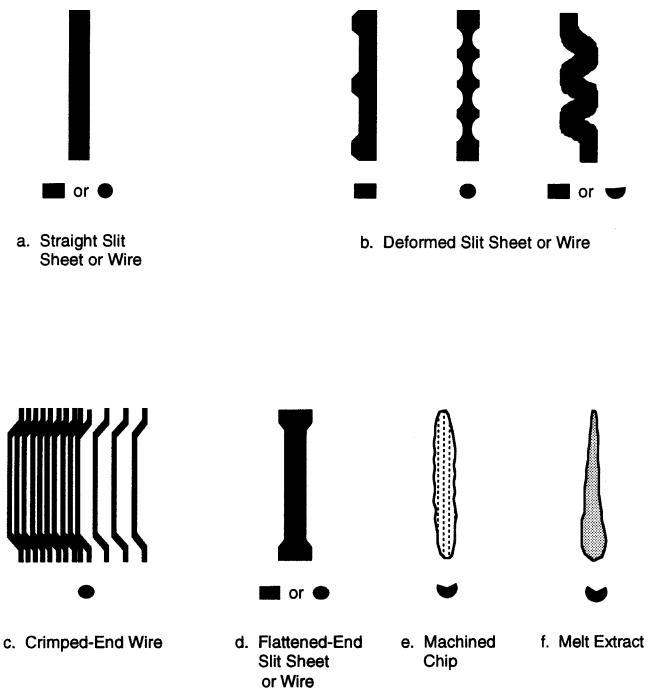


Fig. 2.2—Various steel fiber geometries.

Steel fibers have a relatively high strength and modulus of elasticity, they are protected from corrosion by the alkaline environment of the cementitious matrix, and their bond to the matrix can be enhanced by mechanical anchorage or surface roughness. Long term loading does not adversely influence the mechanical properties of steel fibers. In particular environments such as high temperature refractory applications, the use of stainless steel fibers may be required. Various grades of stainless steel, available in fiber form, respond somewhat differently to exposure to elevated temperature and potentially corrosive environments [2.11]. The user should consider all these factors when designing with steel fiber reinforced refractory for specific applications.

ASTM A 820 establishes minimum tensile strength and bending requirements for steel fibers as well as tolerances for length, diameter (or equivalent diameter), and aspect ratio. The minimum tensile yield strength required by ASTM A 820 is 50,000 psi (345 MPa), while the JSCE Specification requirement is 80,000 psi (552 MPa).

2.2.2 Properties of freshly-mixed SFRC—The properties of SFRC in its freshly mixed state are influenced by the aspect ratio of the fiber, fiber geometry, its volume fraction, the matrix proportions, and the fiber-matrix interfacial bond characteristics [2.12].

For conventionally placed SFRC applications, adequate workability should be insured to allow placement, consolidation, and finishing with a minimum of effort, while providing uniform fiber distribution and minimum segregation and bleeding. For a given mixture, the degree of consolidation influences the strength and other hardened material properties, as it does for plain concrete.

In the typical ranges of volume fraction used for cast in-place SFRC (0.25 to 1.5 volume percent), the addition

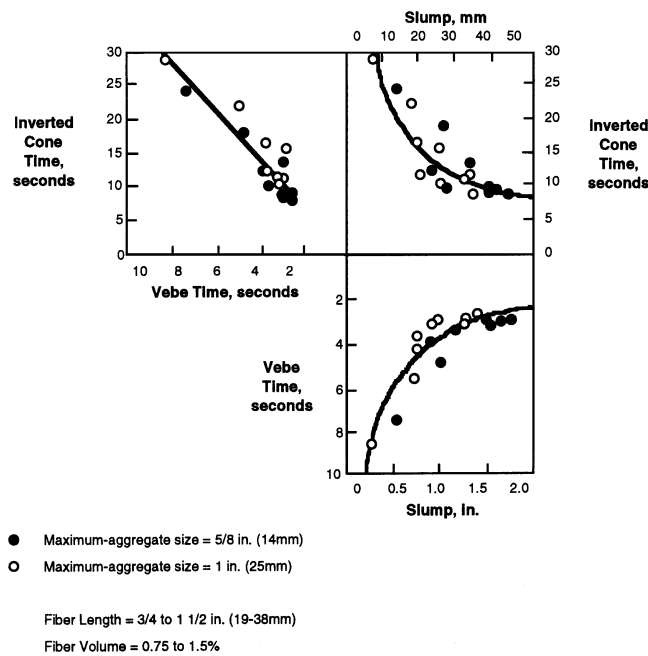


Fig. 2.3—Relationship between slump, vebe time, and inverted cone time.

of steel fibers may reduce the measured slump of the composite as compared to a non-fibrous mixture in the range of 1 to 4 in. (25 to 102 mm). Since compaction by mechanical vibration is recommended in most SFRC applications, assessing the workability of a SFRC mixture with either the Vebe consistometer, as described in the British Standards Institution Standard BS 1881, or by ASTM C 995 Inverted Slump-Cone Time is recommended rather than the conventional slump measurement. A typical relationship between slump, Vebe time, and Inverted Slump-Cone time is shown in Fig. 2.3 [2.13]. Studies have established that a mixture with a relatively low slump can have good consolidation properties under vibration [2.14]. Slump loss characteristics with time for SFRC and non-fibrous concrete are similar [2.15]. In addition to the above considerations, the balling of fibers must be avoided. A collection of long thin steel fibers with an aspect ratio greater than 100 will, if shaken together, tend to interlock to form a mat, or ball, which is very difficult to separate by vibration alone. On the other hand, short fibers with an aspect ratio less than 50 are not able to interlock and can easily be dispersed by vibration [2.16]. However, as shown in Section 2.2.3, a high aspect ratio is desired for many improved mechanical properties in the hardened state.

The tendency of a SFRC mixture to produce balling of fibers in the freshly mixed state has been found to be a function of the maximum size and the overall gradation of the aggregate used in the mixture, the aspect ratio of the fibers, the volume fraction, the fiber shape, and the method of introducing the fibers into the mixture. The larger the maximum size aggregate and aspect ratio, the less volume fraction of fibers can be added without the tendency to ball. Guidance for determining the fiber sizes and volumes to achieve adequate hardened composite properties, and how to balance

these needs against the mix proportions for satisfactory freshly mixed properties is given in Section 2.3.

2.2.3 Properties of the hardened composite

2.2.3.1 Behavior under static loading—The mechanism of fiber reinforcement of the cementitious matrix in concrete has been extensively studied in terms of the resistance of the fibers to pullout from the matrix resulting from the breakdown of the fiber-matrix interfacial bond. Attempts have been made to relate the bond strength to the composite mechanical properties of SFRC [2.17-2.27]. As a consequence of the gradual nature of fiber pullout, fibers impart post-crack ductility to the cementitious matrix that would otherwise behave and fail in a brittle manner.

Improvements in ductility depend on the type and volume percentage of fibers present [2.28-2.30]. Fibers with enhanced resistance to pullout are fabricated with a crimped or wavy profile, surface deformations, or improved end anchorage provided by hooking, teeing or end enlargement (spade or dog bone shape). These types are more effective than equivalent straight uniform fibers of the same length and diameter. Consequently, the amount of these fibers required to achieve a given level of improvement in strength and ductility is usually less than the amount of equivalent straight uniform fibers [2.31-2.33].

Steel fibers improve the ductility of concrete under all modes of loading, but their effectiveness in improving strength varies among compression, tension, shear, torsion, and flexure.

2.2.3.1.1 Compression—In compression, the ultimate strength is only slightly affected by the presence of fibers, with observed increases ranging from 0 to 15 percent for up to 1.5 percent by volume of fibers [2.34-2.38].

2.2.3.1.2 Direct tension—In direct tension, the improvement in strength is significant, with increases of the order of 30 to 40 percent reported for the addition of 1.5 percent by volume of fibers in mortar or concrete [2.38, 2.39].

2.2.3.1.3 Shear and torsion—Steel fibers generally increase the shear and torsional strength of concrete, although there are little data dealing strictly with the shear and torsional strength of SFRC, as opposed to that of reinforced beams made with a SFRC matrix and conventional reinforcing bars. The increase in strength of SFRC in pure shear has been shown to depend on the shear testing technique and the consequent degree of alignment of the fibers in the shear failure zone [2.40]. For one percent by volume of fibers, the increases range from negligible to 30 percent [2.40].

Research has substantiated increased shear (diagonal tension) capacity of SFRC and mortar beams [2.41-2.44]. Steel fibers have several potential advantages when used to augment or replace vertical stirrups in beams [2.45]. These advantages are: (1) the random distribution of fibers throughout the volume of concrete at much closer spacing than is practical for the smallest reinforcing bars which can lead to distributed cracking with reduced crack size; (2) the first-crack tensile strength and the ultimate tensile strength of the concrete may be increased by the fibers; and (3) the shear-friction strength is increased by resistance provided by fibers bridging cracks.

Steel fibers in sufficient quantity, depending on the geometric shape of the fiber, can increase the shear strength of the concrete beams enough to prevent catastrophic diagonal tension failure and to force a flexure failure of the beam [2.44, 2.46-2.48]. Fig. 2.4 shows shear strength as a function of the shear span-to-depth ratio, a/d , for SFRC beams from several published investigations. The bulk of existing test data for shear capacity of SFRC beams are for smaller than prototype-size beams. Limited test data for prototype-size beams indicate that the steel fibers remain effective as shear reinforcement [2.49, 2.50]. The slight decrease in beam shear strength observed in these tests can be explained by the decrease in shear strength with beam size observed for beams without fiber reinforcement.

2.2.3.1.4 Flexure—Increases in the flexural strength of SFRC are substantially greater than in tension or compression because ductile behavior of the SFRC on the tension side of a beam alters the normally elastic distribution of stress and strain over the member depth. The altered stress distribution is essentially plastic in the tension zone and elastic in the compression zone, resulting in a shift of the neutral axis toward the compression zone [2.16]. Although early studies [2.2] gave the impression that the flexural strength can be more than doubled with about 4 percent by volume of fibers in a sand-cement mortar, it is now recognized that the presence of coarse aggregate coupled with normal mixing and placing considerations limits the maximum practical fiber volume in concrete to 1.5 to 2.0 percent. A summary of corresponding strength data [2.34] shows that the flexural strength of SFRC is about 50 to 70 percent more than that of the unreinforced concrete matrix in the normal third-point bending test [2.35, 2.36, 2.51, 2.52]. Use of higher fiber volume fractions, or center-point loading, or small specimens and long fibers with significant fiber alignment in the longitudinal direction will produce greater percentage increases up to 150 percent [2.34, 2.53-2.56]. At lower fiber volume concentrations, a significant increase in flexural strength may not be realized using beam specimens.

2.2.3.2 Behavior under impact loading—To characterize the behavior of concrete under impact loading, the two most important parameters are the strength and the fracture energy. The behavior of concrete reinforced with various types of steel fibers and subjected to impact loads induced by explosive charges, drop-weight impact machines, modified Charpy machines, or dynamic tensile and compressive loads, has been measured in a variety of ways [2.31, 2.32, 2.57-2.68]. Two types of comparisons may be made:

1. Differences between SFRC and plain concrete under impact loading; and
2. Differences between the behavior of SFRC under impact loading and under static loading.

In terms of the differences between SFRC and plain concrete under flexural impact loading, it has been found [2.63-2.66] that for normal strength concrete the peak loads for SFRC were about 40 percent higher than those obtained for the plain matrix. For high strength concrete, a similar improvement in the peak load was observed. Steel fibers increased the fracture energy under impact by a factor of

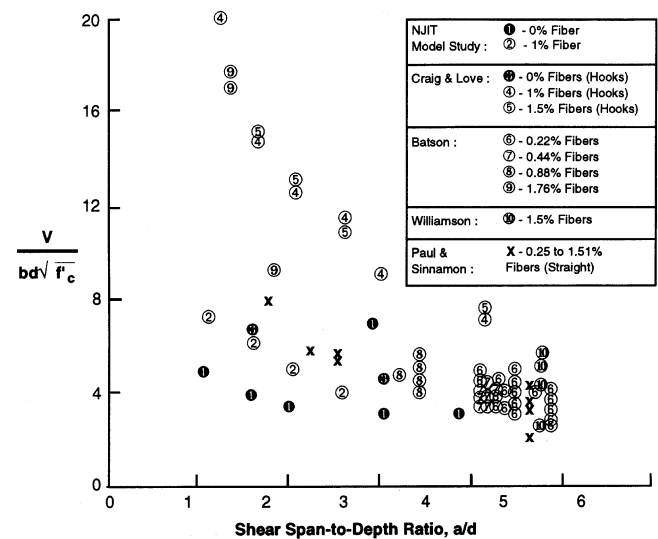


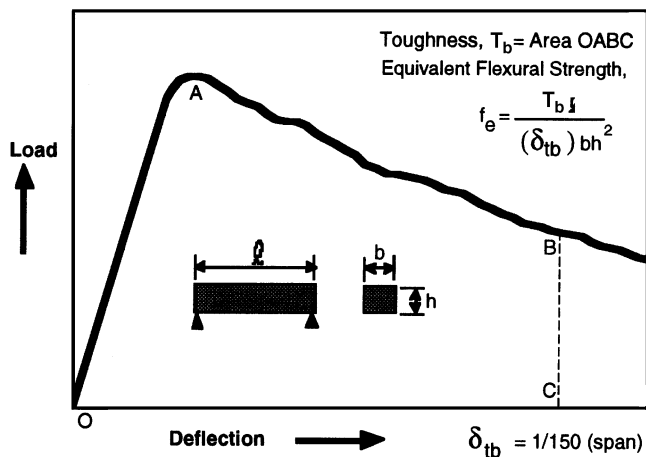
Fig. 2.4—Shear behavior of reinforced SFRC beams.

about 2.5 for normal strength concrete and by a factor of about 3.5 for high strength concrete. However, the improvement observed in the peak load and the fracture energy under impact in some cases was considerably smaller than that obtained in static loading, possibly because of the increased fiber fractures that occurred under impact loading. In comparing the behavior of SFRC under impact loading to its behavior under static loading, steel fibers increased the peak loads by a factor of 2 to 3 times for normal strength concrete, and by a factor of about 1.5 for high strength concrete. Steel fibers increased the fracture energies by a factor of about 5 for normal strength concrete and by a factor of about 4 for high strength concrete.

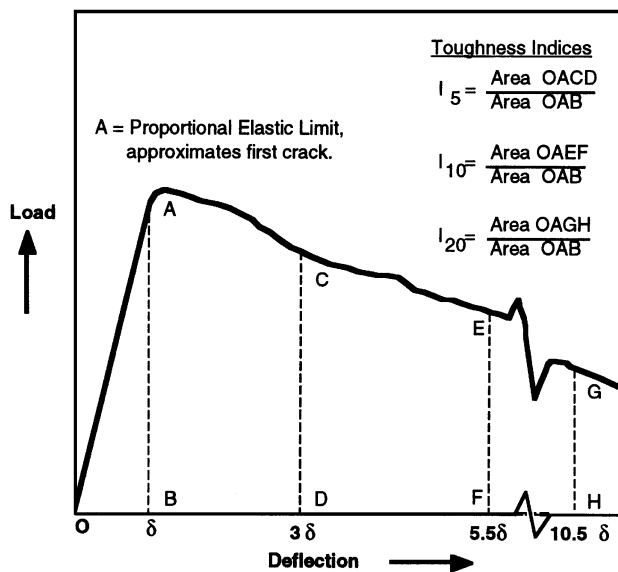
2.2.3.3 Fatigue behavior—Experimental studies show that, for a given type of fiber, there is a significant increase in flexural fatigue strength with increasing percentage of steel fibers [2.31, 2.69-2.72]. The specific mix proportion, fiber type, and fiber percentage for an application in question should be compared to the referenced reports. Depending on the fiber type and concentration, a properly designed SFRC mixture will have a fatigue strength of about 65 to 90 percent of the static flexural strength at 2 million cycles when nonreversed loading is used [2.72, 2.73], with slightly less fatigue strength when full reversal of load is used [2.71].

It has been shown that the addition of fibers to conventionally reinforced beams increases the fatigue life and decreases the crack width under fatigue loading [2.70]. It has also been shown that the fatigue strength of conventionally reinforced beams made with SFRC increases. The resulting deflection changes accompanying fatigue loading also decrease [2.74]. In some cases, residual static flexural strength has been 10 to 30 percent greater than for similar beams with no fatigue history. One explanation for this increase is that the cyclic loading reduces initial residual tensile stresses caused by shrinkage of the matrix [2.75].

2.2.3.4 Creep and shrinkage—Limited test data [2.76, 2.77] indicate that steel wire fabric reinforcement at volumes less



(a) JSCE SF-4 method



(b) ASTM C 1018 method

Fig. 2.5—Schematic of load-deflection curves and toughness parameters.

than 1 percent have no significant effect on the creep and free shrinkage behavior of portland cement mortar and concrete.

2.2.3.5 Modulus of elasticity and Poisson's ratio—In practice, when the volume percentage of fibers is less than 2 percent, the modulus of elasticity and Poisson's ratio of SFRC are generally taken as equal to those of a similar non-fibrous concrete or mortar.

2.2.3.6 Toughness—Early in the development of SFRC, toughness was recognized as the characteristic that most clearly distinguishes SFRC from concrete without steel fibers [2.78, 2.79]. Under impact conditions, toughness can be qualitatively demonstrated by trying to break through a section of SFRC with a hammer. For example, a steel fiber reinforced mortar pot withstands multiple hammer blows before a hole is punched at the point of impact. Even then, the rest of the pot retains its structural integrity. In contrast, a similar pot made of mortar without steel fibers fractures into several pieces after a single hammer blow, losing its structural integrity.

Under slow flexure conditions, toughness can be qualitatively demonstrated by observing the flexural behavior of simply supported beams [2.80]. A concrete beam containing steel fibers suffers damage by gradual development of single or multiple cracks with increasing deflection, but retains some degree of structural integrity and post-crack resistance even with considerable deflection. A similar beam without steel fibers fails suddenly at a small deflection by separation into two pieces.

These two simple manifestations of toughness serve not only to identify the characteristic of toughness in a qualitative sense, but also exemplify the two categories of testing techniques for quantifying toughness; namely, techniques involving either high-rate single or multiple applications of load, or a single slow-rate application of load.

The preferred technique for determining toughness of SFRC is by flexural loading. This reflects the stress condition in the majority of applications such as paving, flooring, and shotcrete linings. Slow flexure is also preferable for determining toughness because the results are lower bound values, safe for use in design. Other fully instrumented tests are often so complex that the time and cost are prohibitive [2.80]. In the standardized slow flexure methods, JSCE SF-4 and ASTM C 1018, a measure of toughness is derived from analysis of the load-deflection curve as indicated in Fig. 2.5. Details of these methods along with a discussion of their merits and drawbacks are presented in References 2.80, 2.81, and 2.82. These test methods provide specifiers and designers with a method to specify and test for toughness levels appropriate to their applications. As an example, for SFRC tunnel linings, I_5 and I_{10} toughness indices sometimes have been specified. Also, toughness indices and residual strength factors corresponding to higher end-point deflections as well as minimum flexural strength requirements as described in ASTM C 1018 are also being used. The JSCE SF-4 equivalent flexural strength is sometimes used as an alternate to design methods based on first-crack strength for slab-on-grade design.

2.2.3.7 Thermal conductivity—Small increases in the thermal conductivity of steel fiber reinforced mortar with 0.5 to 1.5 percent by volume of fiber were found with increasing fiber content [2.83].

2.2.3.8 Abrasion resistance—Steel fibers have no effect on abrasion resistance of concrete by particulate debris carried in slowly flowing water. However, under high velocity flow producing cavitation conditions and large impact forces caused by the debris, SFRC has significantly improved resistance to disintegration [2.31, 2.57, 2.83-2.86]. Abrasion resistance as it relates to pavement and slab wear under wheeled traffic is largely unaffected by steel fibers. Standard abrasion tests (ASTM C 779-Procedure C) on field and laboratory samples confirm this observation [2.87].

2.2.3.9 Friction and skid resistance—Static friction, skid, and rolling resistance of SFRC and identical plain concrete cast into laboratory-size slab samples were compared in a simulated skid test [2.88]. The SFRC had 3/8 in. (9.5 mm) maximum size aggregates. Test results showed that the coefficient of static friction on dry concrete surfaces, with no wear, erosion, or deterioration of

the surface, was independent of the steel fiber content. After simulated abrasion and erosion of the surface, the steel fiber reinforced surfaces had up to 15 percent higher skid and rolling resistance than did plain concrete under dry, wet, and frozen surface conditions.

2.2.4 Durability

2.2.4.1 Freezing and thawing—All the well-known practices for making durable concrete apply to SFRC. For freezing and thawing resistance, the same air content criteria should be used as is recommended in ACI 201. Exposure tests have generally revealed that for freezing and thawing resistance, SFRC must be air-entrained [2.89]. Air void characteristics of SFRC and non-fibrous concrete are similar in nature, supporting the above hypothesis [2.15].

2.2.4.2 Corrosion of fibers: crack-free concrete—Experience to date has shown that if a concrete has a 28-day compressive strength over 3000 psi (21 MPa), is well compacted, and complies with ACI 318 recommendations for water-cement ratio, then corrosion of fibers will be limited to the surface skin of the concrete. Once the surface fibers corrode, there does not seem to be a propagation of the corrosion much more than 0.10 in. (2.5 mm) below the surface. This limited surface corrosion seems to exist even when the concrete is highly saturated with chloride ions [2.90]. Since the fibers are short, discontinuous, and rarely touch each other, there is no continuous conductive path for stray or induced currents or currents from electromotive potential between different areas of the concrete.

Limited experience is available on fiber corrosion in applications subjected to thermal cycling. Short length fibers do not debond under thermal cycling, although such debonding can occur with conventional bar or mesh reinforcement. Since the corrosion mechanism occurs in debonded areas, SFRC has improved durability over conventional reinforced concrete for this application.

2.2.4.3 Corrosion of fibers: cracked concrete—Laboratory and field testing of cracked SFRC in an environment containing chlorides has indicated that cracks in concrete can lead to corrosion of the fibers passing across the crack [2.91]. However, crack widths of less than 0.1 mm (0.004 in.) do not allow corrosion of steel fibers passing across the crack [2.92]. If the cracks wider than 0.1 mm (0.004 in.) are limited in depth, the consequences of this localized corrosion may not always be structurally significant. However, if flexural or tensile cracking of SFRC can lead to a catastrophic structural condition, full consideration should be given to the possibility of corrosion at cracks.

Most of the corrosion testing of SFRC has been performed in a saturated chloride environment, either experimentally in the laboratory or in a marine tidal zone. Corrosion behavior of SFRC in aggressive non-saturated environment or in fresh water exposure is limited. Based on the tests in chloride environments and the present knowledge of corrosion of reinforcement, it is prudent to consider that in most potentially aggressive environments where cracks in SFRC can be expected, corrosion of carbon steel fibers passing through the crack will occur to some extent.

To reduce the potential for corrosion at cracks or surface staining, the use of alloyed carbon steel fibers, stainless steel fibers, or galvanized carbon steel fibers are possible alternatives. Precautions for the use of galvanized steels in concrete must be observed as outlined in ACI 549.

2.2.5 Shrinkage cracking—Concrete shrinks when it is subjected to a drying environment. The extent of shrinkage depends on many factors including the properties of the materials, temperature and relative humidity of the environment, the age when concrete is subjected to the drying environment, and the size of the concrete mass. If concrete is restrained from shrinkage, then tensile stresses develop and concrete may crack. Shrinkage cracking is one of the more common causes of cracking for walls, slabs, and pavements. One of the methods to reduce the adverse effects of shrinkage cracking is reinforcing the concrete with short, randomly distributed, steel fibers.

Since concrete is almost always restrained, the tendency for cracking is common. Steel fibers have three roles in such situations: (1) they allow multiple cracking to occur, (2) they allow tensile stresses to be transferred across cracks, i.e., the composite maintains residual tensile strength even if shrinkage cracks occur, and (3) stress transfer can occur for a long time, permitting healing/sealing of the cracks [2.91].

There is no standard test to assess cracking due to restrained shrinkage. A suitable test method is necessary to evaluate the efficiency of different types and amounts of fibers. ASTM C 157 recommends the use of a long, prismatic specimen to measure free shrinkage. If it is assumed that the length of the specimen is much larger than the cross-sectional dimensions, then the observation of the change in length with time can provide a measure of one-dimensional shrinkage. If this long-prismatic specimen is restrained from shrinking, then uniaxial tensile stresses are produced. If a restrained shrinkage test is carried out such that essentially uniform, uniaxial tensile stresses are produced, then such a test is somewhat similar to a uniaxial tensile test.

An alternate simple approach is to use ring-type specimens as discussed in [References 2.76, 2.77, and 2.93](#) through [2.96](#). While the addition of steel fibers may not reduce the total amount of restrained shrinkage, it can increase the number of cracks and thus reduce the average crack widths. Some results for SFRC ring-type specimens are shown in [Fig. 2.6](#). It can be seen that the addition of even a small amount (0.25 vol. percent) of straight, smooth steel fibers 1 in. long and 0.016 in. in diameter (25 mm by 0.4 mm in diameter) can reduce the average crack width significantly (1/5 the value of the plain concrete specimen).

2.3—Preparation technologies

Mixing of SRFC can be accomplished by several methods, with the choice of method depending on the job requirements and the facilities available. It is important to have a uniform dispersion of the fibers and to prevent the segregation or balling of the fibers during mixing.

Balling of the fibers during mixing is related to a number of factors. The most important factors appear to be the aspect ratio of the fibers, the volume percentage of fibers, the

Table 2.2— Range of proportions for normal weight steel fiber reinforced concrete

Mix parameters	3/8 in. maximum-size aggregate	3/4 in. maximum-size aggregate	1-1/2 in. maximum-size aggregate
Cement, lb/yd ³	600-1000	500-900	470-700
w/c	0.35-0.45	0.35-0.50	0.35-0.55
Percent of fine to coarse aggregate	45-60	45-55	40-55
Entrained air content, percent	4-8	4-6	4-5
Fiber content, vol. percent			
Deformed fiber	0.4-1.0	0.3-0.8	0.2-0.7
Smooth fiber	0.8-2.0	0.6-1.6	0.4-1.4

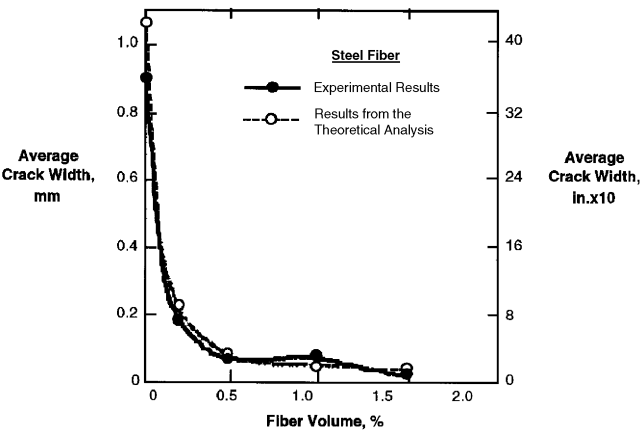


Fig. 2.6—Average crack width versus fiber volume.

maximum size and gradation of the aggregates, and the method of adding the fibers to the mixture. As the first three of these factors increase, the tendency for balling increases. Refer to ACI 544.3R, “Guide For Specifying, Mixing, Placing, and Finishing Steel Fiber Reinforced Concrete” for additional information.

2.3.1 Mix proportions—Compared to conventional concrete, some SFRC mixtures are characterized by higher cement content, higher fine aggregate content, and decreasing slump with increasing fiber content. Since consolidation with mechanical vibration is recommended in most SFRC applications, assessing the workability of a SFRC mixture with ASTM C 995 Inverted Slump-Cone Time or the Vebe test is recommended rather than the conventional slump measurement.

Conventional admixtures and pozzolans are commonly used in SFRC mixtures for air entrainment, water reduction, workability, and shrinkage control. A mix proportioning procedure that has been used for paving and structural applications and in the repair of hydraulic structures is described in [References 2.84 and 2.97](#). Test results indicate that lightweight SFRC can be formulated with minor modifications [2.98]. Also, experience has shown that if the combined fine and coarse aggregate gradation envelopes as shown in [Table 2.1](#) are met, the tendency to form fiber balls is minimized and workability is enhanced [2.99, 2.100]. Alternatively, a mixture based on experience, such as those shown in [Table 2.2](#), can be used for a trial mix. Once a mixture has been selected, it is highly advisable that a full field batch be processed prior to actual start of construction with the mixing equipment that



Fig. 2.7—Adding steel fibers to a loaded mixer truck via conveyor

will be used for the project. Recommendations for trial mixes and the maximum fiber content for good workability are available from the steel fiber manufacturers.

2.3.2 Mixing methods—It is very important that the fibers be dispersed uniformly throughout the mixture. This must be done during the batching and mixing phase. Several mixing sequences have been successfully used, including the following:

1. Add the fibers to the truck mixer after all other ingredients, including the water, have been added and mixed. Steel fibers should be added to the mixer hopper at the rate of about 100 lbs (45 kg) per minute, with the mixer rotating at full speed. The fibers should be added in a clump-free state so that the mixer blades can carry the fibers into the mixer. The mixer should then be slowed to the recommended mixing speed and mixed for 40 to 50 revolutions. Steel fibers have been added manually by emptying the containers into the truck hopper, or via a conveyor belt or blower as shown in. Using this method, steel fibers can be added at the batch plant or on the job site.
2. Add the fibers to the aggregate stream in the batch plant before the aggregate is added to the mixer. Steel fibers can be added manually on top of the aggregates on the charging conveyor belt, or via another conveyor emptying onto the charging belt as shown in [Fig. 2.8](#). The fibers should be spread out along the conveyor belt to prevent clumping.



Fig. 2.8—Adding steel fibers via conveyor onto charging conveyor in a batch plant

3. Add the fibers on top of the aggregates after they are weighed in the batcher. The normal flow of the aggregates out of the weigh batcher will distribute the fibers throughout the aggregates. Steel fibers can be added manually or via a conveyor as shown in Fig. 2.9.

SFRC delivered to projects should conform to the applicable provisions of ASTM C 1116. For currently used manual steel fiber charging methods, workers should be equipped with protective gloves and goggles. It is essential that tightly bound fiber clumps be broken up or prevented from entering the mix. It is recommended that the method of introducing the steel fibers into the mixture be proven in the field during a trial mix.

2.4—Theoretical modeling

It is well recognized that the tensile behavior of concrete matrices can be improved by the incorporation of fibers. Depending upon the fiber geometry and the fiber type, a number of failure mechanisms can be achieved. In general, analytical models are formulated on the basis of one or more of these mechanisms of failure. It is therefore relevant to describe the primary types of failure mechanisms in fiber reinforced concrete composites.

Similar to the behavior of plain concrete, composite failure under most types of loading is initiated by the tensile cracking of the matrix along planes where the normal tensile strains exceed the ultimate values. This may be followed by multiple cracking of the matrix prior to composite fracture, if the fibers are sufficiently long (or continuous). However, when short strong fibers are used (steel, glass, etc.), once the matrix has cracked, one of the following types of failure will occur:

1. The composite fractures immediately after matrix cracking. This results from inadequate fiber content at the critical section or insufficient fiber lengths to transfer stresses across the matrix crack.
2. The composite continues to carry decreasing loads after the peak. The post-cracking resistance is primarily attributed to fiber pull-out. While no significant increase in composite strength is observed, consider-



Fig. 2.9—Adding steel fibers to weigh batcher via conveyor belt

able enhancement of the composite fracture energy and toughness is obtained, as is shown in Fig. 2.10. This toughness allows cracks in indeterminate structures to work as hinges and to redistribute loads. In this way, the failure load of the structure may be substantially higher than for the unreinforced structure although the flexural strength of the plain concrete, tested on beams, is not increased.

3. The composite continues to carry increasing loads after matrix cracking. The peak load-carrying capacity of the composite and the corresponding deformation are significantly greater than that of the unreinforced matrix. During the pre-peak inelastic regime of the composite response, progressive debonding and softening of the interface may be responsible for the energy absorption processes. It is clear that this mode of composite failure is essentially the same as for type 2, but provides higher failure loads and controlled crack growth.

Based in part on the fundamental approach in their formulation, analytical models can be categorized [2.101] as: models based on the theory of multiple fracture, composite models, strain-relief models, fracture mechanics models, interface mechanics models, and micromechanics models. Fairly exhaustive reviews of these models are available elsewhere [2.101, 2.102]. Brief reviews of the fracture mechanics models and the interface mechanics models are given here, as these are typically the most suitable for modeling the inelastic processes in short-fiber composites.

Two broad categories of models can be identified from the fracture mechanics-based models. The more fundamental class of models uses the concepts of linear elastic fracture mechanics (LEFM) to solve the problem of crack initiation, growth, arrest, and stability in the presence of fibers through appropriate changes in the stress intensity factor [2.1, 2.2]. Typically these models assume perfect bond between the fiber and the matrix, and are one-parameter fracture models. Unlike the classical LEFM models, some of the later models implicitly account for the inelastic interface response during crack growth in such composites through a nonlinear stress-

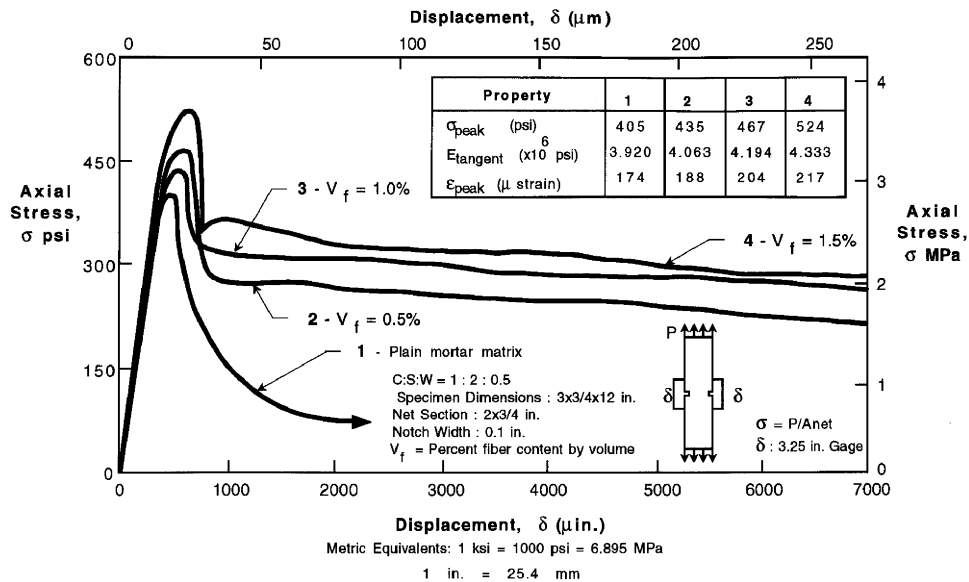


Fig. 2.10—Typical results of stress-displacement curves obtained from direct tension tests on plain mortar matrix and SFRC.

displacement relationship for the fiber-bridging zone (process zone). This approach, which has come to be known as the fictitious crack model (FCM) [2.102], is conceptually similar to that described earlier for the fracture of unreinforced concrete. The major differences in the fictitious crack models [2.103, 2.106] are the singularity assumptions at the crack-tip, the criteria used for crack initiation and growth, and the stability of the crack growth.

Others [2.107] have proposed a fracture mechanics model to predict the crack propagation resistance of fiber reinforced concrete that is somewhat different from either of these two approaches. Fracture resistance in fibrous composites according to this model is separated into the following four regimes: linear elastic behavior of the composite; subcritical crack growth in the matrix and the beginning of the fiber bridging effect; post-critical crack growth in the matrix such that the net stress intensity factor due to the applied load and the fiber bridging closing stresses remain constant (steady state crack growth); and the final stage where the resistance to crack separation is provided exclusively by the fibers. The model uses two parameters to describe the matrix fracture properties (K_{SIC} , modified critical stress intensity factor based on LEFM and the effective crack length, and CTOD, the critical crack tip opening displacement, as described earlier for unreinforced concrete), and a fiber pull-out stress-crack-width relationship as the basic input information.

All of the fictitious crack models rely on the stress-crack-width relations obtained experimentally. There have been some attempts at predicting the macroscopic stress-crack-width relations of the composite from a study of the mechanics of the fiber-matrix interface [2.24, 2.108-2.113]. They can be grouped as models based on the shear-lag theory or modifications thereof [2.108-2.110, 2.113], fracture mechanics based interface models [2.24, 2.113], and numerical models [2.24, 2.112]. Many of these models have been successful to varying degrees in predicting the peak pull-out

loads [2.24, 2.108-2.113] and the load-slip response [2.110, 2.112, 2.113-2.115] of idealized aligned single fiber pull-out. These models have been very useful in understanding the basic mechanics of stress transfer at the interface and showing that the interface softening and debonding play an important role in the fracture of such composites. However, significant research efforts will be needed to modify these models to predict the pull-out characteristics of the inclined fibers that are randomly oriented at a matrix crack (randomness in both the angular orientation as well as the embedment length).

2.5—Design considerations

The designer may best view SFRC as a concrete with increased strain capacity, impact resistance, energy absorption, fatigue endurance, and tensile strength. The increase in these properties will vary from nil to substantial, depending on the quantity and type of fibers used. However, composite properties will not usually increase directly with the volume of fibers added.

Several approaches to the design and sizing of members with SFRC are available. These are based on conventional design methods generally supplemented by special procedures for the fiber contribution. Additional information on design considerations may be found in ACI 544.4R, "Design Considerations for Steel Fiber Reinforced Concrete." These methods generally account for the tensile contribution of the SFRC when considering the internal forces in the member. When supported by full scale test data, these approaches can provide satisfactory designs. The major differences in the proposed methods is in the determination of the magnitude of the tensile stress increase due to the fibers and the manner in which the total force is calculated. Another approach is to consider cracks as plastic hinges in which the remaining moment capacity depends on the type and quantity of fibers present. Other approaches that have been used are often

empirical and may apply only in certain cases where limited supporting test data have been obtained. They should be used with caution in new applications, and only after adequate investigation.

Generally, for flexural structural components, steel fibers should be used in conjunction with properly designed continuous reinforcement. Steel fibers can reliably confine cracking and improve resistance to material deterioration as a result of fatigue, impact, and shrinkage or thermal loads. A conservative but reasonable approach for structural members where flexural or tensile loads occur such as in beams, columns, or elevated slabs (roofs, floors, or other slabs not on grade) is that reinforcing bars must be used to resist the total tensile load. This is because the variability of fiber distribution may be such that low fiber content in critical areas could lead to unacceptable reduction in strength.

In applications where the presence of continuous tensile reinforcement is not essential to the safety and integrity of the structure, such as floors on grade, pavements, overlays, ground support, and shotcrete linings, the improvements in flexural strength, impact resistance, toughness, and fatigue performance associated with the fibers can be used to reduce section thickness, improve performance, or both. For structural concrete, ACI 318 does not provide for use of the additional tensile strength of the fiber reinforced concrete in building design, and therefore the design of reinforcement must still follow the usual procedure. Other applications, as noted above, provide more freedom to take full advantage of the improved properties of SFRC.

There are some applications where steel fibers have been used without reinforcing bars to carry loads. These have been short span, elevated slabs, for example, a parking garage at Heathrow Airport with slabs 3 ft-6 in. (1.07 m) square by 2-1/2 in. (10 cm) thick, supported on four sides [2.116]. In such cases, the reliability of the members should be demonstrated by full-scale load tests and the fabrication should employ rigid quality control.

Some full-scale tests have shown that steel fibers are effective in supplementing or replacing the stirrups in beams [2.44, 2.45, 2.117], although supplementing or replacing stirrups with steel fibers is not an accepted practice at present. These full-scale tests have shown that steel fibers in combination with reinforcing bars can also increase the moment capacity of reinforced and prestressed concrete beams [2.44, 2.118, 2.119].

Steel fibers can also provide an adequate internal restraining mechanism when shrinkage-compensating cements are used so that the concrete system will perform its crack control function even when restraint from conventional reinforcement is not provided [2.120]. Guidance concerning shrinkage-compensating concrete is available in ACI 223.

2.6—Applications

The applications of SFRC will depend on the ingenuity of the designer and builder in taking advantage of the static and dynamic tensile strength, energy absorbing characteristics, toughness, and fatigue endurance of this composite material. The uniform dispersion of fiber throughout the concrete

provides isotropic strength properties not common to conventionally reinforced concrete.

Present applications of SFRC are discussed in the following sections.

2.6.1 Applications of cast-in-place SFRC—Many cast-in-place SFRC applications involve slabs-on-grade, either in the form of pavements or industrial floors. As early as 1983, twenty-two airport paving projects had been completed in the United States [2.121], and over 20 million square feet (1.9 million square meters) of industrial flooring had been constructed in Europe through 1990 [2.122]. Many other projects, including bridge deck overlays and floor overlays, have been reported [2.8, 2.123].

In 1971, the U.S. Army Construction Engineering Research Laboratory performed controlled testing of SFRC runway slabs subjected to C5A airplane wheel loadings. Based on this investigation, the Federal Aviation Administration prepared a design guide for steel fibrous concrete for airport pavement applications [2.124]. Analysis of test data indicated that SFRC slabs need to be only about one-half the thickness of plain concrete slabs for the same wheel loads.

An example of SFRC industrial floors is the 796,000 ft² (74,000 m²) Honda Automobile Assembly and Office Building in Alliston, Ontario, Canada, of which 581,000 sq.ft. (54,000 m²) is slab-on-grade. This slab-on-grade is 6 in. (150 mm) thick and reinforced with 0.25 vol. percent or 33 lbs/yd³ (20 kgs/m³) of 2.4 inch long (60 mm) deformed fibers.

Other cast-in-place applications include an impact resistant encasement of a turbine test facility for Westinghouse Electric Corp., Philadelphia, PA [2.126]. SFRC containing 120 lb/yd³ (71 kg/m³) of 2.0 in. by 0.020 in. diameter (50 mm by 0.50 mm diameter) crimped-end fibers was placed by pumping. Although the concrete encasement included conventional reinforcement, the use of steel fibers reduced the required thickness by one-third.

In 1984, 500,000 ft² (46,000 m²) of 4-in. thick (100 mm) SFRC was placed as a replacement of the upstream concrete facing placed in 1909 at the Barr Lake Dam near Denver, CO [2.127]. The SFRC mixture contained 0.6 vol. percent or 80 lbs/yd³ (47 kgs/m³) of 2.4 in. by 0.039 in. diameter (60 mm by 0.80 mm diameter) crimped-end fibers, and 1 1/2 in. (38 mm) maximum-size aggregate. The SFRC was pumped to a slip-form screed to pave the 47 ft (14 m) high, 2.5 to 1 slope facing.

Several other applications of cast-in-place SFRC include:

1. Repairs and new construction on major dams and other hydraulic structures to provide resistance to cavitation and severe erosion caused by the impact of large waterborne debris [2.99].
2. Repairs and rehabilitation of marine structures such as concrete piling and caissons [2.88].
3. Bonded overlays in industrial floor and highway rehabilitation [2.128].
4. Slip-formed, cast-in-place tunnel lining [2.129].
5. Latex-modified SFRC bridge deck overlays in Oregon [2.130].
6. Highway paving [2.131].



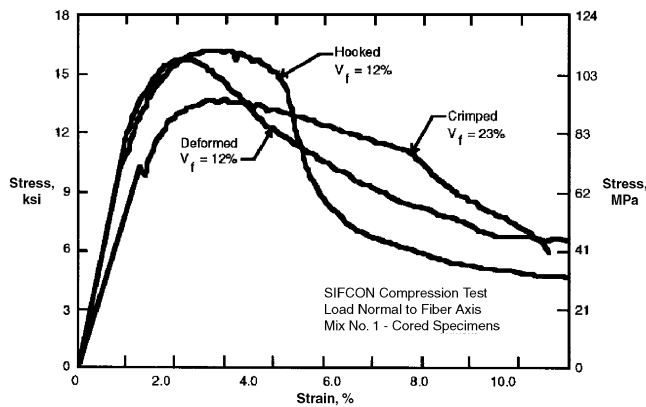


Fig. 2.11—Typical effects of fiber type on the stress-strain curve of SIFCON in compression

7. Large, 77,000 ft² (7150 m²) industrial floor-on-grade [2.132].

8. Roller-compacted concrete (RCC) for pavement construction. Recent work has shown that steel fibers can be incorporated into RCC paving mixes with resulting improvements in material properties [2.133].

9. Bonded overlay repairs to over 50 bridge decks in Alberta, Canada [2.134].

2.6.2 Applications of precast SFRC—Many precast applications for SFRC make use of the improvement in properties such as impact resistance or toughness. Other precast applications use steel fibers to replace conventional reinforcement in utility boxes and septic tanks.

Some recent applications are cited:

Dolosse: In 1982 and 1985 30,000 yd³ (22,900 m³) of SFRC were placed in over 1,500 42 ton (38 MT) dolosse by the Corps of Engineers in Northern California. SFRC was specified in lieu of conventional reinforcing bars to improve the wave impact resistance of the dolosse [2.135].

Vaults and safes: Since 1984, most of the vault and safe manufacturers in North America have used SFRC in precast panels that are then used to construct vaults. Thicknesses of vault walls have been reduced by up to two-thirds over the cast-in-place method. Steel fiber contents vary from less than 1 volume percent to over 3 volume percent. SFRC is used to increase the impact resistance and toughness of the panels against penetration.

Mine crib blocks: These units, made with conventional concrete masonry machines, are routinely supplied throughout the U.S. for building roof support structures in coal mines. Steel fibers are used to increase the compressive toughness of the concrete to allow controlled crushing and thus prevent catastrophic failures [2.136].

Tilt-up panels: SFRC has been used to replace conventional reinforcement in tilt-up panels up to 24 feet high (7.3 m) [2.137].

Precast garages: SFRC is used in Europe to precast complete automobile garages for single family residences.

2.6.3 Shotcrete—Steel fiber reinforced shotcrete (SFRS) was first used in ground support applications. Its first practical application, a trial use for rock slope stabilization in

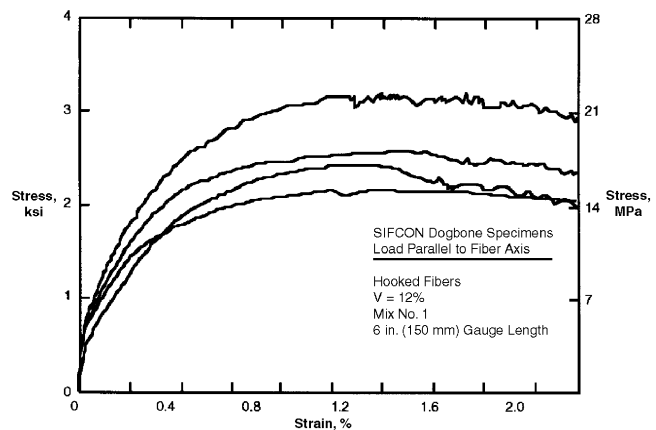


Fig. 2.12—Tensile stress-strain response of hooked fiber SIFCON composites

1974 along the Snake River, Washington, showed very good results [2.138, 2.139]. Since that time, many applications have been made in slope stabilization, in ground support for hydroelectric, transportation and mining tunnels, and in soldier pile retaining walls as concrete lagging that is placed as the structure is constructed from the top down [2.140-2.142]. Additional references and more complete information on SFRS may be found in ACI 506.1R.

Besides ground support, SFRS applications include thin-shell hemispherical domes cast on inflation-formed structures [2.143]; artificial rockscapes using both dry-mix and wet-mix steel fiber reinforced silica fume shotcrete [2.144]; houses in England [2.145]; repair and reinforcing of structures such as lighthouses, bridge piers, and abutments [2.146]; channel lining and slope stabilization on the Mt. St. Helens Sediment Control Structure; lining of oil storage caverns in Sweden; resurfacing of rocket flame deflectors at Cape Kennedy, and forming of boat hulls similar to ferrocement using steel fibers alone and fibers plus mesh.

2.6.4 SIFCON (slurry-infiltrated fiber concrete)—Slurry-infiltrated fiber concrete (SIFCON) is a type of fiber reinforced concrete in which formwork molds are filled to capacity with randomly-oriented steel fibers, usually in the loose condition, and the resulting fiber network is infiltrated by a cement-based slurry. Infiltration is usually accomplished by gravity flow aided by light vibration, or by pressure grouting.

SIFCON composites differ from conventional SFRC in at least two respects: they contain a much larger volume fraction of fibers (usually 8 to 12 volume percent, but values of up to 25 volume percent have been reported) and they use a matrix consisting of very fine particles. As such, they can be made to simultaneously exhibit outstanding strengths and ductilities.

Several studies have reported on the mechanical properties of SIFCON. While most have dealt with its compressive strength and bending properties [2.147-2.154], three have addressed its tensile, shear, and ductility properties. The following is a summary of current information:

1. Compressive strengths of SIFCON can be made to vary from normal strengths (3 ksi or 21 MPa) to more than 20 ksi

(140 MPa) [2.147-2.152]. Higher strengths can be obtained with the use of additives such as fly ash, micro silica, and admixtures.

2. The area under the compressive load-deflection curves for SIFCON specimens divided by the area under load-deflection curves for unreinforced concrete can exceed 50. Strain capacities of more than 10 percent at high stresses have been reported [2.152].

3. Tensile strengths of up to 6 ksi (41 MPa) and tensile strains close to 2 percent have been reported [2.150-2.157].

4. The area under the tensile load-deflection curves for SIFCON specimens divided by the area under load-deflection curves for unreinforced concrete can reach 1000 [2.157].

5. Moduli of rupture in bending of up to 13 ksi (90 MPa) have been reported [2.150-2.155].

6. Shear strengths of more than 4 ksi (28 MPa) have been reported [2.150-2.155].

Examples of stress-strain curves in compression and tension are shown in Figs. 2.11 and 2.12. Since SIFCON is not inexpensive, only applications requiring very high strength and toughness have so far benefitted from its use. These applications include impact and blast resistant structures, refractories, protective revetments, and taxiway and pavement repairs.

2.6.5 Refractories—Stainless steel fibers have been used as reinforcement in monolithic refractories since 1970 [2.158]. Steel fiber reinforced refractories (SFRR) have shown excellent performance in a number of refractory application areas including ferrous and nonferrous metal production and processing, petroleum refining applications, rotary kilns used for producing portland cement and lime, coal-fired boilers, municipal incinerators, plus numerous other applications.

Historically, steel fibers have been added to refractory concretes to provide improvements in resistance to cracking and spalling in applications where thermal cycling and thermal shock have limited the service life of the refractory. The presence of the fibers acts to control the cracking in such a way that cracks having relatively large openings are less frequent and crack-plane boundaries are held together by fibers bridging the crack plane.

When viewed in the above manner, the measure of “failure” of a SFRR involves the measure of the amount of work required to separate the fractured surfaces along a crack plane or completely separate cracked pieces of refractory so that material loss (spalling) occurs. A convenient technique to measure this property involves the measurement of a flexural toughness index (ASTM C 1018).

The following applications serve to illustrate where stainless steel fiber reinforcement can provide improved refractory performance. In each case, knowledge of the service environment and the benefits and limitations of stainless steel fiber reinforcement guided the selection and design of the fiber reinforced product.

1. Petrochemical and refinery process vessel linings: In view of the low processing temperatures involved, typically 600 to 1800 F (315 to 982 C), petrochemical and refinery applications appear ideally suited for the rein-

forcement of refractories with fibers. Steel fiber reinforcement has made it possible to eliminate hex-mesh support and to reduce spalling in various lining situations. Fibers have been used in refractories placed in feed risers and cyclones (the latter in conjunction with abrasion-resistant phosphate-bonded castables).

SFRR is also being used as replacement for dual-layer lining systems. The use of single-layer fiber reinforced refractory eliminates the complex refractory support system in the dual-layer lining which is a source of problems.

Refractories reinforced with steel fibers are currently being specified for cyclones, transfer lines, reactors and regenerators, and for linings in furnaces and combustors. Installation of the refractories by gunning (shotcreting) may limit the length or aspect ratio of the fibers used here. However, the use of high aspect ratio and/or long fibers will provide improved life at the same fiber level or equal life at lower fiber levels (relative to shorter, lower aspect ratio fibers).

The recent discovery that very high fiber levels (4 to 8 percent by volume) can contribute to improved erosion/abrasion resistance in refractories may stimulate increased interest for applications in the petrochemical and refining industry [2.144].

2. Rotary kilns: Fiber reinforced refractories are being used throughout many areas of rotary kilns including the nose ring, chain section, lifters, burner tube, preheater cyclones, and coolers. The use of fibers has extended the life of the refractory to two or three times that of conventional refractory.

3. Steel production: Stainless steel fibers are used in many steel mill applications. Some of the more notable applications include injection lances for iron and steel desulfurizing, arches, lintels, doors, coke oven door plugs, blast furnace cast house floors, reheat furnaces, boiler houses, cupolas, ladles, tundishes, troughs, and burner blocks.

2.7—Research needs

1. Development of rational design procedures to incorporate the properties of SFRC in structural or load-carrying members such as beams, slabs-on-grade, columns, and beam-column joints that will be adopted by code writing bodies such as ACI 318.

2. Development of numerical models for SFRC for one, two, and three dimensional states of stress and strain.

3. Development of material damage and structural stiffness degradation models for large strains and high strain rates to relate or predict SFRC response to stress or shock waves, impact, explosive, and earthquake impulse loadings.

4. Investigation of ductility characteristics of SFRC for potential application in seismic design and construction.

5. Investigation of mechanical and physical properties of SFRC at low temperatures.

6. Investigation of mechanical and physical properties of SFRC using high strength matrix.

7. Investigation of the influence of steel fibers on plastic and drying shrinkage of concrete and shotcrete.

8. Investigation of coatings for steel fibers to modify bond with the matrix and to provide corrosion protection.

9. Development of steel fiber reinforced chemical-bonded ceramic composites including Macro-Defect Free (MDF) cement composites.

10. Investigation of the use of steel fibers in hydraulic non-portland cement concrete.

11. Investigation of interface mechanics and other micro-mechanisms involved in the pull-out of steel fibers not aligned in the loading direction and steel fibers that are deformed.

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