Report on Fiber Reinforced Concrete

Reported by ACI Committee 544

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* Cochairmen, State-of-the-Art Subcommittee; responsible for preparing Chapter 1 and coordinating the entire report.
† Chairman, Steel Fiber Reinforced Concrete Subcommittee; responsible for preparing Chapter 2.
‡ Chairman, Glass Fiber Reinforced Concrete Subcommittee; responsible for perparing Chapter 3.
§ Chairman, Synthetic Fiber Reinforced Concrete Subcommittee; responsible for preparing Chapter 4.
** Cochairmen, Natural Fiber Reinforced Concrete Subcommittee; responsible for preparing Chapter 5.
†† Chairman, Editorial Subcommittee; responsible for reviewing and final editing the entire report.
‡‡ Previous Chairman of Committee 544; responsible for overseeing the development of the majority of this State-of-the-Art Report.
§§ Previous Chairman of Glass Fiber Reinforced Concrete Subcommittee; responsible for overseeing the development of much of Chapter 3.

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 ten-

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sion, 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 characteristics, 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].

CONTENTS

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 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

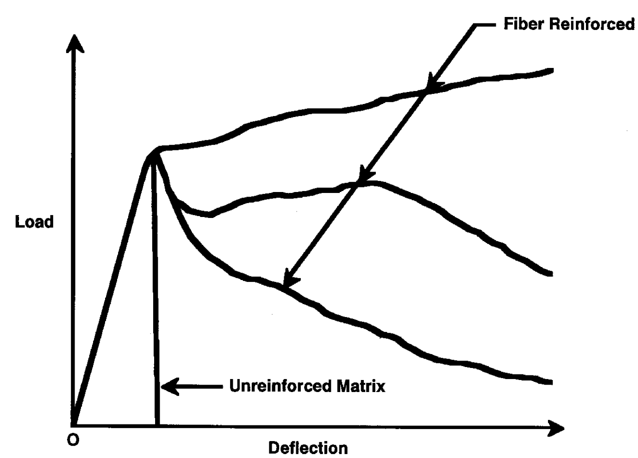


Fig. 1.1—Range of load versus deflection curves for unreinforced matrix and fiber reinforced concrete

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 enhancing 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 properties 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 "SNFRC Terms" 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:

f = 0.0120 for d in mm

f = 0.0005 for d in inches

D = fiber denier

SG = fiber specific gravity

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, USA

American Society for Testing and Materials
1916 Race Street, Philadelphia, PA 19103, USA

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*

116 R 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
304 R Guide for Measuring, Mixing, Transporting, and Placing Concrete
318 Building Code Requirements for Reinforced Concrete
506.1R State-of-the-Art 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 State-of-the-Art 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. Gopalaratnam, 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

1.9—Cited references

1.1 Shah, S. P., “Do Fibers Increase the Tensile Strength of Cement Based Matrices?,” *ACI Materials Journal*, Vol. 88, No. 6, Nov. 1991, pp. 595-602.

1.2 Naaman, A. E., “Fiber Reinforcement for Concrete,” *Concrete International: Design and Construction*, Vol. 7, No. 3, Mar. 1985, pp. 21-25.

1.3 Romualdi, J. P., and Batson, G. B., “Mechanics of Crack Arrest in Concrete,” *J. Eng. Mech. Div.*, ASCE, Vol. 89, No. EM3, June 1963, pp. 147-168.

1.4 Biryukovich, K. L., and Yu, D. L., “Glass Fiber Reinforced Cement,” translated by G. L. Cairns, *CERA Translation*, No. 12, Civil Eng. Res. Assoc., London, 1965, 41 pp.

1.5 Majumdar, A. J., “Properties of Fiber Cement Composites,” *Proceedings*, RILEM Symp., London, 1975, Construction Press, Lancaster, 1976, pp. 279-314.

1.6 Monfore, G. E., “A Review of Fiber Reinforced Portland Cement Paste, Mortar, and Concrete,” *J. Res. Dev. Labs*, Portl. Cem. Assoc., Vol. 10, No. 3, Sept. 1968, pp. 36-42.

1.7 Goldfein, S., “Plastic Fibrous Reinforcement for Portland Cement,” *Technical Report* No. 1757-TR, U.S. Army Research and Development Laboratories, Fort Belvoir, Oct. 1963, pp. 1-16.

1.8 Krenchel, H., and Shah, S., “Applications of Polypropylene Fibers in Scandinavia,” *Concrete International*, Mar. 1985.

1.9 Naaman, A.; Shah. S.; and Throne, J., *Some Developments in Polypropylene Fibers for Concrete*, SP-81, American Concrete Institute, Detroit, 1982, pp. 375-396.

1.10 ACI Committee 544, “Revision of State-of-the-Art Report (ACI 544 TR-73) on Fiber Reinforced Concrete,” ACI JOURNAL, Proceedings, Nov. 1973, Vol. 70, No. 11, pp. 727-744.

1.11 RILEM Technical Committee 19-FRC, “Fibre Concrete Materials,” *Materials and Structures*, Test Res., Vol. 10, No. 56, 1977, pp. 103-120.

1.12 PCI Committee on Glass Fiber Reinforced Concrete Panels, “Recommended Practice for Glass Fiber Reinforced Concrete Panels,” Precast/Prestressed Concrete Institute, Chicago, 1993.

1.13 PCI Committee on Glass Fiber Reinforced Concrete Panels, “Manual for Quality Control for Plants and Production of Glass Fiber Reinforced Concrete Products,” *MNL* 130-91, Precast/Prestressed Concrete Institute, Chicago, 1991.

1.14 *Steel Fiber Concrete*, edited by S. P. Shah and A. Skarendahl, Elsevier Applied Science Publishers, Ltd., 1986, 520 pp.

1.15 *Fiber Reinforced Concrete Properties and Applications*, edited by S. P. Shah and G. B. Batson, SP-105, American Concrete Institute, Detroit, 1987, 597 pp.

1.16 *Thin-Section Fiber Reinforced Concrete and Ferrocement*, edited by J. I. Daniel and S. P. Shah, SP-124, American Concrete Institute, Detroit, 1990, 441 pp.

1.17 Lankard, D. R., “Slurry Infiltrated Fiber Concrete (SIFCON),” *Concrete International*, Vol. 6, No. 12, Dec. 1984, pp. 44-47.

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. 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.

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

	Percent Passing for Maximum Size of				
U. S. standard sieve size	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

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

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].

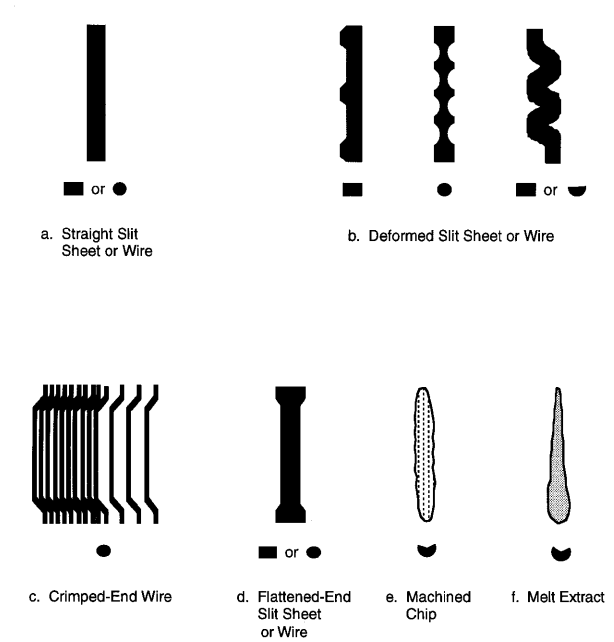


Fig. 2.2—Various steel fiber geometries

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).

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).

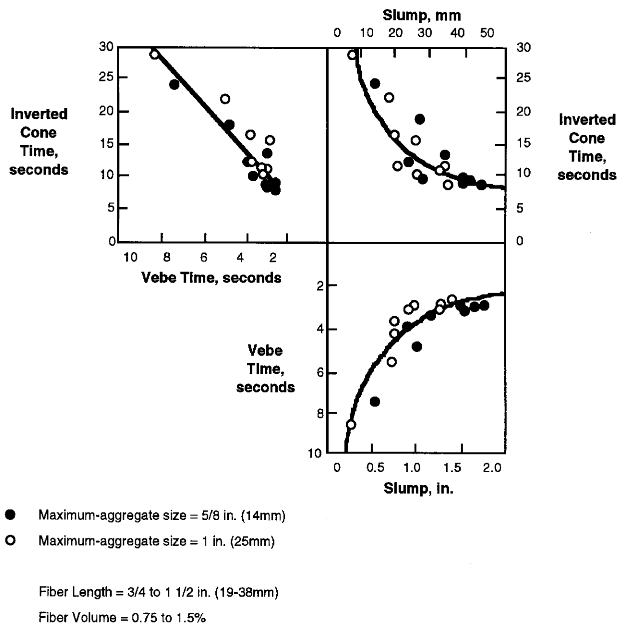


Fig. 2.3—Relationship between slump, vebe time, and inverted cone time

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 fractions used for cast-in-place SFRC (0.25 to 1.5 volume percent), the addition 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 to pull-out and 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 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

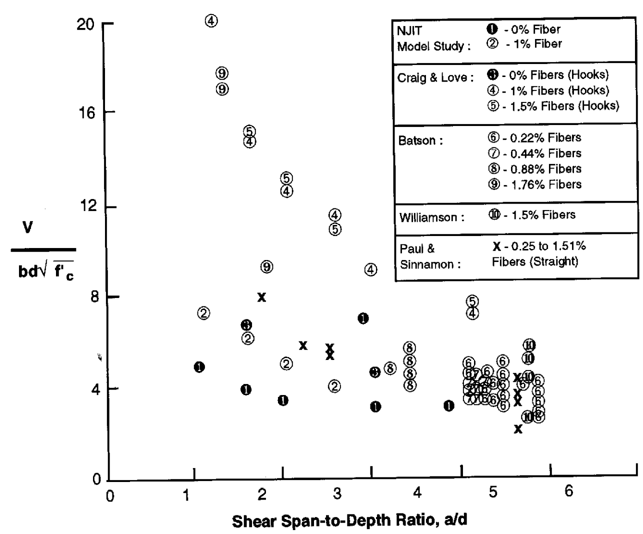
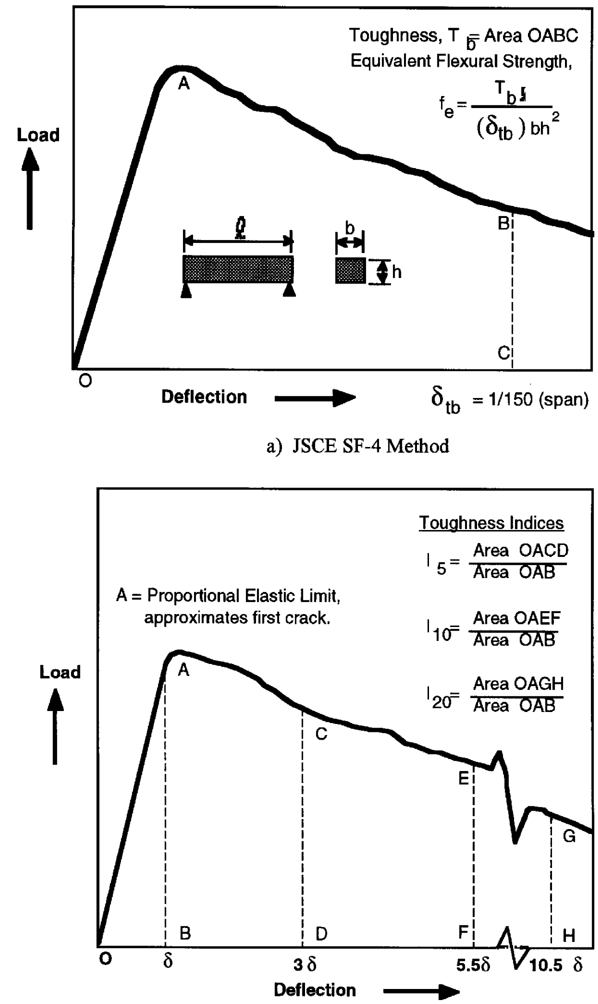


Fig. 2.4—Shear behavior of reinforced SFRC beams



a) JSCE SF-4 Method

b) ASTM C1018 Method

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

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 [2.15, 2.76, 2.77] indicate that steel wire fiber reinforcement at volumes less 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 for 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.

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 Ratio	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

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 inch long and 0.016 inches 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 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 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.

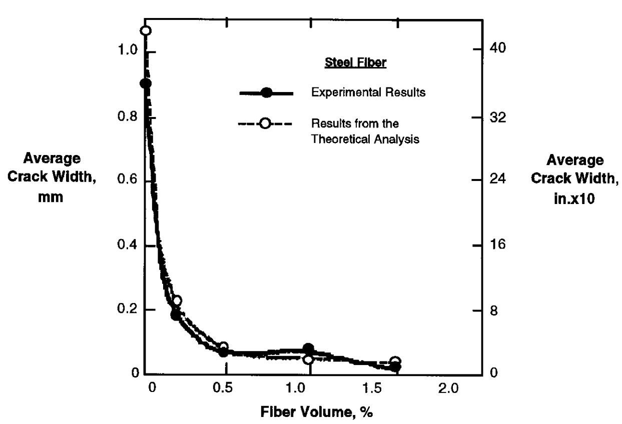


Fig. 2.6—Average crack width versus fiber volume

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

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

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

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.
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, considerable 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 deb-

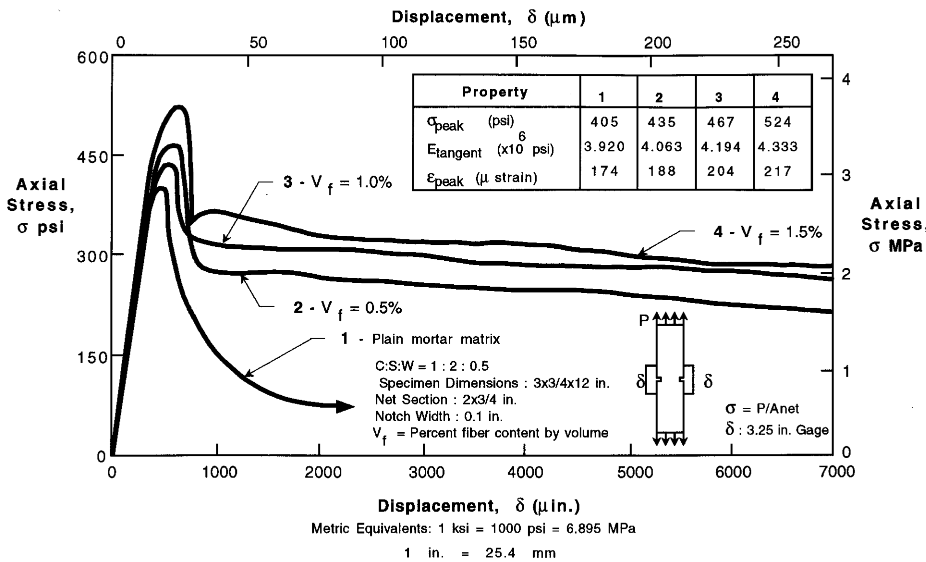


Fig. 2.10—Typical results of stress-displacement curves obtained from direct tension tests on plain mortar matrix and SFRC

onding 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-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_{S1C}, 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 ft^2 (74,000 m^2) Honda Automobile Assembly and Office Build-

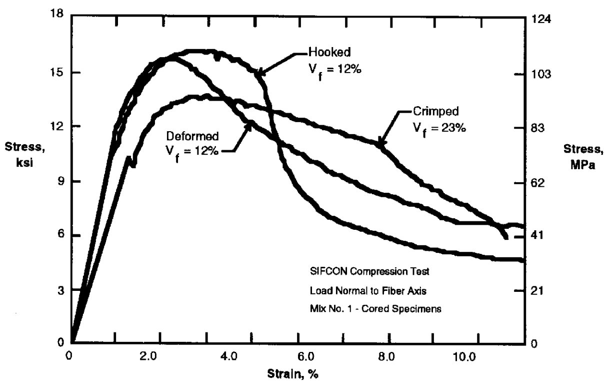


Fig. 2.11—*Typical effects of fiber type on the stress-strain curve of SIFCON in compression*

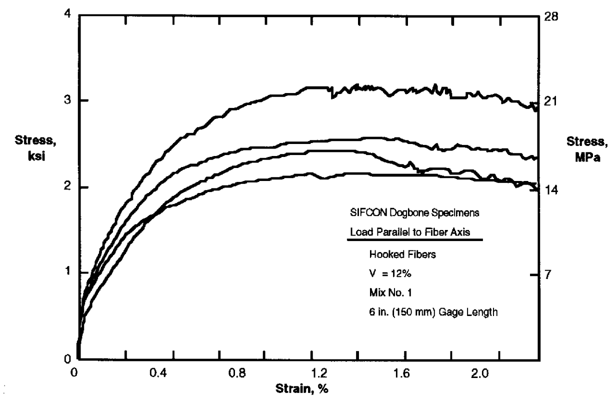


Fig. 2.12—*Tensile stress-strain response of hooked fiber SIFCON composites*

ing in Alliston, Ontario, Canada, of which 581,000 sq.ft. (54,000 m^2) is slab-on-grade. This slab-on-grade is 6 in. (150 mm) thick and reinforced with 0.25 vol. percent or 33 lbs/yd^3 (20 kgs/m^3) 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 lbs/yd^3 (71 kgs/m^3) 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 ft^2 (46,000 m^2) 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/yd^3 (47 kgs/m^3) 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].

7. Large, 77,000 ft^2 (7,150 m^2) 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 cubic yards (22,900 cubic meters) 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 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 reinforcement 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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CHAPTER 3—GLASS FIBER REINFORCED CONCRETE (GFRC)

3.1—Introduction

Much of the original research performed on glass fiber reinforced cement paste took place in the early l960s. This work used conventional borosilicate glass fibers (E-glass) and soda-lime-silica glass fibers (A-glass). The chemical compositions and properties of selected glasses are listed in Tables 3.1 [3.1, 3.2] and 3.2[3.2, 3.3], respectively. Glass compositions of E-glass and A-glass, used as reinforcement, were found to lose strength rather quickly due to the very high alkalinity (pH $\geq$ 12.5) of the cement-based matrix. Consequently, early A-glass and E-glass composites were unsuitable for long-term use [3.4].

Continued research, however, resulted in the development of a new alkali resistant fiber (AR-glass fiber) that provided improved long-term durability. This system was named alkali resistant-glass fiber reinforced concrete (AR-GFRC).

In 1967, scientists of the United Kingdom Building Research Establishment (BRE) began an investigation of alkali resistant glasses. They successfully formulated a glass composition containing 16 percent zirconia that demonstrated a high alkali resistance. Chemical composition and properties of this alkali resistant (AR) glass are given in Tables 3.1 and 3.2, respectively. Patent applications were filed by the National Research Development Corporation (NRDC) for this product [3.5].

The NRDC and BRE discussed with Pilkington Brothers Limited the possibility of doing further work to develop the fibers for commercial production [3.5]. By 1971, BRE and Pilkington Brothers had collaborated and the results of their work were licensed exclusively to Pilkington for commercial production and distribution throughout the world.

Since the introduction of AR-glass in the United Kingdom in 1971 by Cem-FIL, other manufacturers of AR-glass have come into existence. In 1975, Nippon Electric Glass (NEG) Company introduced an alkali resistant glass containing a minimum of 20 percent zirconia [3.3]. In 1973, Owens-Corning Fiberglas introduced an AR-glass fiber. In 1976, Owens-Corning Fiberglas and Pilkington Brothers, Ltd. agreed to produce the same AR-glass formulation to enhance the development of the alkali resistant glass product and related markets. A cross-license was agreed upon. Subsequently, Owens-Corning Fiberglas stopped production of AR-glass fiber in 1984.

Alkali resistant-glass fiber reinforced concrete is by far the most widely used system for the manufacture of GFRC products. Within the last decade, a wide range of applications in the construction industry has been established.

3.2—Fabrication of GFRC material

There are basically two processes used to fabricate GFRC materials. These are the “spray-up” process and the “premix” process.

3.2.1—*Spray-up process*

Since GFRC is principally used in thin sections, it is important that composite GFRC boards have uniform properties in all directions within the plane of the board. Spraying constitutes an effective process of achieving this uniformity. At present, the spray process accounts for the majority of all manufactured GFRC products in the United States. On a world-wide basis, the relation of spray-up to the premix process is more evenly balanced.

Table 3.1— Chemical composition of selected glasses, percent

Component	A-glass	E-glass	Cem-FIL AR-glass	NEG AR-glass
SiO_2	73.0	54.0	62.0	61.0
Na_2O	13.0	—	14.8	15.0
CaO	8.0	22.0	—	—
MgO	4.0	0.5	—	—
K_2O	0.5	0.8	—	2.0
Al_2O_3	1.0	15.0	0.8	—
Fe_2O_3	0.1	0.3	—	—
B_2O_3	—	7.0	—	—
ZrO_2	—	—	16.7	20.0
TiO_2	—	—	0.1	—
Li_2O	—	—	—	1.0

Table 3.2— Properties of selected glasses

Property	A-Glass	E-Glass	Cem-FIL AR-Glass	NEG AR-Glass
Specific gravity	2.46	2.54	2.70	2.74
Tensile strength, ksi	450	500	360	355
Modulus of elasticity, ksi	9400	10,400	11,600	11,400
Strain at break, percent	4.7	4.8	3.6	2.5

Metric equivalent: 1 ksi = 1000 psi = 6.895 MPa

In the spray-up process, cement/sand mortar and chopped glass fibers are simultaneously pre-mixed and deposited from a spray gun onto a mold surface. The GFRC architectural panel industry sets an absolute minimum of four percent AR-glass fibers by weight of total mix as a mandatory quality control requirement [3.7]. The spray-up process can be either manual or automated. Virtually any section shape can be sprayed or cast. This enables architects to design and manufacturers to produce aesthetically pleasing and useful components.

Sprayed GFRC is manufactured in layers. Each complete pass of the spray gun deposits approximately $^3/_{16}$ to $^1/_4$-in. (4 to 6-mm) thickness. A typical $^1/_2$-in. (13-mm) thick panel thus requires two to three complete passes. After each layer is sprayed, the wet composite is roller compacted to ensure that the panel surface will conform to the mold face, to help remove entrapped air, and to aid the coating of glass fibers by cement paste.

Early composite manufacture used a dewatering process to remove the excess mix water that was necessary to achieve a sprayable mix. Dewatering lowers the water-cement ratio and increases the level of compaction. Dewatering involves suction applied to either side of a permeable mold to remove excess water immediately after spraying. The spray-dewatering process is most suited for automation where the composite is transported over a vacuum system using conveyors.

AR-GFRC mix proportions in the late 1960s were primarily composed of only cement, water, and fiber (neat cement mix). When AR-GFRC was introduced commercially in the early 1970s, sand was introduced at weight ratios of one part sand to three parts cement. By the end of the 1970s, some manufacturers were producing AR-GFRC at sand-to-cement ratios of 1-to-2 and as low as 1-to-1 to reduce the amount of volumetric shrinkage. Throughout the 1980s and currently, typical sand-to-cement ratios are 1-to-1. There is currently research underway to investigate AR-GFRC mixes having greater amounts of sand than cement.

For AR-GFRC products, forms are normally stripped on the day following spray-up. Composites are then moist cured until they have attained most of their design strength. Particular attention must be paid to curing. Because of their thin section, AR-GFRC components are susceptible to rapid moisture loss and incomplete strength development if allowed to remain in normal atmospheric conditions. Therefore, to assure adequate strength gain of the cement matrix, a minimum of seven days moist curing has been recommended [3.8]. Also, improper early age curing that leads to excessive drying may result in warping or distortion of the thin GFRC component shape.

The industry requirement of performing a seven-day moist cure created a curing space problem for manufacturers. As a result, many manufacturers were reluctant to perform this necessary moist cure. In the early 1980s, research was conducted by the Portland Cement Association to eliminate the seven-day moist cure in an effort to alleviate the manufacturers' production problems [3.9]. As a result of that research, composites containing at least 5.0 percent polymer solids by total mix volume and having had no moist cure, were shown to develop 28-day Proportional Elastic Limit (PEL) strengths equal to or slightly greater than similar composites containing no polymer and subjected to a seven-day moist cure [3.9]. This indicated that the recommended seven-day moist curing period for AR-GFRC panels could be replaced by the addition of at least 5 percent polymer solids by volume followed by no moist curing, provided a harsh curing environment does not exist (i.e., dry, hot windy weather, or low temperatures).

All of the data published on GFRC from the late 1960s to the mid-1980s was based on composites that were moist cured for seven days and contained no polymer additions. Furthermore, the majority of all published test data up to about 1980 was based on sand-to-cement ratios of 1-to-3.

3.2.2—*Premix process*

The premix process consists of mixing cement, sand, chopped glass fiber, water, and admixtures together into a mortar, using standard mixers, and casting with vibration, press-molding, extruding, or slip-forming the mortar into a product. Manufacturers of AR-glass fiber claim that up to 5 percent by weight of AR-glass fiber can be mixed into a cement and sand mortar without balling [3.5]. Higher concentrations of fiber can be mixed into the mortar using high efficiency undulating mixers. Mixing must be closely controlled to minimize damage to the fiber in the abrasive environment of the mix. Flow aids, such as water-reducers and high-range water-reducing agents, are commonly used to facilitate fiber addition while keeping the water-cement ratio to a minimum. Since premix composites generally have only 2 to 3 percent by weight of AR-glass, they are not as strong as sprayed-up GFRC. Premix GFRC is generally used to produce small complex shaped components and specialty cladding panels.

3.3—Properties of GFRC

Mechanical properties of GFRC composites depend upon fiber content, polymer content (if used), water-cement ratio, porosity, sand content, fiber orientation, fiber length, and curing [3.7]. The primary properties of spray-up GFRC used for design are the 28-day flexural Proportional Elastic Limit (PEL) and the 28-day flexural Modulus of Rupture (MOR) [3.8]. The PEL stress is a measure of the matrix cracking stress. The 28-day PEL is used in design as the limiting stress to ensure that long-term, in-service panel stresses are maintained below the composite cracking strength. In addition, demolding and other handling stresses should remain below the PEL of the material at the specific time that the event takes place [3.8].

A generalized load-deflection curve for a 28-day old GFRC composite subjected to a flexure test is shown in Fig. 3.1. As indicated by this generalized load-deflection curve, young (28-day old) GFRC composites typically possess considerable load and strain capacity beyond the matrix cracking strength (PEL). The mechanism that is primarily responsible for this additional strength and ductility is fiber pull-out. Upon first cracking, much of the deformation is attributed to fiber extension. As load and deformation continue to increase, and multiple cracking occurs beyond the proportional elastic limit, fibers begin to debond and subsequently slip or pull-out to span the cracks and resist the applied load. Load resistance is developed through friction between the glass fibers and the cement matrix as the fibers debond and pull-out [3.10, 3.11].

Typical 28-day material property values for spray-up AR-GFRC are presented in Table 3.3 [3.8]. Flexural strength is

Table 3.3— Typical 28-day material property values for AR-GFRC

Property	AR-GFRC System*
Flexural strength, psi Modulus of Rupture (MOR) Proportional Elastic Limit (PEL)	 2500-4000 900-1500
Tensile strength, psi Ultimate Tensile Strength (UTS) Bend Over Point (BOP)	 1000-1600 700-1000
Shear strength, psi Interlaminar In-plane	 400-800 1000-1600
Impact strength, in. lb/in.^{2} Charpy	 55-140
Dry density, lb/ft^3	120-140

*Sprayed (non-dewatered) with 5 percent by weight of AR-fiber, sand: cement ratios range from 1:3 to 1:1, and water-cement ratios range from 0.25 to 0.35.

Metric equivalents: 1 psi = 6.895 kPa; 1 in.-lb/in.^{2} = 0.175 N-mm/mm^2; 1 lb/ft^3 = 16.019 kg/m^3

determined according to ASTM C 947 and density is determined according to ASTM C 948.

GFRC made of cement, AR-glass fibers, sand, and water is a non-combustible material and meets the criteria of ASTM E 136. When used as a surface material, its flame spread index is zero [3.8]. GFRC made with an acrylic thermoplastic copolymer dispersion for curing purposes will not pass ASTM E 136, but will have a flame spread index of less than 25.

Single skin GFRC panels can be designed to provide resistance to the passage of flame, but fire endurances of greater than 15 minutes, as defined in ASTM E 119, are primarily dependent upon the insulation and fire endurance characteristics of the drywall or back-up core [3.12].

3.4—Long-term performance of GFRC

Extended exposure of GFRC to natural weather environments will result in changes in mechanical properties. Furthermore, exposure of GFRC to normal natural weathering cycles (moisture and temperature cycles) will result in cyclical volumetric dimension changes. Changes in mechanical properties and cyclical dimensional movements must be accounted for by use of proper design procedures, such as those outlined in Sections 3.7 and 3.9.4 and detailed in References 3.5, 3.8, 3.13, and 3.14.

Most commercially manufactured GFRC composites will experience reduction in tensile and flexural strengths and ductility with age if exposed to an outdoor environment. The strength of fully-aged GFRC composites will decrease to about 40 percent of the initial strength prior to aging. However, strain capacity (ductility or toughness) will decrease to about 20 percent of the initial strain capacity prior to aging. This loss in strain capacity is often referred to as composite embrittlement. Embrittlement is time and environment dependent and is accounted for in design of GFRC components as is explained in Section 2.6.

Dimensional changes in GFRC can be considerably greater than those of conventional concrete. This is the result of the high cement content in the mortar matrix. Cyclic strains resulting from wetting and drying can be as large as 0.15 percent, and strains of this magnitude are generally encountered throughout the service life of the facade panel [3.14]. Given sufficient exposure, this dimensional sensitivity can lead to over stressing unless accommodated for in design. Over stressing or stress concentrations can cause cracks to develop. This can be critical in components that are overly restrained. In addition, as the composite ages and becomes less ductile, the most effective and practical way to accommodate dimension change is to eliminate restraint by using flexible connections as described in Section 3.9 [3.5, 3.8, 3.13, 3.14]. Experience with single skin, steel-stud/flex-anchor connection type panels has shown them to be less sensitive to long-term cracking associated with restraint of panel movements caused by normal changes in moisture and temperature [3.15]. In the future, the application of surface coatings to reduce or eliminate moisture movement and thereby reduce shrinkage strains may turn out to be a valuable tool to deal with this phenomena. In addition, surface coatings may reduce the extent of embrittlement which usually takes place in moist conditions.

The durability performance of the composite material itself is usually evaluated by determining the changes in strength and toughness during exposure to natural weather or under accelerated aging conditions (immersion in hot water baths). Two basic theories have been suggested to explain loss in strength and strain capacity in GFRC composites. One theory is that alkali attack on the glass fiber surfaces results in the reduction of the fiber tensile strength and, subsequently, reduction of composite strength [3.16]. The second and most accepted theory suggests that ongoing cement hydration in water-stored or naturally weathered GFRC results in hydration products penetrating the fiber bundles, filling the interstitial spaces between glass filaments, thereby increasing the bond to individual glass filaments. This phenomenon can lead to lack of fiber pull-out and results in a loss in tensile strength and ductility [3.10, 3.17, 3.18, 3.19]. It is possible that both phenomena (alkali attack and filling of the interstitial spaces between glass filaments) are occurring simultaneously and at different rates, with alkali attack being more significant in E-glass fiber systems and the mechanism of filling interstitial space between fibers being the main cause of strength and ductility loss in AR-glass fiber systems [3.19, 3.20].

3.4.1—*Strength and toughness retention of AR-GFRC*

Following the introduction of Cem-FIL AR-glass fiber in 1971, test programs were independently initiated by BRE, Pilkington Brothers Ltd., and Owens-Corning Fiberglas to assess long-term strength and toughness behavior of AR-glass composites when exposed to a range of environmental conditions. Data for l0-year-old long-term strength durability tests have been published [3.16, 3.21] for composites having no sand and no polymer (neat cement composites). These data are presented in Figs. 3.2 through 3.4. As shown in Fig. 3.2, Modulus of Rupture (MOR) decreased with time under natural weathering conditions. After 10 years of natural weathering in

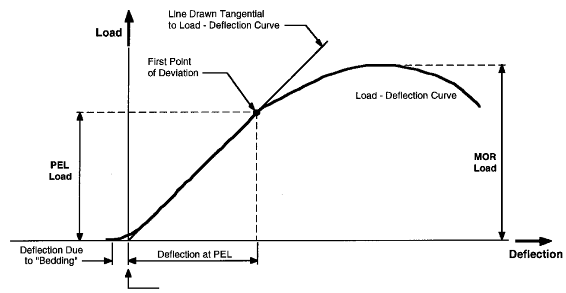

Fig. 3.1—Generalized load-deflection curve for 28-day-old GFRC subjected to a flexural test

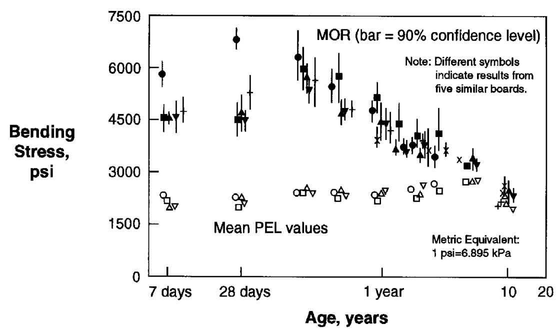

Fig. 3.2—Modulus of rupture and proportional elastic limit versus age for neat cement AF-GFRC composites stored in natural U.K. weathering conditions

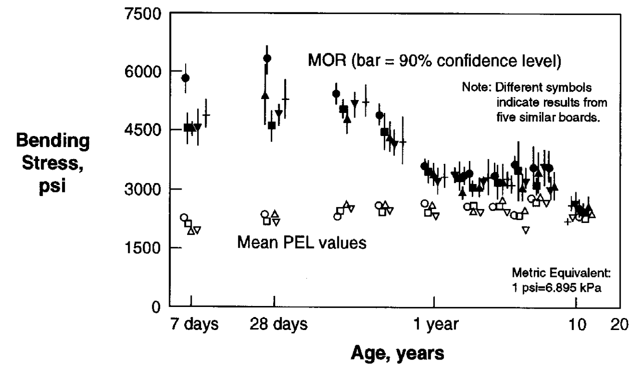

Fig. 3.3—Modulus of rupture and proportional elastic limit versus age for neat cement AR-GFRC composites stored in water at 64 to 68 F (20 C)

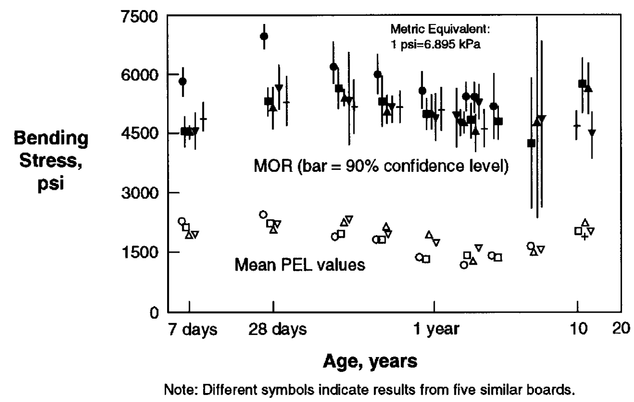

Fig. 3.4—Modulus of rupture and proportional elastic limit versus age for neat cement AF-GFRC composites stored in air at 68 F (20 C) and 40 percent relative humidity

the United Kingdom, the MOR decreased to nearly the strength level of the Proportional Elastic Limit (PEL). In addition, data shown in Fig. 3.3 indicate that AR-GFRC composites stored in water at 64 to 68 F (18 to 20 C) exhibited this same MOR strength loss over the same period of time. However, composites stored at 68 F (20 C) and 40 percent relative humidity exhibited relatively little MOR strength loss with age as shown in Fig. 3.4 [3.21].

In addition to the long-term natural aging test programs, accelerated aging programs were conducted by all three major glass fiber producers so that projections of aged properties could be made in advance of the natural aging data. Accelerated aging is accomplished by immersing composites in water at elevated temperature to expedite the cement hydration process [3.22, 3.23]. However, true aging of a specific GFRC product can only be accomplished through actual use of the product under normal in-place environmental conditions. Any attempt to characterize the aged behavior of GFRC using accelerated methods is only an approximation.

For GFRC panels (containing no polymer and made with either neat cement or sand-to-cement ratios of 1-to-3), accelerated aging data have been correlated with data obtained from natural weathering conditions for the purpose of projecting long-term durability. In an investigation conducted by Pilkington Brothers Ltd., this correlation was accomplished for different climates throughout the world. Based on this investigation, it is projected that for many exposure conditions, the MOR of GFRC composites will eventually decrease to nearly the strength level of the PEL. For many GFRC products exposed to outdoor environments, this strength reduction is shown to occur within their normal life spans and may be a function of panel surface treatment (exposed aggregate and surface sealers) and environment. However, neither panel loading histories nor the effects of possible panel surface treatments were considered in the investigation.

In addition, strength reduction has been shown to occur at faster rates in warmer, more humid climates [3.22, 3.24]. Figure 3.5 presents modulus of rupture data for composites exposed to natural weathering in the United Kingdom and for composites having undergone accelerated aging at elevated temperatures [3.22]. Data indicate that as the accelerated aging temperature increases, a faster drop in MOR strength is observed. A lower limit exists for the MOR strength that is essentially equal to the PEL of the composite, which is a measure of the matrix cracking strength of the reinforced composite.

Use of accelerated aging procedures has led to strength predictions extending over many years. Modulus of Rupture strengths shown in Fig. 3.5 for composites aged at 122, 140, and 176 F (50, 60, and 80 C) have been combined with the actual U.K. weathering results out to 10 years in Fig. 3.6 [3.25]. This has been accomplished by displacing the higher temperature accelerated strength results along the log-time axis until they coincide with the strength results of composites stored in the U.K. weathering conditions. As shown in

Fig. 3.6, results for the different acceleration temperatures form a common curve that extends forward for many years.

Loss in strain capacity is also observed upon aging of GFRC composites. Shown in Fig. 3.7 are representative stress-strain curves in tension and bending for composites tested at 28 days and 5 years. All composites were stored in water at approximately 68 F (20 C) [3.26, 3.27]. Unaged composites, tested at 28 days, exhibit strain capacities on the order of 1 percent for both tension and bending tests as shown in Fig. 3.7a. Composites aged for five years in water at 68 F (20 C) show a substantial decrease in strain capacity as indicated in Fig. 3.7b. Loss in strain capacity with aging, which is much greater than reduction in tensile or flexural strength, may be of greater significance to the long-term performance since it leads to an increased sensitivity to cracking. This characteristic of the material can be estimated by impact resistance testing. For an in-depth discussion of toughness durability, see Ref. 3.28.

It has been reported [3.29, 3.30]that additions of polymers to AR-GFRC provide valuable advantages, such as reducing absorption and reducing wet/dry shrinkage movements. However, the AR-GFRC composites with polymer additions did not correlate well with predictions of long-term strength from hot water accelerated aging tests versus performance in real weathering exposure.

In hot water aging, polymer additions have been shown to provide no significant advantage in strength retention. However, there have been reports of improvements in strength retention during actual weathering exposure over several years [3.29]. It has been reported that after 2 years in the hot Florida and Arizona climates, AR-GFRC with 5 percent polymer solids by volume of total mix and 5 percent by weight of total mix of a specially coated AR-glass (to be discussed in Section 3.4.3.1) showed no loss in MOR strength and retention of high strain to failure [3.29]. With regard to comparisons of strength durability between accelerated aging and real weathering, one researcher reports that polymer additions do not inhibit embrittlement of the fiber system in total water immersion and hence do not lead to strength retention [3.11]. However, in natural weathering conditions, the water absorption is reduced, thereby postponing the time effects of fiber embrittlement [3.29, 3.31]. The study has also shown that under natural weathering conditions, a minimum addition of 5 percent polymer solids by volume of total mix to GFRC provides improved strength retention over standard GFRC [3.29, 3.32].

Due to the difference in measured performance between GFRC with and without polymer additions using the standard hot water immersion accelerated aging test, a test procedure adapted from the European asbestos-cement industry has been substituted [3.33]. The alternate accelerated aging test involves immersion in water at 68 F (20 C) for 24 hours followed by forced air drying at 158 F (70 C) at a speed of 3.3 fps (1 m/sec) for 24 hours. This is considered one cycle. The test typically involves at least 160 exposure cycles. Better correlation between accelerated aging results of this test and natural weathering have been observed for composites containing polymer [3.31, 3.33].

The results show that for a polymer content of 5 percent by volume of mix, modest improvements in MOR, PEL, and strain at MOR have been obtained. MOR after 160 wet/dry cycles was approximately 2175 psi (15 MPa) compared to 1450 psi (10 MPa) for unmodified AR-GFRC. Values for initial MOR (before wet/dry cycling) was approximately 3915 psi (27 MPa) with 5 percent polymer content by volume of mix compared to

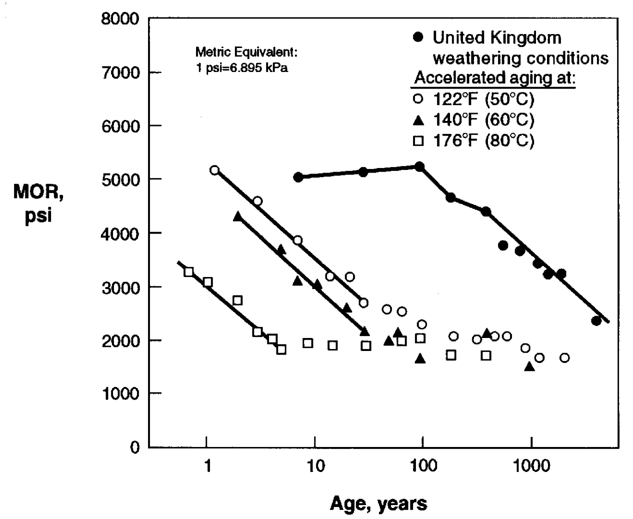

Fig. 3.5—Projected MOR versus age for neat cement AR-GFRC composites stored in natural U.K. weathering conditions and accelerated aging conditions

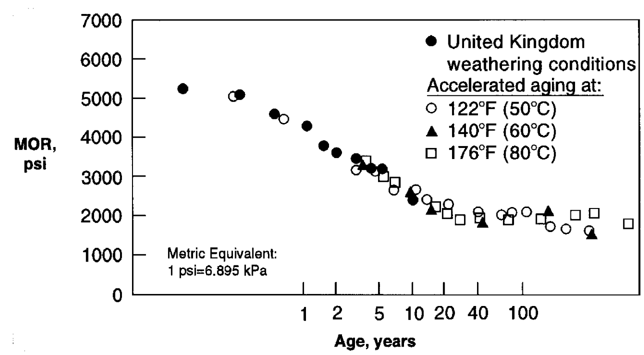

Fig. 3.6—Accelerated aging data used to project long-term strength of AR-GFRC under natural U.K. weathering conditions

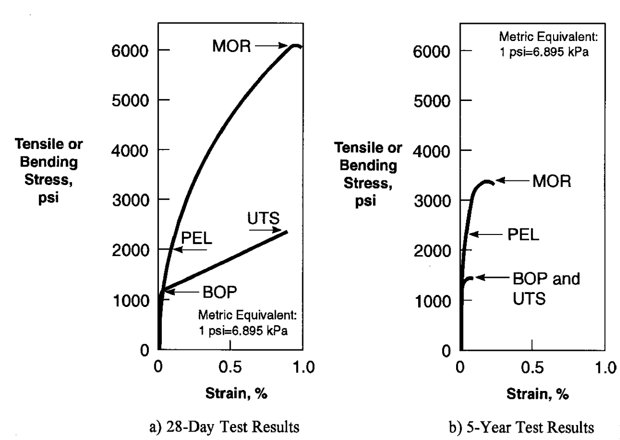

Fig. 3.7—Representative stress-strain curves in tension and bending for 1 AR-GFRC stored in water at 68 F (20 C)

4205 psi (29 MPa) without polymer. Strain at the MOR was approximately 0.25 percent compared to 0.1 percent for unmodified AR-GFRC. Polymer contents of 9 and 12.5 percent by volume of mix showed more substantial retention of MOR strength and strain. After 160 wet/dry cycles, MOR remained at approximately 3300 and 4000 psi (23 and 28 MPa), respectively. Strain at the MOR was approximately 0.8 and 1.0 percent, respectively [3.33].

3.4.2—*Polymer (modified) E-glass fiber reinforced concrete (P-GFRC)*

In 1979, a different type of glass fiber reinforced concrete was introduced in Europe [3.34, 3.35]. It consisted of E-glass fibers embedded in a matrix that was made up of cement, sand, and a minimum of 10 percent polymer by volume of mix. At the present time, there is little use of this system in the United States. The majority of its use has been in the European countries. The reason for incorporating a polymer into the cement matrix-glass fiber system is to provide improved long-term durability. The concept behind achieving long-term strength durability through polymer modification of GFRC is described below [3.35, 3.36].

There are generally 204 individual glass filaments within a glass fiber bundle. The diameter of a single filament is approximately 10 microns. The width of spaces between glass filaments is only two to three microns. The average diameter of an anhydrous cement particle is approximately 30 microns. Therefore, most cement particles cannot pass into the spaces between the glass filaments within a typical glass fiber bundle. However, formation of hydration products, specifically calcium hydroxide [$Ca(OH)_2$], can occur inside these spaces and is thought by some to be the major cause of embrittlement and the decrease in composite strength with time.

In an attempt to reduce both physical embrittlement and chemical attack of the glass fibers, polymer particles were introduced into a system of E-glass fibers, cement, sand, and water. These polymer particles are only a fraction of a micron in diameter. Therefore, they can penetrate into the spaces between the glass filaments. Upon combining glass and a mortar containing a polymer dispersion, glass bundles take up water due to capillary forces acting in the spaces. The water carries the polymer particles into these spaces. The polymer particles adhere to each other as water is removed through both evaporation and hydration of the cement. The result is a polymer film that spreads in and around the individual glass filaments within each glass bundle [3.35-3.38].

The polymer film reportedly performs two functions. It protects some of the individual glass filaments from alkali attack and it partially fills the spaces between filaments thereby reducing the effects of fiber embrittlement [3.36-3.38]. However, there are reports that polymer modification as high as 15 percent solids by volume only provides about 50 percent coverage of the E-glass filament surfaces and that those filaments not protected by the polymer film become severely etched by alkali attack after 17 weeks of accelerated aging at 122 F (50 C) [3.11].

3.4.3—*Recent developments for improvement of GFRC durability*

Even though polymer additions to AR-GFRC have been shown to reduce the rate at which GFRC composites lose strength and ductility [3.29, 3.33, 3.39-3.41], commercially available GFRC systems will still experience reductions in strength and ductility at a rate that is environment dependent. Over the past few years, several new methods of improving the long-term durability of GFRC have been developed. All of these methods involve either specially formulated chemical coatings on the glass fibers or modification of the cement matrix.

3.4.3.1 *Glass fiber modifications*—Since the introduction of alkali-resistant glass fiber in 1971, several attempts have been made to further improve glass fibers for use in GFRC. Most of these attempts have been directed towards improving commercially available AR-glass fibers by application of special fiber coatings. These special coatings are intended to reduce the affinity of the glass fibers for calcium hydroxide, the hydration product that is primarily responsible for composite embrittlement. Some second generation AR glass fibers, which are currently commercially available, are examples of the potential benefits of fiber coatings. Long-term durability data for composites manufactured with these fibers indicate that strength and ductility decrease at slower rates than conventional AR-glass composites. However, there is still some loss in strength and toughness indicated by current test results. Since predictions of long-term material properties are based on a correlation of accelerated aging data with natural aging data, it is still too early to make an accurate prediction of how effective these fibers will ultimately be for improving the long-term strength and ductility [3.25].

Nippon Electric Glass Company, Ltd., [3.42] has found that certain alkali resistant organic materials used as coatings for conventional AR-glass fiber will result in noticeable improvements in fiber tensile strength retention. Figure 3.8 illustrates the improved strength durability of conventional AR-glass fiber strand when alkali-resistant organic coatings are used. As indicated in Fig. 3.9, flexural strength tests performed on aged GFRC composites containing coated AR-glass fibers confirmed that the improved fiber strength retention does result in some improvement in the flexural strength retention of the GFRC composite [3.42].

A method called "silica fume slurry infiltration" was developed [3.43]to incorporate silica fume directly into the spaces between individual glass filaments in a fiber glass roving. It was discovered that by hand-dipping the rovings into a commercially dispersed silica fume slurry, the spaces between the individual glass filaments could be adequately filled with silica fume. Results of tests performed on aged composites containing 3 percent AR-glass fiber by weight and fabricated using silica fume slurry infiltration indicated a substantial decrease in the rate at which strength loss takes place [3.43]. It has not been determined whether this manufacturing method is commercially feasible.

Nippon Electric Glass Research laboratories have produced sprayed-up composites having 5 percent AR-glass and concentrations of silica fume up to 30 percent by weight of cement without significantly improving the aged strain capacity of the composite [3.42].

3.4.3.2 *Cement matrix modifications*—Over the years, several researchers have approached the GFRC strength durability problem by altering the cement matrix. Most of these efforts

were geared towards trying to reduce or eliminate the formation of calcium hydroxide produced during hydration.

Development of high alumina cement (HAC) and supersulphated cement represented early attempts at trying to modify the cement matrix. Although both of these cements were somewhat effective in improving the long-term strength durability of GFRC composites, other undesirable effects such as increased porosity and strength loss of the cement matrix were evident [3.44].

A more recent development is the use of lime reactive materials as cement additives. Silica fume and metakaolin as used in standard portland cement have proved to be effective agents for early reaction and elimination of calcium hydroxide. However, in order to significantly reduce the levels of calcium hydroxide, very large percentages (greater than 20 percent) of the materials must be used [3.42].

Methods have been developed to incorporate large percentages of silica into the cement matrix without dispersion problems [3.42, 3.43]. However, incorporation of large percentages of silica fume has not shown to be a very cost effective method of improving the long-term durability or aged strain capacity of GFRC.

Recently completed research [3.45] has resulted in the commercialization of a system, developed by Vetrotex, a subsidiary of St. Gobain, utilizing the addition of selected metakaolinites and an acrylic polymer to the GFRC mix. This system, which uses conventional production techniques, has shown to develop significantly higher aged properties than obtained using a conventional AR-GFRC mix [3.46].

Another new development regarding improved long-term strength durability of GFRC is CGC cement [3.42]. CGC cement was developed in Japan by Chichibu Cement Company in cooperation with Nippon Electric Glass Company, Ltd. This cement is claimed to produce no calcium hydroxide during hydration. As indicated in Fig. 3.10, tests performed on GFRC composites fabricated using CGC cement and AR-glass fibers indicated that initial 28-day strengths and ultimate strains (not shown in Fig. 3.10) are essentially retained after exposure to accelerated aging conditions. However, use of CGC cement in composites fabricated using E-glass fibers was unsuccessful because of the alkali attack on the glass fibers [3.42]

Primary curing after manufacture of sprayed or cast CGC cement is very important. Primary curing must be done according to the time-temperature curing regime shown in Fig. 3.11. Temperature must be automatically controlled using temperature sensors at the heat sources (usually steam). In the winter months, precuring is an effective way of saving time within the curing regime up to the final trowel finishing. The heating rate for primary curing must be maintained as noted to achieve optimum properties. The secondary curing after steam curing should be done indoors or in a protected area. In the case of products stored outside, items should be covered with a plastic sheet during the 7 days after demolding to prevent adverse drying from direct sunlight and wind.

Another promising candidate is a new cement introduced by Blue Circle Cement Company of England [3.47]. This cement, when combined with an additive developed by Molloy and Associates of Hutchins, Texas, is similar to CGC in terms of aged performance, and is available as a concentrate for addition to portland cement composites. Data indicate improved aged

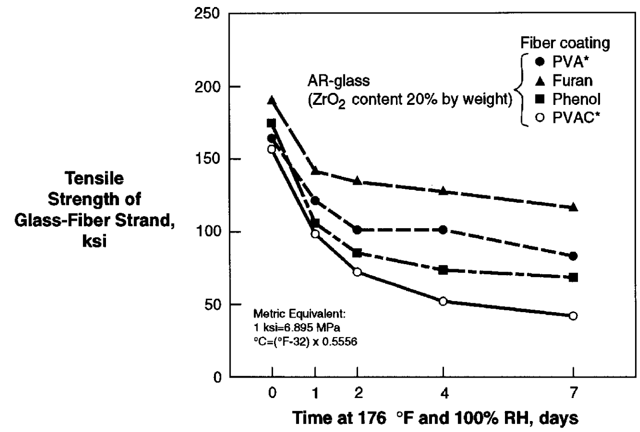

Fig. 3.8—Tensile strength of glass fiber strand with various coatings stored in OPC paste at 176 F (80 C)

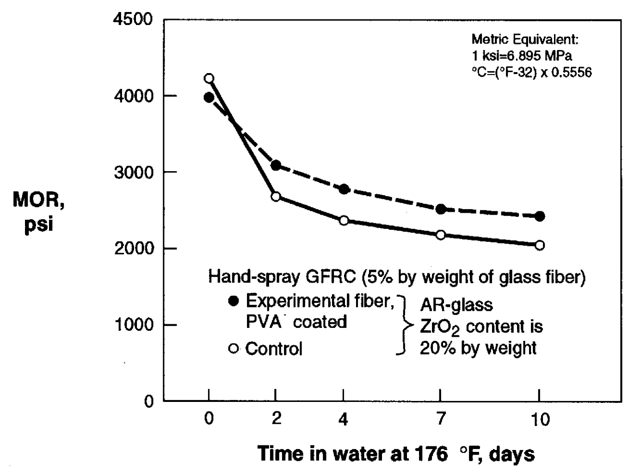

Fig. 3.9—Flexural strength of GFRC composites incorporating AR-glass fiber with alkali-resistant organic coating stored in water at 176 F (80 C)

strain capacity and unlike CGC cement, this material does not require a specific temperature controlled curing environment [3.48]. This cement is in commercial use in England. Research on the Blue Circle cement and other similar cements is currently underway in the United States [3.49]. These new cements are based on calcium sulphoaluminate and do not contain the cement phases that cause the conversion problems associated with high alumina cement. Tests are continuing to identify any other possible secondary reactions.

3.5—Freeze-thaw durability

Freeze-thaw durability of both AR-GFRC and P-GFRC composites has been studied [3.11, 3.36, 3.46]. Research has indicated that AR-glass fibers effectively preserve the cement matrix against significant freeze-thaw deterioration in comparison with an unreinforced matrix. There are some indications of a slight decrease in PEL strength due to the effects of freeze-thaw cycling [3.11].

Another study concluded that the freeze-thaw resistance of P-GFRC composites is good due to the lower absorption and greater ductility of the polymer modified matrix [3.36].

3.6—Design procedures

In the United States to date, design procedures have only been developed for AR-GFRC wall panels [3.8]. Design stress levels are based on a projection of the long-term properties. The long-term flexural strength of AR-GFRC exposed to natural weathering environments decreases with time to nearly, but not less than, the strength level of the unaged Proportional Elastic Limit (PEL). Furthermore, the PEL strength of AR-GFRC composites increases slightly with age. Therefore, design is conservatively based on the assumption that the long-term Modulus of Rupture (aged MOR) is equal to the 28-day PEL [3.8].

When designing GFRC panels, service loads are set by the designing, governing building code and are multiplied by the appropriate load factor from ACI 318 to determine factored loads. The following load factors and load combinations should be considered as a minimum [3.8]:

$$0.75\,[\,1.4\,D + 1.7\,(\text{greater of } L, W \text{ or } 1.1\,E) + 1.6\,(\text{greater of } M \text{ or } T)\,]$$

where:

D = Dead load
E = Earthquake load
L = Live load
M = Self-straining forces and effects arising from contraction or expansion due to moisture changes
T = Self-straining forces and effects arising from contraction or expansion due to temperature changes
W = Wind load

3.6.1—*Design stresses*

3.6.1.1 *Flexural*—Based on straight line theory of stress and strain in flexure, stresses due to factored loads should not exceed f_u:

$$f_u = \varphi s f'_u$$

Where:

φ = strength reduction factor
s = shape factor
f'_u = assumed (aged) modulus of rupture or ultimate flexural strength

The strength reduction factor (φ) is taken as 0.67. Derivation of this factor has been based on experience and judgment and is not intended to be precise. The shape factor (s) is a reduction factor to account for stress redistributions that occur in special cross sections. The basic strength test for GFRC in flexure uses a solid rectangular specimen. The shape factor for this cross section, which is also used for design of single skin panels, is 1.0. Shape factor suggested for flanged, box, or I sections is 0.5. Other values may be used if substantiated by test.

The assumed (aged) modulus of rupture (f_u) for design purposes is given by the lesser of the following:

$$\frac{f_{yr}(1-tV_y)}{0.9} \text{ or } \frac{1/3\,f_{ur}(1-tV_u)}{0.9} \text{ or 1200 psi (8MPa)}$$

where:

f_{yr} = average 28-day PEL strength of 20 consecutive tests (each test being the average of six individual test coupons).
f_{ur} = average 28-day MOR strength of 20 consecutive tests (each test being the average of six individual test coupons).
t = "Students t," a statistical constant to allow for the proportion of tests that may fall below f_u. The value is 2.539 for the recommended 20 tests.
V_y, V_u = coefficient of variation of the PEL and MOR test strengths, respectively.

The average 28-day PEL and MOR strengths are determined according to ASTM C 947.

3.6.1.2 *Shear*—Reference 3.8 states that direct shear seldom controls the design of GFRC elements. Interlaminar shear seldom controls design unless the shear span-to-depth ratio is less than 16. In-plane shear, occurring in diaphragms and webs, seldom controls design. However, in-plane shear should be checked based on principal tensile stresses that are limited by the allowable tensile stress. The allowable tensile stress is assumed to be equal to 0.4 $\varphi f'_u$.

3.6.1.3 *Deflection*—Deflections due to service loads are generally limited to $^1/_{240}$ of the span. This limit can be exceeded when investigation shows that adjacent construction is not likely to be damaged by deflection.

3.6.2—*Connections*

There are several methods being used to fasten GFRC panels to buildings. The fastening detail must provide for and accommodate creep, thermal and moisture induced panel movement, field tolerances, and dimensional changes in the structural frame of the building.

Each manufacturer is required to test production connections to establish test data for use in design. Test values are reduced by the appropriate safety factors to determine connection strength for use in design.

3.7—Applications of GFRC

By far, the single largest application of GFRC has been the manufacture of exterior building facade panels. This application makes up at least 80 percent of all GFRC architectural and structural components manufactured in the U.S. Since the introduction of AR-glass in the 1970s, growth in applications has been appreciable. According to the Precast/Prestressed Concrete Institute, over 60 million square feet of GFRC architectural cladding panels have been erected from 1977 to 1993. Initial problems in controlling panel warpage were solved using steel-stud frames, which also facilitated efficient attachment to building structures.

Another large application of GFRC is surface bonding, which is discussed in Section 3.10. Use of GFRC in other applications, such as electrical utility products—e.g., trench systems and distribution boxes—continue to increase as does surface bonding and floating dock applications. A growing application for GFRC is building restoration, replacing existing walls and ornate tile facades capitalizing on the light weight and shape versatility of the composite. Other application areas in which GFRC components are either already commercially produced, under development, or show future potential are listed in Table 3.4 [3.50, 3.51].

3.8—GFRC panel manufacture

Good GFRC manufacturing requires that manufacturers have the required physical plant and equipment, trained personnel, as

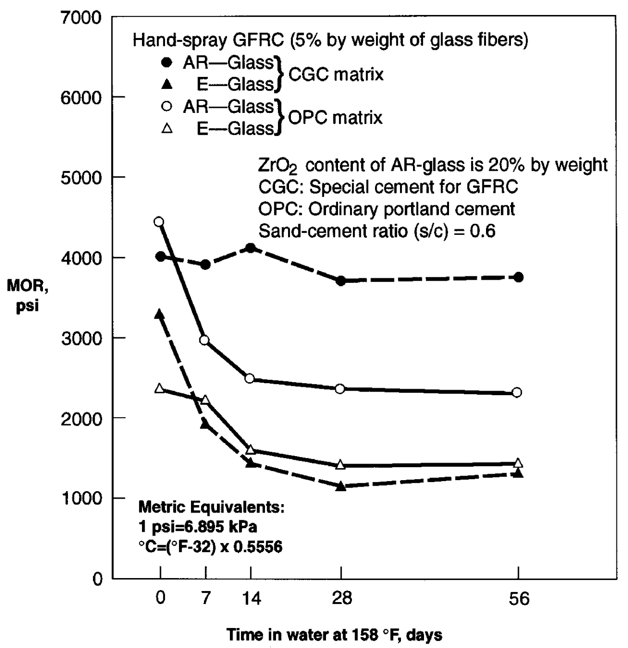

Fig. 3.10—Relative flexural strength of CGC-matrix GFRC composites stored in water at 158 F (70 C)

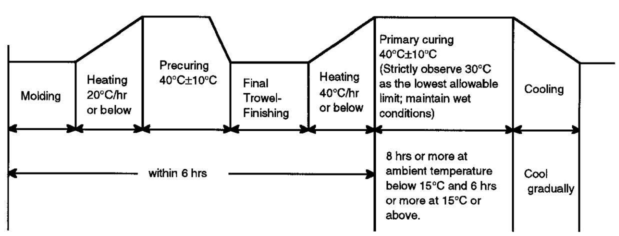

Fig. 3.11—Required curing regime for AR-GFRC composites manufactured with CGC cement

well as in-house quality control procedures to ensure a consistency in quality from panel to panel and project to project [3.7].

It is not the objective of this document to describe specific items relating to plant size or equipment type. However, the GFRC plant should be clean, have an enclosed area for the spraying or casting operation, the ability to maintain temperatures for adequate curing, well-maintained equipment for the proper proportioning and mixing of the materials, as well as equipment to deposit the materials in the forms. Furthermore, a GFRC plant should have a comprehensive quality control (QC) program for monitoring composite materials, in-process manufacturing operations, finished product, as well as a comprehensive testing program to determine production composite properties and a system for maintaining QC records [3.7, 3.52, 3.53].

Since the introduction of GFRC panels in the early l970s, three basic panel types have been manufactured: (1) sandwich panel, (2) integral rib panel, and (3) steel-stud/flex-anchor panel. Since the early l980's, the industry has evolved such that the majority of facade panels being manufactured in the U.S. is the steel-stud/flex-anchor panel. Therefore, this section on panel manufacture is exclusively devoted to the steel-stud/flex-anchor type of panel construction. There are a few producers that manufacture a sandwich panel using GFRC premix construction.

3.8.1—*Steel-stud framing system [3.7, 3.8]*

The steel-stud frame should be fabricated in accordance with Metal Lath/Steel Framing Association's "Lightweight Steel Framing Systems Manual." The studs are generally placed at 16 to 24 in. (0.4 to 0.6 m) on center with the flex-anchors (discussed in Section 3.8.2) spaced 16 to 36 in. (0.4 to 0.9 m) on center, based on design considerations. The prefabricated stud frame will be moved several times both before and after skin attachment; therefore, welded rather than screw connections are more desirable, although both systems are acceptable. With welding, studs are usually a minimum of 16 gauge material. Touch-up paint or coatings should be applied to accessible welds of the light gauge material after the stud frame has been fabricated. A photograph of a steel-stud frame being manufactured is shown in Fig. 3.12.

Environmental conditions will usually determine to what extent steel framing needs corrosion protection. Steel-studs are available with a red oxide paint or galvanized finish (before slitting and forming). Flex-anchor and gravity anchors may be zinc or cadmium plated before or after fabrication, painted with a zinc-rich coating, or they may be stainless steel, where the additional cost is justified by severe environmental conditions.

After fabrication, the stud frame is ready to be attached to the GFRC skin after the skin is sprayed and roller compacted to its design thickness. The stud frame is positioned over the skin with jigs to fix its location. Flex-anchors sometimes telegraph through and show on the face of the panel, so for production convenience they are usually set from $^1/_8$ to $^3/_8$ in. (3 to 10 mm) away from the surface of the GFRC skin. With some finishes, they may touch the surface of the GFRC skin. Where the flex-anchor is attached to the GFRC skin, the bonding pad is manufactured in one of two ways. They are the "green sheet overlay process" and the "hand-pack method." Both methods require the operators to hand apply the bonding pads and knead them into the GFRC skin. Time delay between the final roller compaction of the GFRC skin and the placement of the frame and the bonding pads should be kept to a minimum. This is necessary to ensure monolithic bonding of the bonding pads. If there is a significant time delay, initial set of the skin could prevent the bonding pad from achieving monolithic bonding to the skin and there could be a potential for subsequent delamination [3.52, 3.53].

The bonding pad thickness over the top of the flex-anchor contact foot should be a minimum of $^1/_2$ in. (13 mm) with a bonding area of 18 to 32 in.^{2} (13 to 20 x 10^3 mm^2). Care must also be taken not to build up the bonding pad over the heel of the flex-anchor and thus add undue restraint to skin movement.

The bonding pad over the cross piece of the flat bar tee gravity anchor should be sized to adequately support the tributary weight of the GFRC skin. Sizing of bonding pads should be based on actual axial and shear pull-off tests of bonding pads in the fully aged condition. This is discussed further in Section 3.9.4.

Table 3.4— Applications of GFRC

General area	Specific examples
Agriculture	Livestock products -water troughs -feeding troughs -sheep dips -pig slurry channels Sheds Irrigation channels Reservoir linings
Architectural cladding	Interior panels -single skin -double skin (thermally insulated) -paint, tile, aggregate facings Exterior panels -single skin -double skin (thermally insulated) -profile -paint, tile, aggregate facings, single skin
Architectural component	Doors and door frames Windows, sub-frames, and sills Elements for suspended ceilings Raised access floor panels Interior fixtures -prefabricated bathroom units -lavatory units -bench tops -shelving Shells
Asbestos replacement	Simple sheet cladding -flat -profiled Promenade and plain roof tiles Fire resistant pads General molded shapes and forms Pipes
Ducts and shafts	Track-side ducting for cables and switchgear Internal service ducts
Fire protective systems	Fire doors Internal fire walls, partitions Calcium silicate insulation sheets
General building (excluding wall systems and cladding panels)	Roofing systems (tiles, shingles) Lintels Cellar grills and floor gratings Decorative grills and sun shades Hollow non-structural columns or pillars Impact resistant industrial floors Brick facade siding panels Cellular concrete slabs
Low-cost housing, schools, factory buildings	Single and double skin cladding onto timber frame construction Prefabricated floor and roof units
Marine applications	Hollow buoys Floating pontoons Marina walkways Workboats, dinghies
Metal placement	Sheet piling for canal, lake, or ocean revetments Covers -manholes -meters -gasoline storage tanks at service stations -grating covers for guttering Hoods Stair treads
Miscellaneous	Sun collector castings Artificial rocks for zoo or park settings

Table 3.4— Applications of GFRC, continued

General area	Specific examples
Pavements	Overlays (to control reflection cracking)
Permanent and temporary	Bridge decking formwork Parapets Abutments Waffle forms Columns and beams
Reparations	Repair of deteriorating sculptured architectural—cornice, frieze, architrave
Site-applied surface bonding	Bonding of dry-block walls Single skin surface bonding to metal lath substrates Ultra-low- cost shelters (stacked unmortared mud brick)
Small buildings and enclosures	Sheds Garages Acoustic enclosures Kiosks Telephone booths
Small containers	Telecommunication junction boxes Storage tanks, silos Stop-cock and meter encasements and covers Manhole encasements and covers Utility boxes
Street furniture and associated	Seats and benches components Planters Litter bins Signs Noise barriers Bus shelters Revetment facing panels
Water applications	Low pressure pipes -drainage -sewerage Sewer linings Water channels (culverts) Canal linings Field drainage components -inspection chambers -hydrant chambers -head wall liners -pipe drain inlets -drainage covers, traps -guttering Tanks -swimming pools, ponds -fish farming -sewage treatment -septic tanks -storage tanks

Fig. 3.12—Fabrication of steel-stud frame

3.8.2—*Flex-anchor connections [3.7, 3.8, 3.49]*

In one connection method, the GFRC skin is attached to the steel-stud frame using flex-anchor connections. The weight of the GFRC skin is transferred to the steel-studs by the bending strength of the flex-anchors. To ensure structural integrity, the anchors must be of ample rigidity and strength to carry their tributary gravity and wind loads while still remaining flexible enough to allow relatively unrestrained thermal or moisture movements of the skin. This method is recommended for panels small enough that flex-anchor restraint stresses are acceptable.

If the flex-anchors are too rigid, they can induce high tensile stresses in the GFRC skin. Substantial GFRC skin movements caused by normal temperature and moisture effects, both uniform and gradient (through the skin thickness), can occur. In most circumstances, they result in the flex-anchors being stressed to their yield level. Flex-anchor stresses in excess of the actual yield stress may cause excessive deflections and, subsequently, material fatigue problems. For design simplicity, it is suggested that all flex-anchors be assumed to exert a restraining tensile stress in the GFRC skin equivalent to that which develops when their yield strength is reached.

This simplified approach is proposed in recognition of the difficulty in quantifying all factors. Gravity anchors then are required, and they should be flexible in the horizontal direction.

Figure 3.13 shows the most common type of flex-anchor. Although it is used with many variations, it is usually made with a smooth, round rod not less than $^1/_4$ in. (6 mm) in diameter. (Diameter choice is influenced by the clear length of flex anchor from weld to bonding pad and by whether or not a separate gravity anchor is provided.) It is welded at the top for flexibility with groove welds, although a square bar may be used for fillet welding convenience.

A plastic sleeve may be put over the anchor foot to minimize restraint. Anchor orientation with the toes positioned toward the center of the panel is advisable so that initial drying shrinkage will tend to move the flex-anchor away from rather than toward the stud. Also, rigid fire protection or thermal insulations should be installed so as not to inhibit skin movement.

Unsupported edges of GFRC panels can bow or warp due to moisture or temperature effects. This can present a problem with panel alignment, as well as an unsightly joint. It is, therefore, recommended that the edge distance to the end steel-stud be kept small to minimize warpage.

3.8.3—*Gravity anchor connections [3.7, 3.8]*

In larger, heavier panels, if the GFRC skin is attached to the steel-stud frame with only flex-anchors, the flex-anchors may provide excessive restraint and over-stress the skin. If the dead load is carried separately by special gravity anchor connections, the flex-anchors can be made smaller ($^1/_4$ in. or 6 mm minimum diameter), thereby substantially reducing the in-plane restraint.

In its plane the skin is quite rigid. If the steel-stud frame is made rigid with diagonals or heavy upper and/or lower tracks or if the frame is uniformly supported by the structure, the gravity load of the skin can be carried with a series of gravity anchors. This is usually accomplished with the trussed round bar gravity anchors located on every typical steel-stud or every other typical steel-stud as shown in Fig. 3.14.

If the frame is supported at two points, it may be convenient to support the skin's dead weight at the two corresponding locations. This allows the in-plane rigidity of the stud frame to be lower since the skin weight is carried only by the panel connector studs or tubes directly to the building connections. The connector studs or tubes may need strengthening locally for full height. The remaining typical studs then act as floating stiffeners. This is usually accomplished with the flat plate tee gravity anchor shown in Fig. 3.15. By adjusting the plate height and thickness, vertical strength of the anchor is achieved without sacrificing horizontal flexibility.

In seismic areas, the longitudinal seismic force resistance requirements must be achieved without excessive restraint. When using flex-anchors alone or a flex-anchor/gravity anchor system, stiffness of the steel-stud along the weak axis

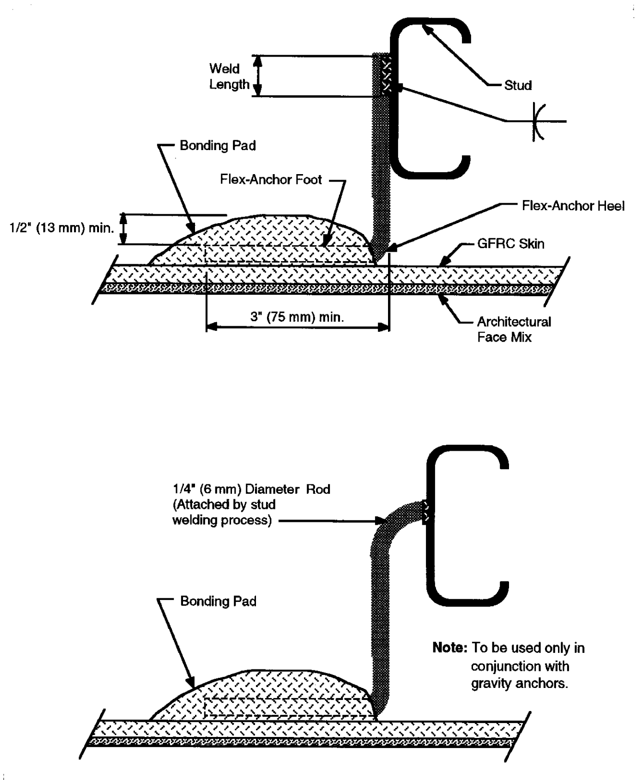

Fig. 3.13—Examples of flex-anchors

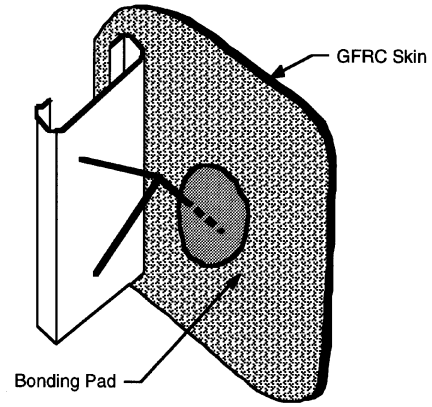

Fig. 3.14—Round-bar trussed gravity anchor

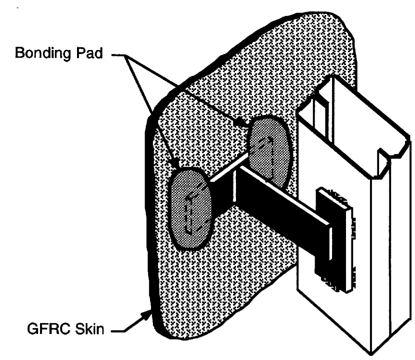

Fig. 3.15—Flat-plate tee gravity anchor

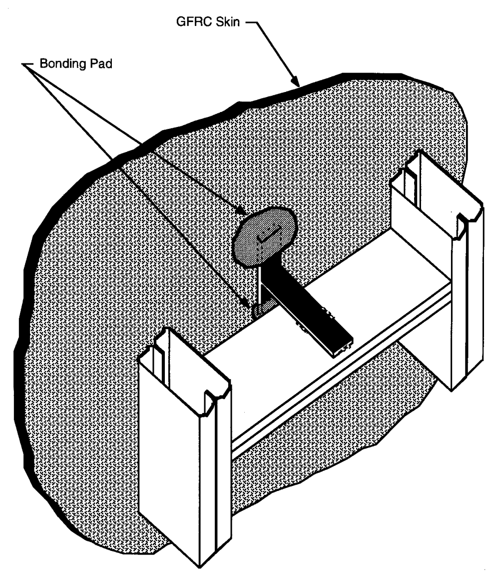

Fig. 3.16—Flat-plate tee longitudinal seismic anchor

must be considered. With a flat-plate tee system, it is advisable to strengthen only one (not both) of the gravity anchors to carry the seismic load. A horizontally oriented flat-plate tee anchor may be used to carry the longitudinal seismic force to the stud frame as shown in Fig. 3.16. There will be rotational forces that the anchor system must carry, if the seismic anchor system is not colinear with the center of mass of the skin.

Since the gravity anchors provide the fixed point from or toward which the GFRC skin moves, it may be advantageous to put the gravity anchors at mid-height for vertical panels. This also has seismic advantages in that overturning moments are reduced. However, permanent tensile stresses are produced, since the bottom half of the panel is hanging from the gravity anchors. Generally, it is preferable to have permanent stresses compressive, although they would have to be weighed against the seismic stresses. Stresses in both directions may also have to be considered at times [3.52, 3.53].

3.8.4—*Connection tests [3.89, 3.49]*

It is necessary that each producer perform a sufficient number of tests to develop a data base from which an allowable design load can be determined for each type of flex-anchor or gravity anchor. Seven test specimens made in an identical manner to the panel anchors should be tested. The highest and lowest values should be eliminated and the average of the five remaining values should be used for determining the allowable design load [3.8].

It is preferable to perform tests on representative, artificially aged specimens so that long-term material property variations are accounted for in design. Tests of artificially aged connections and bonding pads indicate strength reductions of 25 to 50 percent with the failure plane occurring typically at the bonding pad/panel interface or as a shear wedge above the flex-anchor foot [3.52, 3.53]. A conservative safety factor of 4 to service loads should be used on the aged test results. If the test specimens are unaged, a safety factor of 5 to service loads is

used on the test results. Test procedures that accurately simulate in-service conditions should be developed.

3.8.5—*Steel-stud frame/GFRC panel design approaches [3.8]*

Depending on the panel configuration and skin attachment system, the stud frames may need to provide in-plane rigidity comparable to the GFRC skin so that each stud can support its tributary portion of vertical loads. The frame must also have sufficient rigidity perpendicular to its plane to resist skin bowing forces caused by restraint of skin shrinkage. Bowing tendencies are generally greatest when the GFRC skin and the bonded face mix are not dimensionally compatible.

It has become apparent that some designers have not sufficiently recognized the effects of differential shrinkage and thermal expansion when panels are faced with a material that has different volume change properties than the GFRC [3.54]. If polymer addition is used in the GFRC, it should also be used in the face mix when possible, to ensure compatibility and to increase the aggregate-to-cement bond.

For integrally bonded facings, these effects can be minimized when the facing materials are selected to establish compatible material properties. When this is not possible, careful consideration of the induced stresses must be recognized in the design to ensure proper serviceability. For applied facings, the use of flexible adhesives or bond breakers and flexible anchors is recommended. In any case, properties used in analyses and design must be confirmed by each manufacturer through testing of the materials.

The GFRC skin should not be relied on to provide bracing for stud stability. Depending on stud dimensions, support conditions, interior finish, etc., bridging may be required to prevent stud buckling.

The steel-stud frame for a GFRC panel can be analyzed by many different methods. The GFRC skin spans between flex-anchors. It can be analyzed as (1) a simple beam between flex-anchors, (2) a continuous beam over a row of flex-anchors, or (3) a two-way slab system over an area of flex-anchors. In most cases, the edge GFRC skin is unsupported and needs to be checked by the designer.

The load from the GFRC skin is transmitted through the gravity and flex-anchors to the steel-studs. From the studs, the load is transmitted by horizontal tracks and vertical connector studs to the building connections and then to the structure. When the loads in the steel-stud frame exceed the capacity of the single stud, it is necessary to weld steel-studs together or to use a rolled structural steel shape.

Depending on the skin's gravity transfer system and its relationship to the panel bearing connectors, diagonal braces or strengthening of the horizontal tracks may be required. Also, greater stud capacity is required at the connection locations since they will resist the loads collected by the horizontal tracks. Increased capacity is usually accomplished by using double or boxed studs or by using a rolled structural shape.

Generally, the stud frame is attached to the structure with two load bearing connections (to eliminate indeterminate reactions) and additional non-load bearing (lateral) connections. At the connection of the steel-stud frame to the structure, it is common to supplement the light gauge steel-stud framing by welding heavier plate or angle assemblies to the studs in order to achieve better distribution of the load. However, in designs where welding is not practical or economical, rolled structural shapes can be used in lieu of steel-studs. Since the freedom from restraint of the GFRC skin is achieved by the flex-anchors, the stud-to-structure connection usually needs to address only the typical building movements such as floor deflections and wind and seismic drift. However, the horizontal deflection perpendicular to the plane of the panel should be limited to prevent damage to interior finishes or windows that are attached to the steel-stud frame.

3.8.6—*Surface finishes [3.8]*

Most types of surface finishes used successfully with architectural precast concrete will be acceptable on GFRC panels. The absence of large coarse aggregate in the GFRC mix allows it to follow closely the surface texture or pattern of the mold. A wide variety of surface patterns and textures can be achieved by casting the panels against form liners. It is advisable to avoid sharp angles and thin projections whenever possible and to incorporate chamfers or radii at inside corners of the form.

A smooth, off-the-form finish may be the most economical but is not recommended, because color uniformity of gray, buff, or pigmented surfaces may be difficult to achieve and the cement film on the GFRC may develop surface crazing, that is, fine and random hair-line cracks. This crazing has no structural or durability significance, but may become visually accentuated when dirt settles in the cracks. The esthetic limitations of smooth GFRC may be minimized by the shading and depth provided by creating profiled surfaces, such as fluted, sculptured, or board finishes; by subdividing the panel into smaller surface areas; by using white cement; or by using of applied coatings.

Panels can be produced with a $^1/_8$ - $^1/_2$-in. (3 to 13 mm) thick face mix with decorative aggregates. The aggregate may be exposed by retarders; sand or abrasive blasting; acid etching; or honing and polishing to produce the desired effect. Light, medium, or deep exposure of aggregates is possible.

Differential shrinkage between the face mix and the GFRC backing is important and should be considered in the mix proportions. Mix proportions should be developed such that moisture and thermal related movements between the bonded face mix and GFRC backing are dimensionally compatible.

The cement matrix also offers a wide choice of color variations through the use of gray, white, or buff-colored portland cements or through the use of color pigments. Concrete coatings or stains that are vapor permeable can be applied after adequate surface preparation.

When the surface of a GFRC panel has two or more different mixes or finishes, a demarcation feature is necessary. Different face mixes should have reasonably similar shrinkage behaviors to avoid cracking at the demarcation feature due to differential shrinkage.

Natural stone veneers (such as limestone, marble, or granite in narrow strips, small squares and rectangles, or regular-sized ashlar pieces) may also be attached to the GFRC skin.

A bond breaker between the veneer and GFRC skin is necessary to minimize bowing of the panel due to differential shrinkage.

Clay products, such as thin brick veneer, facing tile, and architectural terra cotta (ceramic veneer), may be attached to GFRC, but it is necessary to consider the differential moisture and thermal movements of the clay product facing and GFRC backing. Exact replicas of original ornamental work, such as terra cotta from historic buildings, can be made of GFRC.

Sample panels of adequate size may be necessary to translate design concepts into realistic production requirements. With any integral or attached surface finishing material, consideration must be given to the thermal and moisture induced dimensional changes and the compatibility of these dimensional changes. These considerations must account for the aged properties of the GFRC.

3.9—Surface bonding

Surface bonding is a new building concept used extensively for small commercial buildings as well as for sealing walls. Surface bonding has also been extensively used in mining applications.

Standard concrete block construction yields a wall very strong in compression, but weak in tension and flexural properties. The surface bonding concept provides properties of compression and flexure in a unique way. Concrete blocks are dry-stacked without mortar courses. Very small quantities of mortar are used on a selective basis to ensure that the concrete blocks are stacking vertically plumb to a predetermined height. After stacking, a layer of surface bonding material composed of cement, sand, and alkali resistant glass fiber is applied to the inside and outside surface to an approximate thickness of $^{3}/_{16}$ in. (5 mm). Usually the material is applied in two passes by trowel or by spray. If sprayed, the coatings are then troweled smooth. This application essentially forms a sandwich which, when fully cured, provides an extremely strong wall that is virtually airtight.

For higher walls, reinforcing steel is inserted in the vertical cores of the concrete block at specific intervals. These cores are then filled with concrete. Buildings as high as four stories have been erected using this method.

In addition, surface bonding is used extensively as a mine shaft sealant. In this particular case, a surface bonding material is applied to only one side of the concrete block wall. This system has increased in popularity because of low labor costs and the high performance of the structure.

3.10—Research recommendations

GFRC is an excellent material system producing significant weight savings in non-structural architectural cladding panels and other concrete products. It is recommended that programs generating new data on a continuing basis be encouraged. Some suggestions are listed below:

1. Research long-term strength durability of new and existing GFRC systems to evaluate both natural aging and accelerated aging techniques.
2. Research to evaluate the stability of the PEL strength of fully aged GFRC composites under cyclic environmental conditions such as wetting and drying and changes in temperature.
3. Continued research to determine characteristics of fiber-to-matrix bond, mechanisms of debonding, and fiber pullout.
4. Research to evaluate the state of microcracking that may exist at stress levels below or equal to the measured PEL.
5. Research to continue to develop guidelines for the use of applied surface treatments on GFRC products. Surface treatments include paint, stain, exposed aggregate, tile, and attached natural stone slabs. Production procedures should be documented, service performance evaluated, and the effect on long-term performance determined.
6. Research to identify architectural face mixes having properties compatible with GFRC back-up mixes in regard to temperature and moisture induced volume changes.
7. Research to evaluate the long-term performance of GFRC flex-anchor/bonding pad connections using accelerated aging procedures.
8. Research to document all design-related GFRC composite properties using the most recently introduced mix designs that have since formed the current industry standard for GFRC manufacture.

Improvements in composite performance is a challenge for every materials-oriented scientist or engineer. The work described above will provide information and accelerate improvement where needed. Research currently in progress on new mix proportions, additives, cements, and manufacturing methods continues to improve the performance and properties of GFRC.

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CHAPTER 4—SYNTHETIC FIBER REINFORCED CONCRETE (SNFRC)

4.1—Introduction

A variety of fiber materials other than steel, glass, or natural fibers have been developed for use by the construction industry for fiber reinforced concrete. These fibers are categorized as synthetic fibers for use in synthetic fiber reinforced concrete, SNFRC for identification.

4.1.1—*Synthetic fiber types*

Synthetic fibers are man-made fibers resulting from research and development in the petrochemical and textile industries. SNFRC utilizes fibers derived from organic polymers which are available in a variety of formulations. Fiber types that have been tried in portland cement concrete based matrices are: acrylic, aramid, carbon, nylon, polyester, polyethylene and polypropylene. For many of these fibers, there is little reported research or field experience, while others are found in commercial applications and have been the subject of extensive reporting.

Table 4.1 summarizes the range of physical properties of selected synthetic fiber types. The effect of temperature on synthetic fibers is shown in this table by listing the temperature at which fibers melt, oxidize, or decompose. Synthetic fibers are said to be melted when the crystalline portions of the polymers that they are made of are converted on heating from a solid to a glassy or liquid state. The temperature at which this physical change occurs is called the melting point. If on heating a fiber decomposes before it melts, it is because one of many possible chemical reactions as occurred at a lower temperature before reaching the melting point. A typical type of decomposition is oxidation. Oxidation is caused by the chemical reaction of the fiber with the oxygen in the air. The temperature at which a decomposition occurs is called the decomposition temperature. Decomposition is usually noticed because the fiber quickly changes color, fumes or undergoes an obvious chemical change.

4.1.2—*Historical background*

Twentieth century interest in synthetic fibers as a component of construction materials was first reported in 1965 [4.1]. Synthetic monofilament fibers were used in blast resistant structures for the U.S. Army Corps of Engineers Research and Development Section [4.2]. The fibers were of a size and shape (geometry) similar to that which was then being tested using steel fibers (SFRC) and glass fibers (GFRC). They were one-half to one inch (13 to 25 mm) in length with a fiber aspect ratio (length to diameter, l/d) of between 50 and 100. In this project, it was also discovered that the addition of what then was considered small quantities, 0.5 percent by volume, of synthetic fibers to concrete resulted in a composite with increases in both ductility and impact resistance [4.2]. However, it was another fifteen years before large scale development activities began with synthetic fibers.

Since the time of this early work, commercially available synthetic fibers in the 6 to 60 denier range have been shown to better distribute cracking, reduce crack size, and improve other properties of concrete as discussed later in this report. The earlier applications of synthetic fibers first used in the late 1970s had denier in the 300 to 400 range and lower aspect ratios. The finer denier fibers were used through the 1980s.

Applications with finer denier fibers, that is, relatively small diameter and high aspect ratio fibers, began with fiber volume percentages of approximately one-fifth of that which had been previously used with the coarser fibers. These low volume applications appeared at 0.1 to 0.3 percent by volume. However, even at these low volume additions, the fiber count (number of fibers in a unit volume of matrix) and specific surface (surface area of fibers per unit volume of matrix) are comparable with values found with higher volume percentages of coarser size fibers.

4.1.3—*Developing technologies*

With the emergence of new areas of application, research interest has moved to higher fiber contents where toughness index and other factors are design considerations. Toughness index is an indication of the load-carrying capabilities of the fibers within the concrete matrix after first crack.

Basically, cast-in-place concrete will accommodate up to 0.4 percent by volume of synthetic fibers with minimal mix proportion adjustments. Wet mix shotcrete with up to 0.75 percent by volume will provide major increases in toughness index values [4.3]. Fiber length and fiber configuration are important factors at this fiber content. In slab-on-grade applications, with collated fibrillated polypropylene fiber contents up to 0.3 percent by volume, the fatigue strength has increased dramatically [4.4].

The use of synthetic fibers in the form of layered mesh is similar in concept to the system known as ferrocement. Progress in research and in the development of commercial products has been rapid and has been reported in publications on ferrocement in the U.S. and in publications on fiber reinforced concrete principally in Europe. Readers interested in this development should refer to the work of ACI Committee 549.

4.2—Physical and chemical properties of commercially available synthetic fibers

The durability and chemical compatibility of fibers in the particular encapsulating matrix must be individually determined. The fibers indicated below have generally performed well in portland cement matrices. Fiber manufacturers and suppliers should confirm the suitability of their fibers for the intended application through independent third-party testing.

4.2.1—*Acrylic*

Acrylic fibers contain at least 85 percent by weight of acrylonitrile units. Selected properties of acrylic fibers are shown in Table 4.1. Generally, acrylic fibers used in the textile industry have a tensile strength ranging from 30 to 50 ksi (207 to 345 MPa). However, special high tenacity acrylic fi-

Table 4.1— Selected synthetic fiber types and properties*

Fiber type	Equivalent diameter, in. x 10^{-3}	Specific gravity	Tensile strength, ksi	Elastic modulus, ksi	Ultimate elongation, percent	Ignition temperature, degrees F	Melt, oxidation, or decomposition temperature, degrees F	Water absorption per ASTM D 570, percent by weight
Acrylic	0.5-4.1	1.16-1.18	39-145	2000-2800	7.5-50.0	—	430-455	1.0-2.5
Aramid I	0.47	1.44	425	9000	4.4	high	900	4.3
Aramid II[†]	0.40	1.44	340	17,000	2.5	high	900	1.2
Carbon, PAN HM[‡]	0.30	1.6-1.7	360-440	55,100	0.5-0.7	high	752	nil
Carbon, PAN HT[§]	0.35	1.6-1.7	500-580	33,400	1.0-1.5	high	752	nil
Carbon, pitch GP**	0.39-0.51	1.6-1.7	70-115	4000-5000	2.0-2.4	high	752	3-7
Carbon, pitch HP[††]	0.35-0.70	1.80-2.15	220-450	22,000-70,000	0.5-1.1	high	932	nil
Nylon[‡‡]	0.90	1.14	140	750	20	—	392-430	2.8-5.0
Polyester	0.78	1.34-1.39	33-160	2500	12-150	1100	495	0.4
Polyethylene[‡‡]	1.0-40.0	0.92-0.96	11-85	725	3-80	—	273	nil
Polypropylene[‡‡]	—	0.90-0.91	20-100	500-700	15	1100	330	nil

*Not all fiber types are currently used for commercial production of FRC.
†High modulus.
‡Polyacrylonitrile based, high modulus.
§Polyacrylonitrile based, high tensile strength.
**Isotropic pitch based, general purpose.
††Mesophase pitch based, high performance.
‡‡Data listed is only for fibers commercially available for FRC.
Metric equivalents: 1 in. = 25.4 mm; 1 ksi = 6.895 MPa; (degrees F - 32)/1.8 = degrees C.

bers have been developed to replace asbestos fiber in many fiber reinforced concrete products. These fibers have tensile strengths of up to 145 ksi (1000 MPa) [4.5, 4.6].

4.2.2—*Aramid*

Aramid (aromatic polyamide) is a high-modulus, man-made polymeric material that was first discovered in 1965. After many years of experimental research, a method to produce that material in fiber form was finally developed. Aramid fibers were initially produced for commercial applications by the early 1970s. Attempts to incorporate this fiber into concrete as a form of reinforcement began by the late 1970s. It has been concluded that the mechanical properties of a cement matrix reinforced with aramid fibers are sufficiently attractive to warrant further studies [4.7]. However, the high cost of aramid fibers has been a limitation to commercial acceptance.

Aramid fibers have relatively high tensile strength and a high tensile modulus, as shown in Table 4.1. Aramid fibers are two and a half times as strong as E-glass fiber and five times as strong as steel fibers per unit weight.

The strength of aramid fiber is unaffected up to 320 F (160 C). Aramid fiber exhibits dimensional stability up to 392 F (200 C) and is creep resistant [4.8, 4.9]. Aramid strand with different numbers of fibers of varying diameter is also available.

4.2.3—*Carbon*

Carbon fibers were developed primarily for their high strength and stiffness properties for applications within the aerospace industry. Compared with most other synthetic fiber types, carbon fibers are expensive and, as previously mentioned with aramid fibers, this has limited commercial development. However, laboratory research has continued to determine the physical properties of carbon fiber reinforced concrete (CFRC) [4.10-4.18].

Carbon fibers have high tensile strength and elastic modulus as shown in Table 4.1. They are also inert to most chemicals. Polyacrylonitrile (PAN) based carbon fibers are manufactured by carbonizing polyacrylonitrile yarn at high temperatures while aligning the resultant graphite crystallites by a process called “hot-stretching.” They are manufactured as either HM (high modulus) fibers or HT (high-tensile strength) fibers and are dependent upon material source and extent of hot-stretching for their physical properties. They are available in a variety of forms.

It has been shown that carbon fibers can be made from petroleum and coal pitch, which are less expensive than the polyacrylonitrile fiber used to make PAN based carbon fiber. Pitch based fibers are also manufactured in two types. General purpose (GP) fibers are made from isotropic (non-oriented fiber structure) pitch and are low in tensile strength and elastic modulus. High performance (HP) fibers are made from mesophase (highly oriented fibers) pitch which produces fibers with high tensile strength and high elastic modulus.

Carbon fiber is typically produced in tows (strands) that may contain up to 12,000 individual filaments. Tows are commonly pre-spread prior to incorporation in CFRC to facilitate cement matrix penetration and to maximize fiber effectiveness.

4.2.4—*Nylon*

Nylon is a generic name that identifies a family of polymers characterized by the presence of the amide functional group—CONH [4.19]. Various types of nylon fibers exist in the marketplace for use in apparel, home furnishings, industrial, and textile applications. A nylon fiber’s properties are imparted by the base polymer type (molecular weight, end groups, residual monomer, etc.), addition of different levels of additives (light and heat stabilizers, delusterants, etc.), manufacturing conditions (spinning, drawing, texturing, etc.), and fiber dimensions (cross-sectional shape and area, fiber length, etc.). Currently, only two types of nylon fiber are marketed for fiber reinforced concrete. They are nylon 6 and nylon 66.

Nylon fibers are spun from nylon polymer. The polymer is transformed through extrusion, stretching, and heating to form an oriented, crystalline, fiber structure. In addition to conventional yarns produced by standard drawing, nylon fiber properties may be enhanced by special treatments including over finishing, heating, air texturing, etc. Nylon fibers are available as multifilament yarns, monofilament, staple, and tow. For concrete applications, high tenacity (high tensile strength) heat and light stable yarn is spun and subsequently cut into shorter lengths.

Nylon fibers exhibit good tenacity, toughness, and excellent elastic recovery [4.20]. Selected properties for nylon fibers are shown in Table 4.1. Nylon is very heat stable and is readily used in commercial applications requiring this property, such as tires [4.20]. Nylon is hydrophilic, with a moisture regain of 4.5 percent [4.21]. The moisture regain property does not affect concrete hydration or workability at low prescribed contents ranging from 0.1 to 0.2 percent by volume, but should be considered at higher fiber volume contents. Nylon is a relatively inert material, resistant to a wide variety of organic and inorganic materials including strong alkalis. It has been shown to perform well under accelerated aging conditions [4.22].

4.2.5—*Polyester*

Polyester fibers—for example, polyethylene terephthalate (PET)—are available only in monofilament form. Denier of polyester fibers used in cement composites ranges from 15 to 100 [4.23]. To date, polyester fibers available to the concrete industry belong to the thermoplastic polyester subgrouping. This type of polyester exhibits physical and chemical characteristics that depend on manufacturing techniques. Selected fiber properties are shown in Table 4.1. One of several techniques involves the production of highly crystalline pellets, which are converted to filaments in a melt extraction process and subsequently stretched approximately 400 percent before cutting to desired length.

All thermoplastics are temperature sensitive. At temperatures above normal concrete service temperatures, fiber characteristics are altered. Temperatures above 536 F (280 C) cause molecular breakdown [4.20].

Polyester fibers are somewhat hydrophobic (do not absorb much water) and have been shown not to affect the hydration of the portland cement concrete [4.24]. Bonding of polyester fibers within the cement matrix is mechanical.

There is no consensus on the long-term durability of polyester fibers in portland cement concrete.

4.2.6—*Polyethylene*

Polyethylene has been produced for use as concrete reinforcement [4.25] in monofilament form with wart-like surface deformations along the length of the fiber. These deformations are intended to improve the mechanical bonding in cement paste and mortar. Selected fiber properties are shown in Table 4.1.

It has been reported that polyethylene fibers could be easily dispersed in concrete mixtures in volume percentages of up to 4 percent using conventional mixing techniques [4.26]

Polyethylene in pulp form has also been applied in concrete mixtures. In this application the pulp, a fine irregular form of fiber, acts to retain cement fines by acting as filter fibers [4.27-4.29] and its use is intended as an alternate to the use of asbestos fibers.

4.2.7—*Polypropylene*

Monofilament form fibers are produced in an extrusion process in which the material is hot drawn through a die of circular cross section, generating a number of continuous filaments at one time called a tow.

Fibrillated polypropylene fibers are the product of an extrusion process where the die is rectangular. The resulting film sheets of polypropylene are slit longitudinally into equal width tapes. To achieve a lattice pattern, the tape is mechanically distressed or fibrillated with a patterned pin wheel or split film technique to produce the main and cross fibril networks. In some cases, the fibrillated tape is twisted prior to cutting to enhance the opening of the bundle. Fibers thus produced are termed collated, fibrillated polypropylene and are cut to desired lengths [4.14, 4.30].

Selected properties of polypropylene fibers are shown in Table 4.1. Polypropylene is hydrophobic, meaning it does not absorb water. Polypropylene fibers are not expected to bond chemically in a concrete matrix, but bonding has been shown to occur by mechanical interaction [4.31]. Polypropylene fibers are produced from homopolymer polypropylene resin. The melting point and elastic modulus, which are low relative to many other fiber types, may be limitations in certain processes such as autoclaving [4.32]. However, refractory product manufacturers use polypropylene fibers for early strength enhancement and because they disappear at high temperatures, providing a system of “relief channels” for use in controlling thermal and moisture changes.

4.3—Properties of SNFRC

Design methods for particular applications using low volume synthetic fibers have not yet been developed. Depending on the intended application, different manufacturers may suggest different volume content and fiber geometry. Acceptance criteria are prescribed in the ASTM Standard Specification C 1116 [4.33].

Reports on compression strength, splitting tensile strength, and flexural strength tests generally result in the conclusion that significant improvement in these strength properties will not be observed in mature specimens when synthetic fibers are applied at relatively low (0.1 to 0.2) volume percentages [4.34]. However, synthetic fibers have been shown to be effective in the early lifetime of the composite when the matrix is itself weak, brittle, and of low modulus. For mature concrete, improved material toughness is dependent on the fiber volume content and fiber durability in the matrix.

Improved toughness and crack control properties with SNFRC have been demonstrated for some fiber types [4.35]. Test methods used for flexural strength and toughness testing of FRC have been published [4.36, 4.37]. These methods have been applied to SNFRC as have other specialized tests, such as for shrinkage and crack control. Work on standard test procedures to evaluate shrinkage and crack control is presently being undertaken by ASTM Subcommittee C09.42.

The bonding of current commercially available synthetic fibers (nylon, polyester, and polypropylene) within the concrete matrix is mechanical. There is no chemical bond. The modulus of elasticity and Poisson’s ratio of each material will have an effect on bonding properties as will the fiber geometry and type derived from monofilament or fibrillated tape. Tests like the drop weight impact test and the toughness index test will show the bonding potential of various fiber types as well as the effect of other parameters such as fiber volume, fiber configuration, and fiber length.

4.3.1—*Acrylic FRC*

Acrylic fibers have been applied in cement-based composites as a replacement for asbestos fiber. In this process, fibers are initially dispersed in a dilute water and cement mixture. A pressure forming process follows in combination with vacuum dewatering. Composite thickness is built up in layers and the finished product has a low water to cement ratio and has sufficient pre-set and pre-hardened strength permitting it to be handled immediately [4.5, 4.42]. In this method other fibers, termed process fibers, are added to maintain mixture homogeneity and reduce segregation during vacuum dewatering. These are generally cellulose or polyfiber pulp fibers.

Acrylic fibers have also been added at low volumes in conventional batch mixing processes to reduce the effects of plastic shrinkage cracking [4.6, 4.41]. This application is similar to that discussed for polypropylene fibers, although far less field experience or research has been reported.

One study has provided data regarding the effects of certain manufacturing parameters on the performance of composites reinforced with high-tenacity acrylic fibers [4.5]. This research was conducted to determine the effects of acrylic fiber content, process fiber content and type, and pressing pressure used during fabrication, on the mechanical properties of the product. Composites were fabricated using vacuum-dewatering and pressing techniques in an attempt to simulate the Hatschek process, which is normally used for commercial, large-scale production of fiber-cement board. Flexural strength tests were used as a basis for evaluating composite performance. The Hatschek process was developed in 1898 by Ludwig Hatschek. When producing composites using the Hatschek process, the fibers are initially dispersed in a dilute water/cement mixture. During the fabri-

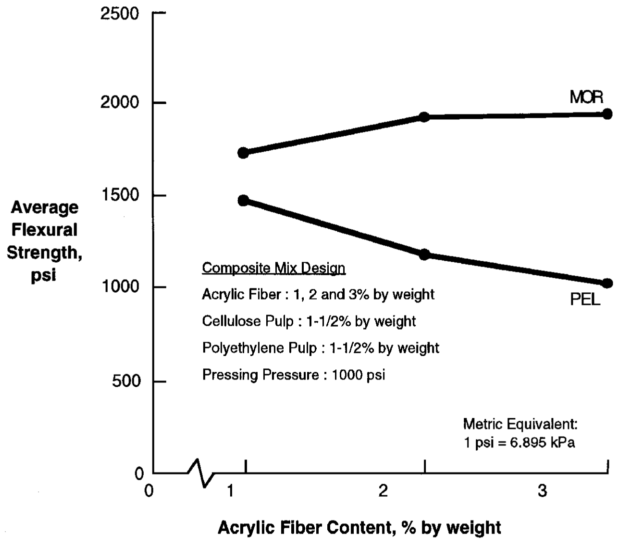

Fig. 4.1—Average flexural strength versus acrylic fiber content

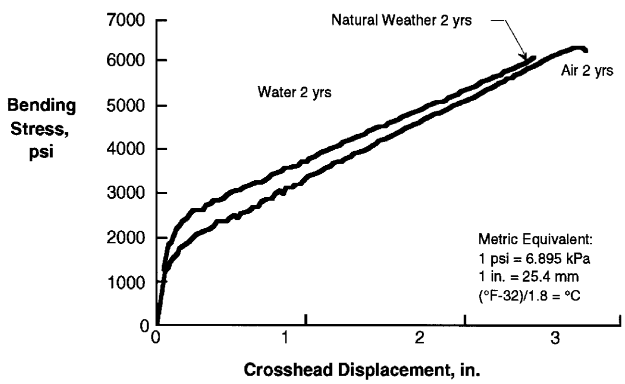

Fig. 4.2—Flexural strength of aramid FRC (1.78 percent fibers by volume) after two years of aging

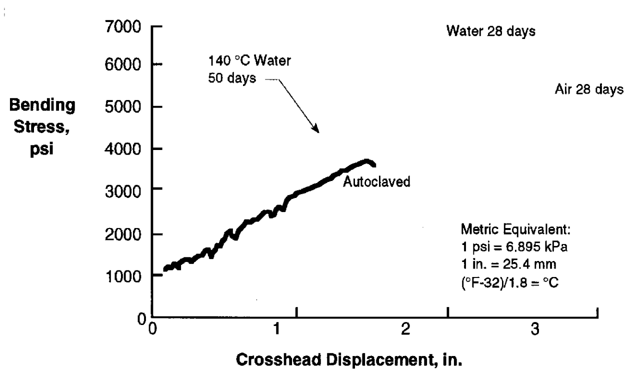

Fig. 4.3—Flexural strenngth of aramid FRC (1.78 percent fibers by volume) after autoclaving and after aging for several weeks

cation process, a great deal of the initial mixing water is removed through vacuum-dewatering. Composite thickness is gradually built up by layering. Finally, the composite is pressed to densify and remove still more of the water. Finished composites have very low water-cement ratios and sufficient "green strength" to be handled immediately [4.5, 4.42].

In one test series, acrylic fiber contents ranged from 1 to 3 percent by weight. Process fibers used for cement retention in these specimens consisted of $1^1/_2$ percent by weight of cellulose pulp in conjunction with $1^1/_2$ percent by weight of polyethylene pulp. Average flexural strength versus acrylic fiber content is shown in Fig. 4.1. As indicated by this figure, there is a trend for the Modulus of Rupture (MOR) to increase and the Proportional Elastic Limit (PEL) to decrease as the primary acrylic fiber content increases [4.5]. The investigation also determined that the total weight percentage of process fibers used had little effect on the average flexural strength of composites. Also, average flexural strength increased as pressing pressure used during fabrication increased from 500 to 1500 psi (3.5 to 10.5 MPa) [4.5].

4.3.2—*Aramid FRC*

Aramid fiber reinforced cement composites can be fabricated using conventional mixing and forming techniques or by using fabrication processes similar to those used to make asbestos cement products [4.8, 4.9]. Because aramid fibers are comparatively more expensive than other polymeric fibers, aramid fiber reinforced concrete has primarily been used as an asbestos cement replacement in certain high stress applications. As with other asbestos replacement fibers, aramid fibers exhibit poor filtration characteristics when used in the Hatschek fabrication process. They should therefore be used with a suitable filtration fiber whenever the Hatschek or similar fabrication method is employed [4.25].

Aramid FRC composites have also been prepared using a spray-suction technique [4.7]. With this technique, aramid fibers and an atomized cement slurry were supplied from separate sources and sprayed simultaneously onto a flat surface to achieve a random fiber distribution. Excess water was removed from the resulting mixture using suction from below, and the top surface was troweled flat. Fiber contents of up to 2 percent by volume were obtained [4.7].

Results of tensile, flexural, and the Izod impact tests for test specimens subjected to various curing conditions are reported in Table 4.2 [4.14].

Curing and aging conditions were varied among the test specimens. The test results were compared with results from tests performed on "control" specimens in order to assess the long term strength durability of the aramid FRC. The control specimens were subjected to a normal 28-day moist cure prior to testing. The test results as shown in Table 4.2 indicated the following [4.14]:

1. For three selected curing environments (two years in water at 68 F [20 C], two years in air at 68 F [20 C], and two years in natural weathering at Garston, U.K.) the UTS and MOR did not decrease. For the air storage condition, the strain to failure and impact strengths increased and the PEL stress decreased. For the water storage condition, the strain to failure and the impact strength decreased.

2. Material behavior for underwater storage at 140 F (60 C) was similar to that observed after storage at 68 F (20 C).

3. Exposure in air at 300 F (150 C) for 45 days resulted in a slight decrease in tensile PEL and UTS.

Table 4.2— Material properties of aramid fiber reinforced concrete composites

Curing/aging conditions		Tensile properties: UTS stress, psi	Tensile properties: UTS strain, percent	Tensile properties: PEL stress, psi	Tensile properties: PEL strain, millionths	Tensile properties: Young's Modulus, ksi	Bending properties: MOR stress, psi	Bending properties: PEL stress, psi	Bending properties: PEL strain, millionths	Bending properties: Modulus of elasticity, ksi	Impact strength, ft-lb/in.^{2}
Water 68 F	28 days	2335	1.53	1285	318	4045	6440	2235	891	2900	8.1
	180 days	2175	1.28	1340	252	5380	6440	2365	773	3115	7.0
	2 years	1970	1.08	1030	210	4915	6310	2565	850	3250	5.7
Air 68 F	180 days	2088	1.79	1050	265	3990	6775	1825	853	2235	8.4
	2 years	2146	1.69	554	167	3495	6585	1395	587	2540	10.5
Weather	2 years	2088	1.40	685	168	4105	6315	2275	768	3205	6.7
Water 140 F	7 days	2130	1.24	1295	258	4945	5730	1915	713	2725	8.1
	50 days	2390	1.26	1045	230	4555	6020	1855	785	2320	5.9
	180 days	1780	1.11	910	185	4915	5540	2305	710	3320	5.2
Air 300 F	7 days	1900	1.69	1075	348	3335	4990	1985	1300	1665	7.1
	45 days	1755	1.91	530	252	2335	5455	1990	964	2405	9.5
Autoclave 180 F	16 hrs	1365	1.14	805	212	3990	3610	1915	1290	1535	7.5
Control	28 days	1940	1.41	1110	283	3930	5280	1740	883	1985	10.9

Metric equivalents: 1 ksi = 1000 psi = 6.895 MPa; 1 ft-lb/in^2 = 2.102 kJ/m^2; (deg F-32)/1.8 = deg C.

4. Tensile, flexural, and impact strengths for the autoclaved specimens were approximately 30 percent less than strengths for the control specimens.

Figure 4.2 shows the composite behavior in flexure after two years of aging in various environments. Figure 4.3 shows the composite behavior in flexure after autoclaving and after several weeks of aging in various environments. These test results indicated that aramid FRC composites can be expected to retain most of their initial strength and ductility after long periods of exposure in adverse environments [4.7, 4.14].

Cyclic flexural loading was conducted to evaluate the fatigue resistance of aramid FRC composites. Test results indicated that the composite was resistant to fatigue at stresses significantly greater than the Proportional Elastic Limit (PEL). No failures were recorded below the PEL (approximately 2175 psi [15 MPa]) after one million loading cycles [4.7, 4.14].

Tension tests were conducted to evaluate the effects of different fiber contents on tensile strength of aramid FRC composites. Fiber contents ranged between zero and 2 percent by volume and the fiber orientation was unidirectional. Results indicated that the Bend-Over-Point (BOP) decreased for fiber contents above 1.45 percent. However, the UTS, Young's Modulus, and toughness increased as fiber contents increased.

Researchers [4.43] have demonstrated the performance, particularly in toughness, impact resistance, and flexural performance, of aramid fiber reinforced cement, concrete, and mortar. The relative cost of these fibers has limited widespread application.

4.3.3—*Carbon FRC*

Carbon fiber reinforced concrete (CFRC) may be fabricated by batch casting. Carbon fiber can be incorporated into a cement matrix as individual fibers. Fibers incorporated during the batch mixing process are oriented randomly throughout the mix.

A satisfactory mix of chopped carbon fiber, cement, and water is difficult to achieve because of the large surface area of the fiber. Uniform dispersion of discontinuous low modulus carbon fibers can be achieved [4.44] by use of a high energy flexible base-type mixer, the addition of methyl cellulose, and the use of a defoaming agent to eliminate air bubble formation. The use of condensed silica fume along with a proper dose of superplasticizer is reported to be an effective way of obtaining a uniform distribution in a cement paste [4.45, 4.46].

The effects of fiber orientation and distribution in carbon fiber reinforced concrete composites has been reported [4.11]. Instrumented impact test results using low modulus carbon fibers demonstrated substantial increases in impact strength and fracture energy in proportion to the volume fraction of fibers used [4.45].

Strength retention with age for composites was measured after storing specimens in water at 64 and 122 F (18 and 50 C) for one year [4.11]. Little change in strength was reported. This trend was confirmed with the report that no significant loss of strength was found for composite specimens stored under water at 140 F (60 C) for one year. These composite specimens were produced by the sprayed-dewatered process and used two different fiber lengths, 0.43 in. (11 mm) and 1.25 in. (32 mm), and contained 0.6 to 1.3 percent fiber by weight [4.11].

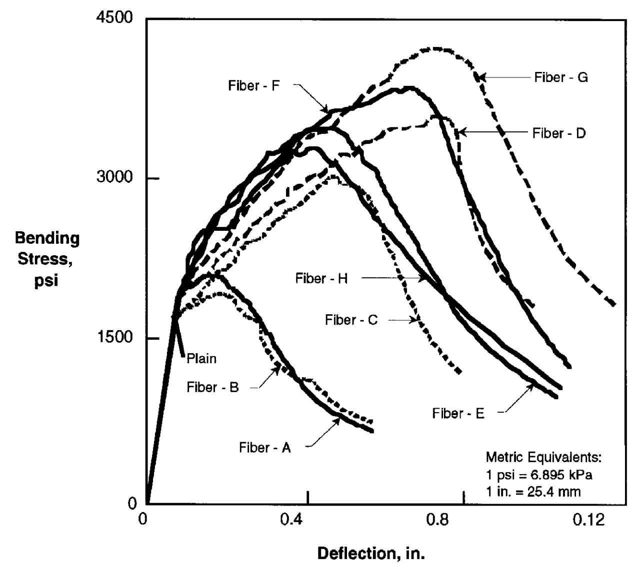

Fig. 4.4—Typical bending stress versus deflection curves for composites containing 3 percent by volume of carbon fibers of various tensile strengths

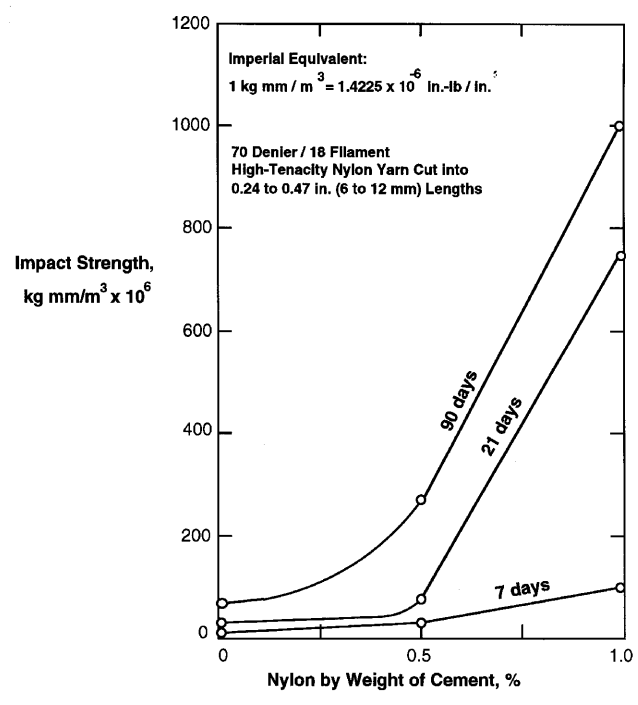

Fig. 4.5—Nylon content versus impact strength at different ages

In another report [4.13], information on several other engineering properties of CFRC has shown that the addition of carbon fibers results in improved impact strength, fracture toughness, and dimensional stability. Both impact strength

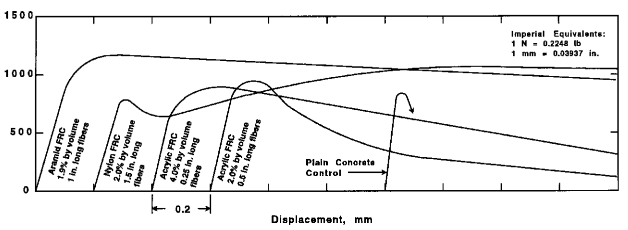

Fig. 4.6—Load versus load-line displacement curves for acrylic, aramid, and nylon FRC

and fracture toughness of composites increased with increase in fiber content. Measured shrinkage of composites containing approximately 6 percent high-modulus carbon fiber by volume was reportedly one-tenth that of the unreinforced cement matrix. Similarly, expansion of composites stored in water was also less than that of the unreinforced cement matrix. Reduction in creep strain was also noted due to the addition of carbon fibers.

The same study also investigated the effects of carbon fiber addition on creep caused by static sustained loads and fatigue due to dynamic loads [4.13]. Results of dynamic load tests indicate that CFRC composites initially decrease in strength due to fatigue and then level off at some limiting strength. This limiting strength was found to be much greater than the matrix cracking strength. Results of static load tests indicate ultimate strength reductions due to sustained loads even when the applied stress was less than the matrix cracking strength [4.13].

Another study reported the effects of the tensile strength of low modulus pitch-based carbon fibers on the flexural strength of CFRC composites [4.46]. Table 4.3 shows the tensile strength, elastic modulus, and elongation for each of the fiber types considered in the tests. Figure 4.4 shows the bending stress-deflection curves obtained for composites containing each fiber type. According to the results, the tensile strength of the fiber should be greater than 93 ksi (640 MPa) in order to reinforce the cement matrix effectively. Composites contained 3 percent carbon fiber by volume. Fibers were 0.40 in. (10 mm) long and were randomly dispersed in the cement matrix.

4.3.4—*Nylon FRC*

Nylon fiber was one of the earliest fiber types evaluated for use in concrete. Initial interest stemmed from the Army Corps of Engineers, whose primary purpose was to develop blast-resistant concrete [4.1, 4.2]. It was found that nylon fibers were particularly effective in controlling the impact forces present in a blast situation, as measured by fragment velocity, percent slab intact, and distance to the farthest fragment. One study confirms nylon's ability to resist impact forces as a result of blast. In this study, 3.28 ft (1.0 m) hollow cubes were reinforced on two adjoining sides with 12 percent by weight of 0.24 and 0.47 in. (6 and 12 mm) long fibers, respectively. The hollow cubes were filled with water and a 1.76 oz (50 gm) explosive placed in the center. The authors confirmed the ability of nylon fibers to withstand blast effects and act as a crack arrestor [4.47].

The ability of nylon fibers to impart impact resistance and flexural toughness is well documented [4.1, 4.18, 4.47-4.51]. One study [4.50] of nylon FRC reports Izod impact strengths ranging from 4.5 to 17.1 ft-lb/in. (0.24 to 0.91 Nm/mm) versus 0.64 ft-lb/in. (0.03 Nm/mm) for plain concrete. Experimental variables including fiber denier (15d to 235d), fiber content (2 to 3 percent by weight), and curing conditions (moist vs. dry) accounted for the range in impact strengths. Another evaluation [4.47] of nylon FRC at a fiber content of 0.5 percent by weight using a drop weight setup revealed impact strengths 5 times greater than plain concrete. At a fiber content of 1 percent by weight, the impact strength was 17 times greater than plain concrete as shown in Fig. 4.5. The nylon evaluated was a 70 denier/18 filament high tenacity yarn cut into 0.24 to 0.47 in. (6 to 12 mm) lengths at contents of 0.5 to 1.0 percent by weight of cement. A third testing program examining the effects of several parameters including fiber denier (4 to 50d), fiber length (0.5 to 2 in. [13 to 51 mm]), curing condition, and fiber content (0.5 to 4.0 percent by weight) shows nylon to increase impact resistance from 7.5 to 15 times that of plain concrete. The Izod Pendulum method was also used in this evaluation [4.18].

Several researchers have shown significant improvement in toughness, ductility, and control of cracking with the use of nylon fibers at contents ranging from 0.5 to 3 percent by volume [4.22, 4.48, 4.49]. One particular study, using a Type III (high early strength) cement and silica sand matrix, measured first-crack stress, maximum strength, and toughness using a compact tension test. Notched specimens were subjected to a four point bending load. A clip gauge was attached to the specimen crack mouth to measure load-line displacement. As shown in Fig. 4.6, the data indicated a modest increase in first-crack stress and maximum strength while the ability to absorb energy in the post-crack region (toughness) improved dramatically with the addition of 2 to 3 percent by volume of nylon fibers [4.49].

Nylon has been shown to be particularly effective in sustaining and increasing the load carrying capability of con-

Table 4.3— Mechanical properties of carbon fibers

Fiber type	Tensile strength, ksi	Elastic modulus, ksi	Elongation, percent
Fiber-A	63.8	3860	1.65
Fiber-B	83.6	4426	1.89
Fiber-C	93.4	4237	2.22
Fiber-D	96.9	4498	2.17
Fiber-E	98.4	4455	2.19
Fiber-F	99.0	4295	2.33
Fiber-G	106.6	4469	2.38
Fiber-H	110.9	4701	2.36

Metric equivalent: 1ksi = 6.895 MPa.

crete following first crack [4.1, 4.48, 4.49]. Other researchers have demonstrated nylon's ability to provide improved toughness and crack control following exposure to an accelerated aging environment [4.22]. The accelerated environment, a saturated brine solution heated to 122 F (50 C), was used to determine long-term durability. Flexural beams, reinforced with 0.75 in. (19 mm) long nylon fibers at 0.5 percent by volume, were subjected to this environment for specific time intervals up to 360 days.

Conflicting results have been obtained with respect to flexural strength. A number of researchers have shown increased flexural strength [4.1, 4.49-4.51]. Others assert nylon fibers contribute very little to the improvement of flexural strength even at high fiber contents [4.18, 4.48].

The effect of nylon fibers on compressive and splitting tensile strength has been shown to be negligible in several cases [4.49, 4.51]. One researcher concluded that compressive strength of mortar mixes decreases with increasing fiber content. The nylon fiber, a 0.5 in. (13 mm), 15 denier material was added at contents up to 1 percent by volume [4.51]. With respect to splitting tensile strength, the addition of nylon at 2.4 percent by volume was shown not to significantly increase strength. For the purposes of this evaluation, a mortar mix containing high-early strength cement and silica sand was used [4.49].

The effectiveness of low modulus, synthetic fibers to reinforce concrete and enhance its properties is controlled by the fiber/cement interface, fiber geometry, and fiber distribution [4.49]. Property improvements seen with nylon fibers are reported as being primarily a function of fiber geometry (high aspect ratio) and fiber distribution. Low bond strength between a certain type of nylon fiber and the cement matrix has been reported [4.49].

The ability of nylon fiber to reduce concrete shrinkage has been demonstrated in one test series. Nylon fibers added at contents ranging from 1 to 3 percent by volume were shown to decrease shrinkage by as much as 25 percent as measured by length change [4.52].

4.3.5—*Polyester FRC*

Polyester fibers have been used in concrete to control plastic shrinkage-induced cracking [4.49, 4.53, 4.54]. The fiber is added at relatively low fiber contents, approximately 0.1 percent by volume for this purpose, as it is for other synthetic fiber types.

4.3.6—*Polyethylene FRC*

As indicated in Fig. 4.7 concrete reinforced with polyethylene fiber contents ranging from 2 to 4 percent by volume exhibited a linear flexural load deflection behavior up to first crack. This behavior is followed by an apparent transfer of load to the fibers permitting an increase in load until fibers begin to break [4.26]. Multiple cracking is observed to occur.

4.3.7—*Polypropylene FRC*

Test data have been compiled for composites containing polypropylene fibers at volume percentages ranging from 0.1 to 10.0 percent. The material properties of these composites vary greatly and are affected by the fiber volume, fiber geometry, method of production and composition of the matrix. This is true for all synthetic fiber types.

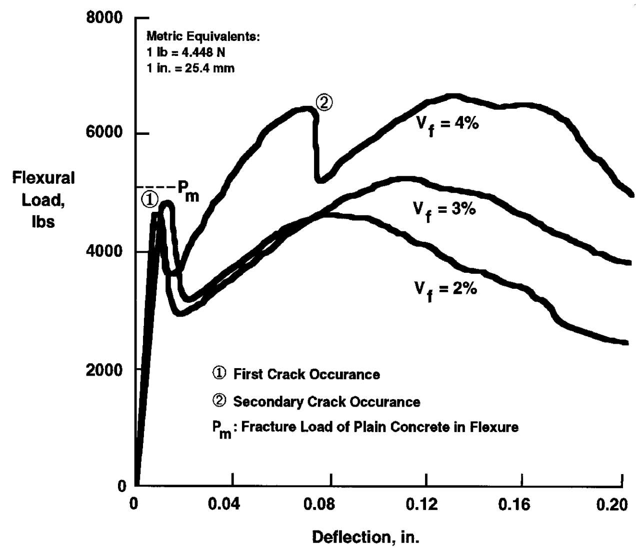

Fig. 4.7—Typical flexural load-deflection curves of polyethylene fiber reinforced concrete for various fiber contents

4.3.7.1 *Fresh concrete properties and workability*—Fresh concrete properties and workability determined by three different methods (slump, inverted slump cone time, and Vebe time) were reported for collated fibrillated polypropylene fiber reinforced concrete having fiber contents ranging from 0.1 to 2.0 percent by volume [4.55-4.59].

Satisfactory workability was maintained even with a relatively high fiber content (2.0 percent by volume) with the addition of an appropriate amount of high-range water reducer to maintain equal strength and water-cement ratio [4.59]. Although fibrillated polypropylene fibers, cement, and aggregates were added to the mixer simultaneously, no balling occurred even at higher quantities of fibers. The fresh concrete with fibrillated polypropylene fibers had no surface bleeding and no segregation [4.55, 4.56, 4.58, 4.59].

4.3.7.2 *Compressive strength*—Compressive strengths have been reported for polypropylene FRC with fiber contents ranging from 0.1 to 2.0 percent by volume [4.14, 4.34, 4.55, 4.56, 4.58-4.61]. There is no consensus in the reported results. In general, it can be stated that the addition of polypropylene fibers at different quantities has no effect on the compressive strength. The minor differences noticed are expected variation in experimental work. They can also be due to variations in the actual air contents of the hardened concrete and the differences in their unit weights.

However, the addition of polypropylene fibers has a significant effect on the mode and mechanism of failure of concrete cylinders in a compression test. The fiber concrete fails in a more ductile mode. This is particularly true for higher strength fiber concretes, whereas plain control concrete cylinders typically shatter due to an inability to absorb the energy release imposed by the test machine at failure. Fiber concrete cylinders continue to sustain load and endure large deformations without shattering into pieces [4.55-4.58].

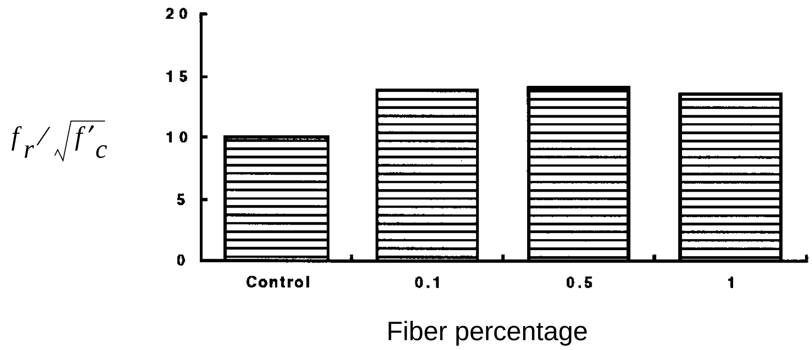

Fig. 4.8—Ratio of modulus of rupture to the square

It was also reported [4.57] that, for a specific concrete mix used for both control concrete and fiber concrete, high quantities of fiber (2.0 percent by volume) produced concrete with poorer workability, more bleeding and segregation, relatively higher entrapped air (13.9 percent), and lower unit weight. This resulted in a decrease in the compressive strength. This observation indicates the importance of adjusting aggregate proportions when high quantities of fibers are used [4.57]. Optimum mixture proportions should be obtained by trial mixes when using higher fiber volumes. This was demonstrated in another investigation by the same author [4.58]. It was shown that there was no reduction in compressive strength when 0.1 to 1.0 percent by volume of fibers were added.

4.3.7.3 *Static modulus and pulse velocity*—When compared on an equal compressive strength basis, it was shown [4.55-4.59] that the addition of fibrillated polypropylene fibers in quantities varying from 0.1 to 2.0 percent by volume had no effect on the static modulus of elasticity as determined using ASTM C 469 test procedure. This was true when the concrete cylinders were tested at both 7 and 28 days.

Beams and cylinders were tested at 7 and 28 days for pulse velocity according to ASTM C 597 for fibrillated polypropylene FRC with fiber contents ranging from 0.1 to 2.0 percent by volume [4.55-4.59]. The results showed that there was little or no effect on the measured pulse velocities due to the addition of fibers to the control concrete indicating that concrete matrix qualities were not compromised by the addition of fibers.

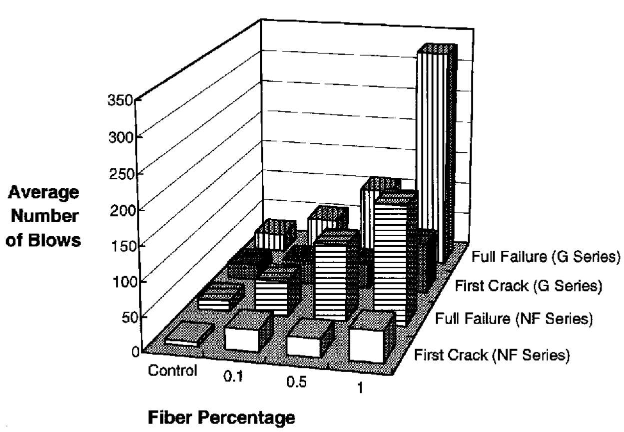

Fig. 4.9—Impact test results for polypropylene FRC

4.3.7.4 *Flexural strength (modulus of rupture)*—Similar to the compressive strength results, there is no consensus in the published literature about the effect of adding polypropylene fibers on the first-crack strength and modulus of rupture. It has been reported [4.34] that at a fibrillated polypropylene fiber content of 0.1 percent by volume, there was a slight increase in flexural strength (0.7 to 2.6 percent), and at 0.2 to 0.3 percent by volume there was a slight decrease. Others [4.56] have reported that the modulus of rupture determined at 7 and 28 days was slightly greater for fibrillated polypropylene FRC at fiber contents of 0.1 to 0.3 percent by volume in comparison to plain concrete.

When the same basic mix proportions were used, the modulus of rupture decreased as the fiber content was increased from 0.1 to 2.0 percent by volume [4.59]. For 2.0 percent by volume fibrillated polypropylene FRC, the compressive strength was low due to the higher air content and, hence, the flexural strength was also low. Similarly, for 1.0 and 1.5 percent fibrillated polypropylene fiber volumes, the compressive strengths were low, and hence, the flexural strengths were also low. As a result, the direct flexural strength comparisons may be misleading [4.59]. Figure 4.8 illustrates the effect of adding varying quantities of fibrillated polypropylene fibers to a basic plain concrete mix. In Fig. 4.8, note that the modulus of rupture, f_r, values were normalized by dividing them by $\sqrt{f'_c}$. It is obvious that the mix proportions should be properly designed when higher quantities of fibers are added in order to obtain suitable workability and strength. In another investigation, the mix proportions were optimized by trial mixes for higher quantities of fibrillated polypropylene fibers [4.58]. When these optimized mix proportions were used, there was no change in compressive strength and no change in modulus of rupture for higher volume percentages of fibrillated polypropylene fibers.

4.3.7.5 *Impact strength*—A large number of test setups has been used to investigate the performance of polypropylene FRC under impact loading. Due to the variable nature of such testing and the need to apply specialized analytical techniques to each test setup, cross test comparisons cannot be made. There are reports of increased impact strength

when using polypropylene fibers [4.1, 4.55, 4.57, 4.62-4.65]. However, in other tests no improvement was found [4.66-4.68]. Impact strength improvement was reported to be as high as 15 percent in uniaxial tension mode [4.64] and 50 percent in a flexural mode [4.63]. Using the ACI “drop-weight” test according to ACI Committee Report 544.2R, the impact strength was measured for polypropylene fiber reinforced concretes with fiber contents ranging from 0.1 to 2.0 percent by volume and the same basic mixture proportions for all the concretes [4.57]. Both impact strength at first crack and at complete failure increased significantly with the addition of polypropylene fiber compared to the plain control concrete. In another investigation [4.55], concretes with two different mixture proportions (water-cement ratio 0.40 for NF Series and 0.5 for G Series) and three different fiber contents (0.1, 0.5, and 1.0 percent by volume) were tested for impact strength using the ACI drop-weight test method. The comparison bar chart for first crack and complete failure shown in Fig. 4.9 shows that, for all fiber contents, the number of blows for first crack and complete failure are considerably greater than that for plain concrete. Also, the impact strength increases as fiber content is increased. Improvement in fracture energy for polypropylene FRC was reported between 33 and 1000 percent [4.63, 4.66].

The effect of polypropylene FRC used with conventionally reinforced beams under impact loading has been reported [4.69]. In addition to the conventional reinforcement both moderate strength and high strength concrete specimens contained 0.5 percent by volume of 1.5 in. (37 mm) long fibrillated polypropylene fibers. The improvement in impact fracture energy was twofold using moderate strength concrete (6000 psi [42 MPa]) and almost ten fold using high strength concrete (12,000 psi [82 MPa]).

4.3.7.6 *Fatigue strength and endurance limit*—One of the important attributes of FRC is the enhancement of fatigue strength compared to plain concrete. Failure strength is defined as the maximum flexural fatigue stress at which the beam can withstand two million cycles of non-reversed fatigue loading. In many applications, particularly in pavements and bridge deck overlays, full depth pavements and industrial floors, and offshore structures, flexural fatigue strength and endurance limit are important design parameters mainly because these structures are subjected to fatigue load cycles. The endurance limit of concrete is defined as the flexural fatigue stress at which the beam could withstand two million cycles of non-reversed fatigue loading, expressed as a percentage of the modulus of rupture of plain concrete.

The flexural fatigue strengths and endurance limits have been reported for polypropylene FRC with various fiber contents [4.4, 4.55-4.59]. Specifically, the addition of polypropylene fibers, even in small amounts, has increased the flexural fatigue strength. Using the same basic mixture proportions, the flexural fatigue strength was determined for three fiber contents (0.1, 0.2, and 0.3 percent by volume) and it was shown that the endurance limit for two million cycles had increased by 15 to 18 percent [4.56]. Another extensive investigation [4.57] was conducted to determine the behavior and performance characteristics of FRC subjected to fatigue loading for four types of fibers including polypropylene fibers. Concretes with two fiber contents (0.5 and 1.0 percent by volume) and using the same basic mixture proportions were tested up to four million cycles. In this study, the endurance limits were not significantly improved. For polypropylene FRC with 0.5 and 1.0 percent fibers by volume, the endurance limits were 67 and 70 percent, respectively. For the plain control concrete, the endurance limit was 65 percent [4.57].

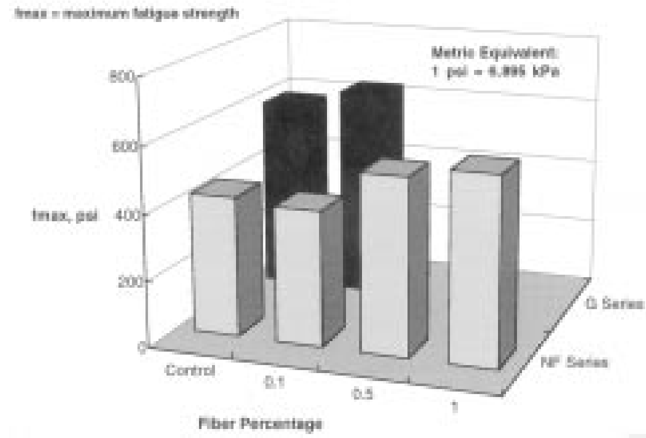

Fig. 4.10—Fatigue strength for polypropylene FRC

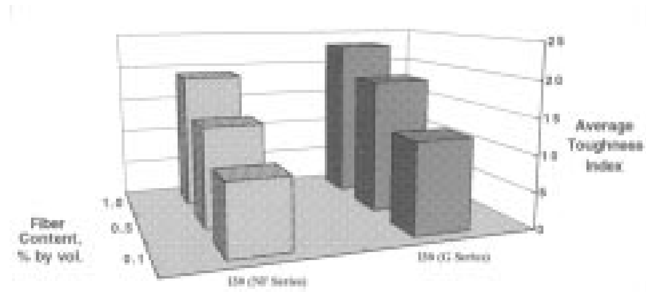

Fig. 4.11—I_{30} toughness indices for polypropylene FRC

In another investigation, using optimized mixture proportions, the flexural fatigue strengths were determined for concretes having fiber contents of 0.1, 0.5, and 1.0 percent by volume [4.58]. The flexural fatigue strengths are shown in Fig. 4.10. As shown in the figure, there is a trend toward increasing fatigue strength as the fiber content is increased. The endurance limits for two million cycles (the ratio of the maximum flexural fatigue strength to the modulus of rupture) increased by 16, 18, and 38 percent for 0.1, 0.5, and 1.0 percent fiber content by volume, respectively, in comparison to plain concrete [4.58].

Similar to steel FRC, polypropylene FRC also shows increased static flexural strengths after being subjected to fatigue loading [4.55]. Thus, it can be stated that for polypropylene FRC subjected to fatigue stress below the endurance limit value, there is an increase in the potential modulus of rupture value.

4.3.7.7 *Flexural toughness and post-crack behavior*—Flexural toughness and post-crack behavior have been reported for fiber contents ranging from 0.1 to 2.0 percent by volume [4.3, 4.4, 4.30, 4.56-4.59, 4.70-4.73]. The toughness

was determined using the ACI method reported in ACI Committee Report 544.2R and ASTM C 1018. Mostly, the earliest reported results were based on the ACI method and the most recent reported results were based on the ASTM method. It should be noted that the toughness index values depended to a large extent on the type of machine and type of loading method employed [4.73]. When load-controlled machines were used, polypropylene FRC with 0.1 percent fibers by volume failed suddenly without any appreciable increase in toughness compared to control concretes [4.56]. This was true for both 7 and 28 day tests. Beams with 0.2 and 0.3 percent by volume of fibers showed considerable increase in toughness. A toughness index (I_5) value between 2 and 3 was obtained. When the tests were conducted according to ASTM C 1018 with deflection-controlled machines or by closed-loop testing machines, even beams with fiber contents of 0.1 percent by volume had toughness index values of 3 or more [4.57]. However, even plain concrete beams (without fibers) gave toughness index values of 3 when tested on closed-loop deformation-controlled machines. The reported toughness index (I_5) values varied from 3.5 to 4.8 for concretes with 0.5 and 1.0 percent fibers by volume. The calculated values for toughness index I_{30}, determined according to ASTM C 1018, are shown in Fig. 4.11 [4.55]. The toughness index depends largely on the estimate of the first-crack load. Therefore, caution should be exercised in interpreting published toughness results.

At higher fiber contents, there is considerable improvement in the I_{30} toughness index for polypropylene FRC as shown in Fig. 4.11.

Factors such as fiber length, fiber material, fiber geometry, and bonding characteristics also influence the toughness and post-crack behavior. It has been reported that, due to the addition of polypropylene fibers at a fiber content of 0.1 percent by volume, there is an improvement in the post-crack behavior and energy absorbing capacity of concrete [4.57, 4.63]. Beams reinforced with polypropylene fibers can sustain loads beyond the first crack-load, but at a reduced load level. The ability to absorb elastic and plastic strain energy and to conduct tensile stresses across cracks is an important performance factor for serviceability. These factors provide a mechanism for controlling the growth of cracks after crack opening deformations have occurred. The fiber content has an influence on the post-crack load carrying capacity. Tests [4.55] have shown that the post-crack reduction in load expressed as a percentage of maximum load were 45, 27, and 26 percent for beams with 0.1, 0.5, and 1.0 percent fiber by volume, respectively. The post-crack reduction in load generally decreases as the fiber content increases, as shown in Fig. 4.12 [4.55].

Researchers [4.70] have also shown that composites reinforced with collated fibrillated polypropylene fibers displayed excellent post first-cracking behavior if produced under certain optimized conditions. Mechanical bonding properties of the polypropylene fiber were found to be greater for twisted collated fibrillated polypropylene fibers or for fibers with buttons (enlargements) added to the fiber ends. It was also determined that premixing the fibers to achieve a 3-dimensional random fiber distribution resulted in stronger and tougher composites than alternatively preplacing the fibers in a 3-dimensional mat. A representative flexural load-deflection curve for the collated fibrillated polypropylene fiber reinforced concrete composite described above is shown

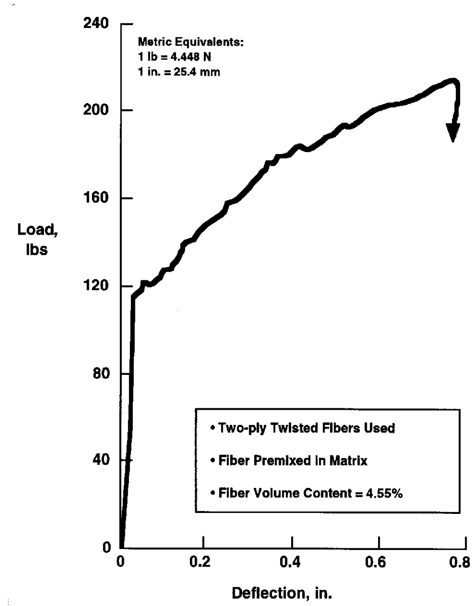

Fig. 4.13—Representative load-deflection curve for optimized composite containing chopped polypropylene fiber

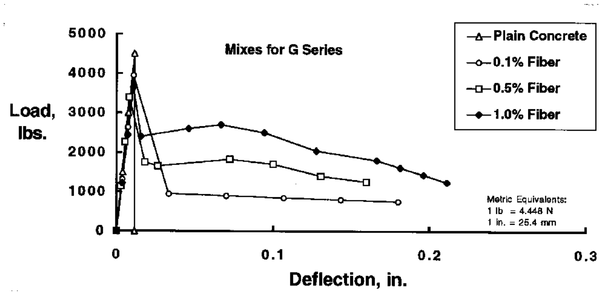

Fig. 4.12—Load-deflection comparison curves for polypropylene FRC

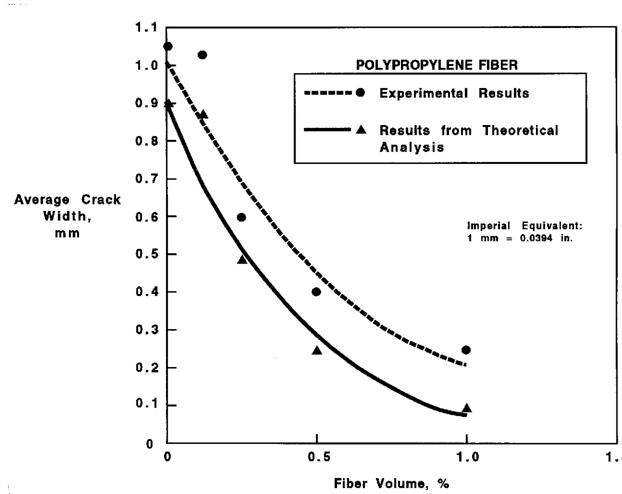

Fig. 4.14—Average crack width versus fiber volume content

in Fig. 4.13. Multiple matrix cracking was associated with the post-cracking behavior of the composite.

Another testing program [4.30] showed that composites reinforced with polypropylene fibers can sustain loads beyond the first cracking load. Research was conducted using composites reinforced with either monofilament or fibrillated fibers. Tests were conducted to determine the effects of fiber content as well as several other variables on the mechanical properties of composites. Increases in fiber content resulted in decreases in the first cracking strength and increases in the ultimate strength of composites in flexure.

Considerable shotcrete research, both in the laboratory and in the field, has been conducted with collated fibrillated polypropylene fibers at contents ranging from 0.4 to 0.7 percent by volume [4.3, 4.74-4.76]. Collated fibrillated polypropylene fibers are being used to replace conventional reinforcement materials in tunnel lining and slope stabilization applications.

Research comparing post-crack properties of fibrillated polypropylene fiber, steel fiber, and welded-wire fabric (WWF) reinforced shotcrete show the fibrillated polypropylene fiber at 0.6 percent by volume to have load carrying properties similar to approximately 100 lb/yd^3 (59 kg/m^3) of steel fiber and 4 x 4 - W2.1 x W2.1 and 6 x 6 - W2.9 x W2.9 [4.3].

4.3.7.8 *Shrinkage and cracking*—Rectangular and square slab specimens have been used to demonstrate the ability of SNFRC at low volume fiber additions to control cracking resulting from volume changes due to plastic and drying shrinkage. Several reports [4.38-4.41] have shown that low denier fiber, and therefore high fiber count (number of fibers per unit volume), reduces the effects of restrained shrinkage cracking.

One report [4.77] shows the ability of polypropylene FRC to control drying shrinkage cracking. The tests were conducted using ring type specimens to simulate restrained shrinkage cracking. With the dimension of these specimens, it can be assumed that the concrete ring is subjected to approximately uniaxial tensile stresses, when the shrinkage of the concrete annulus is restrained by the steel ring. Then the crack width is measured using a special microscope. Concretes made with different amounts of polypropylene fiber were studied. Results are shown in Fig. 4.14. It can be seen that the addition of polypropylene fiber reduced the average crack width significantly (compared to plain concrete). A theoretical mathematical model to predict crack width of ring specimens subjected to drying was also developed.

There is presently no standardized procedure for quantifying the effects of polypropylene, or any other synthetic fiber, on plastic or drying shrinkage or on cracking that results from volume changes under restrained conditions. However, many procedures have been suggested and their results are being studied by the ASTM Subcommittee C09.42 Task Group on shrinkage testing.

Reductions in drying shrinkage (or volume change) in unrestrained specimens have been reported using polypropylene fibers at 0.1 percent by volume [4.35]. Unrestrained drying shrinkage tests conducted at an early age and using accelerated drying conditions [4.35] indicated reductions of 18, 59, and 10 percent for fiber volumes of 0.1, 0.2, and 0.3 percent, respectively. Due to the high degree of variability associated with such testing, the authors caution against using these data to form the relationship between fiber amount and shrinkage reduction. Test specimens were cured under water, then subjected to accelerated drying. Shrinkage strain versus time was plotted to compare specimens containing fibers with control specimens treated identically and simultaneously. These curves are shown in Fig. 4.15.

These same authors [4.35] also reported plastic shrinkage reductions of 12 to 25 percent for polypropylene contents ranging from 0.1 to 0.3 percent by volume. Plastic shrinkage tests followed ASTM C 827. During the tests, it was noted that the quantity of surface bleed water was significantly reduced by the addition of fibers. It was suggested that the presence of fibers reduced settlement of the aggregate particles, thus eliminating damaging capillary bleed channels and preventing an increase in inter-granular pressures in the plastic concrete. This reduced settlement helps account for the

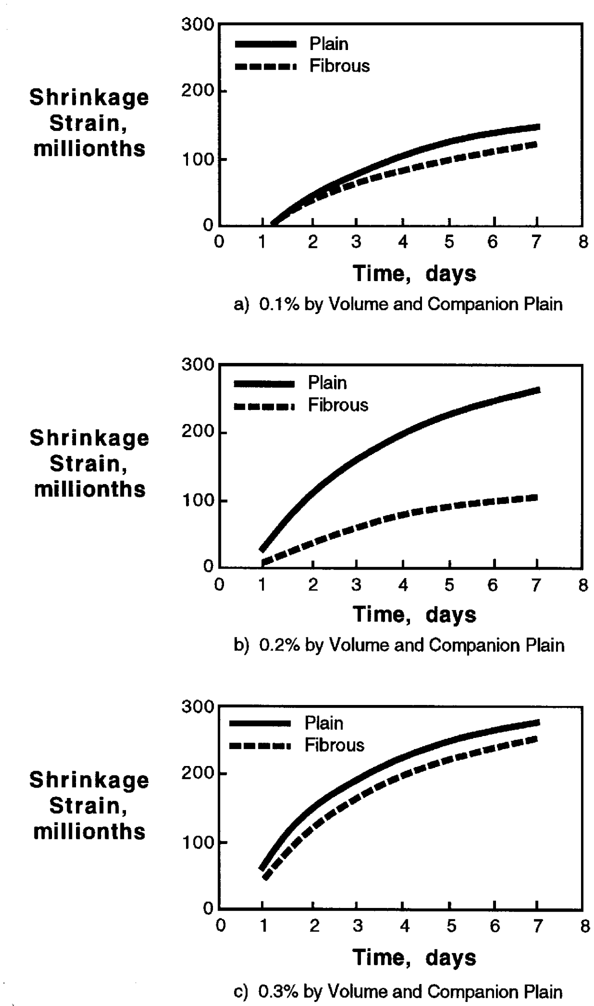

Fig. 4.15—Drying shrinkage strain versus time plots for polypropylene fiber reinforced concrete sptcimens and companion plain concrete specimens

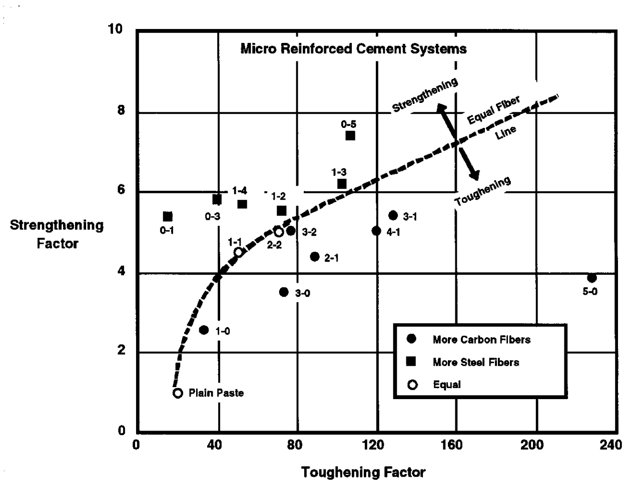

Fig. 4.16—Carbon-steel hybrid fiber reinforced concrete

greater volume (lower density) with fibrous mixes discussed earlier.

Although unrestrained shrinkage tests do provide some information about the shrinkage characteristics of fiber reinforced composites, results of these tests may not provide any useful information regarding how composites respond to shrinkage-induced stresses in a restrained condition. In the restrained condition, shrinkage strains translate into tensile stresses in concrete. After cracking, polypropylene fibers are believed to transfer tensile stress across cracks and act to arrest or confine crack tip extension so that many fine (hairline) cracks occur instead of fewer larger cracks [4.78].

Other research has shown that low volume contents, 0.1 percent, of low effective diameter polypropylene fiber significantly limit crack size for plastic shrinkage cracks that occur within the first few hours after casting [4.40, 4.41].

Composites reinforced with higher volume contents of polypropylene fiber have also been shown to have an influence on restrained shrinkage and shrinkage induced cracking [4.71]. Composites reinforced with 2 percent polypropylene fibers by volume can provide significant post-cracking toughness effectively distributing shrinkage induced cracking in mature concrete.

Multiple cracking displayed by hardened composites during restrained shrinkage tests indicates the ability of the fiber concrete to distribute shrinkage induced cracking strains.

4.3.7.9 *Bond strength*—Generally speaking, the effectiveness of polypropylene fibers in fiber reinforced concrete depends upon the mechanical bond between the fiber and cement paste. Polypropylene is chemically inert and hydrophobic, thus eliminating the potential for chemical bonding. As a result, the mechanical bond of fibrillated polypropylene fibers can be greater than monofilament polypropylene fibers [4.14]. The fibrillated polypropylene fiber exhibits improved mechanical bonding as a direct result of cement matrix penetrating the fibrillated network that anchors the network in the matrix [4.14]. This feature is called pegging. A mechanical bond or adhesion with calcium silicate hydrate has been reported [4.31].

4.3.7.10 *Tests at elevated temperatures*—It has been shown that polypropylene fiber reinforced concrete may not be compatible with certain autoclave curing techniques [4.32]. Results of tests indicate that composites cured in an autoclave at 58 psi (0.4 MPa), 284 F (140 C) for 24 hours and then oven-dried at 241 F (116 C) for 24 hours suffer a considerable loss in ductility due to thermal oxidative degradation of the polypropylene fibers. It was later proven that the thermal degradation was caused by the high oven-drying temperature employed and that autoclave curing in conjunction with oven-drying could be used only if drying temperatures are greatly reduced.

Full scale fire testing of metal deck composite slabs, utilizing fibrillated polypropylene fibers and no other reinforcement, has been reported [4.79, 4.80]. Test results indicated that the presence of fibers had no adverse effect and that a two-hour fire rating could be achieved for unprotected steel deck composite slab system and a three-hour fire rating could be achieved for a protected steel deck composite slab system.

4.3.8—*Hybrid fiber reinforced concrete*

Although not investigated extensively, the use of two or more fiber types in the same concrete mix is considered promising. The decision to mix two fibers may be based on the properties that they may individually provide or simply based on economics. Considerable improvement in the load-deflection response was observed mixing steel with polypropylene fibers [4.81].

In a more recent study [4.82], steel micro-fibers (25 microns in diameter and 3 mm long) and carbon micro-fibers (18 microns in diameter and 6 mm long) both in mono- and hybrid- forms were investigated. In the mono-form, steel fiber provided better strengthening than the carbon fiber and carbon fiber provided better toughening than the steel fiber. Interestingly, in the hybrid form (in combination), they both retained their individual capacities to strengthen and toughen as shown in Fig. 4.16. It appears possible, therefore, that by properly controlling fiber properties and combining them in appropriate proportions, one can actually tailor-make hybrid fiber composites for specifically designed applications.

4.4—Composite production technologies

Batch mixing is a widely used production method for all types of SNFRC. Fibers are added to the wet mix directly from bags, boxes, or feeders. Collated fiber types require mechanical agitation during the mixing process to encourage the breakup of fiber bundles and their dispersion through the mixture. Prepackaged dry mixes that contain dispersed fibers and to which only water need be added are also available. Preweighed fiber quantities in degradable bags are also widely used to facilitate batching.

After batching, placement techniques include all the standard methods such as batch casting, pumping, wet-mix shotcreting, and plastering. The use of dry-mix shotcrete for SNFRC is difficult due to the propensity for the relatively low density fibers, specific gravity of approximately 1.0, to be blown out either by the shotcrete nozzle air pressure

stream or by environmental air streams. Slip form machines pose no problems with SNFRC mixes.

Polypropylene fibers have been incorporated into concrete using several methods [4.18, 4.30, 4.63, 4.83]. They may be mixed as short discrete fibers of monofilament or fibrillated form. It has been reported that polyethylene fibers could be easily dispersed in concrete matrices in volume percentages of up to 3 percent using conventional mixing techniques [4.26].

Acrylic fibers have been used in the Hatschek process, which is used to manufacture asbestos-cement board.

Asbestos fiber conforms very well to the Hatschek process because these finely fibrillated fibers provide excellent filtration characteristics that keep the cement particles uniformly dispersed in the fiber/cement slurry and prevent segregation during vacuum dewatering. Acrylic fibers cannot perform this function due to their relatively large diameter and specific surface properties. Therefore, it is necessary that certain "process" fibers be used as filler in addition to acrylic reinforcing fibers to provide filtering characteristics and prevent segregation of fine particles. Generally, acrylic fiber is incorporated at 1 to 3 percent by weight while process fibers are added at 3 to 6 percent by weight. Some examples of effective process fibers are kraft cellulose pulp fiber and polyethylene pulp fiber [4.5, 4.42].

Concrete panels with monofilament polypropylene fiber have been produced using a spray suction dewatering technique [4.18]. Monofilament fibers also have been used in a pressing technique [4.30].

With the hand lay-up technique, higher fiber volume percentages (up to 12 percent) can be obtained than with conventional batch mixing techniques (up to about 1 percent). Spray suction dewatering techniques can produce composites with as high as 11 percent fiber by volume.

Consistency is commonly measured by the slump test, ASTM C 143. An apparent slump difference should be expected when comparing non-fibrous and SNFRC for otherwise similar mix designs. In the case of hydrophobic fibers, there is no loss of water to the fiber, but the fiber will provide a plastic shear strength to the mix that will reduce slump.

Conventional ready-mixed concrete can easily be produced using monofilament or fibrillated fibers at 0.1 percent volume with little loss of consistency as measured by slump. However, slump loss will increase more rapidly beyond this point [4.14, 4.60]. The slump loss is dependent upon the fiber length as well. Slump is often, though improperly, used as a measure of workability, and it is often said that the workability of concrete is reduced in the presence of fibers. However, with standard placement practices, fiber concrete will work, place, and pump readily. No additional mixing water is required and none should be added. Since the conventional slump test is an inappropriate measure of workability for FRC, it is recommended that the inverted slump cone test (ASTM C 995) or the Vebe Test (ACI 211.3) be used to evaluate workability.

Synthetic fibers are usually added to ready-mix concrete at the batch plant [4.14]. Conventional placement methods are applicable, including batch placement and pumping.

4.5—Fiber parameters

In current commercial and industrial bulk concrete applications, synthetic fibers are added to concrete in the low range of fiber additions, approximately 0.1 percent based on the volume of concrete. In these applications, the strength of the concrete is considered to be unaffected and crack control characteristics are sought.

Fiber additions of two or three times the volume above are being tested and flexural strength and toughness increases are being reported when concrete placement can be accomplished without compaction difficulties.

Size and weight classification of fibers used in these applications use terminology originating in the textile industry. One example is the use of the term "denier." Denier is defined as the weight in grams of 9000 meters of fiber. When determining the denier of a fiber, a single filament is used. For a fibrillated tape, a standard width of the extruded film is used. The fiber denier is thus a measure of the fineness of the fiber. When applied to concrete mixtures, there may be differences between the fiber denier as it exists prior to batching (pre-mix fiber denier) and as it exists after mixing (post-mix fiber denier), since some fiber types are designed as collated fiber bundles that separate during the mixing process. Furthermore, the fibrillation pattern of an extruded sheet of polypropylene can vary from manufacturer to manufacturer. Thus, the denier of the main fibrils and cross fibrils may be considerably different within the fibrillated network and from product to product.

Denier is a measure of fiber fineness and may be correlated to an equivalent fiber diameter or an equivalent fiber cross-sectional area. Figure 4.17 is a plot of the relationship between the fiber type, as defined by denier and specific gravity, and the equivalent fiber diameter in either inches or millimeters [4.84]. Specifying the fiber denier alone is not enough, as the parent material, or the specific gravity, must also be known to obtain an average fiber geometry.

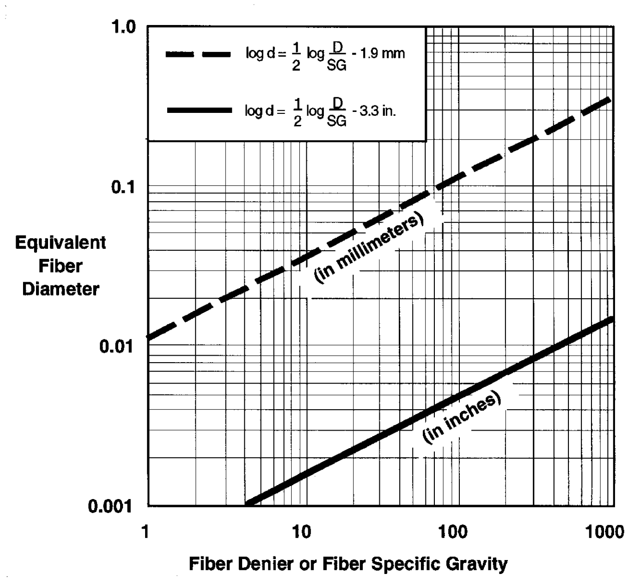

Fig. 4.17—Fiber diameter versus denier relationship

To determine the equivalent fiber diameter, *d*, before or after mixing, for a fiber of known specific gravity apply the following equation:

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

where:

f = .0120 for d in mm
f = 0.0005 for d in inches
D = pre-mix or post-mix fiber denier
SG = fiber specific gravity

where SG is the specific gravity of the fiber material and D can be either the before-mix denier or the post-mix denier as desired. With these equations, synthetic fibers can be compared with other fiber types by their aspect ratio, L/d, where L is the length of fiber and d is the equivalent fiber diameter.

For example, synthetic fibers of polypropylene with a specific gravity of 0.91 and which are comparable in size to steel fibers, approximately 0.01 inches (0.025 mm) in diameter, are approximately 360 denier. The denier of the same size fibers of steel would be approximately 3100. These are the type and size of synthetic fibers, 360 denier, which were first applied in synthetic fiber concrete production. Monofilament, multifilament, or fibrillated synthetic fibers are currently applied at far lower denier, down to 5 to 50. For these fibers, the equivalent diameter is only 0.001 inches (0.025 mm) and therefore the aspect ratio is increased by ten times for equal length fibers.

The following series of equations and tables is helpful [4.84]. They provide the relationship between various geometric and material type fiber parameters.

4.5.1—*Fiber spacing and surface area*

Fiber spacing and specific surface are key parameters influencing the behavior of fiber reinforced concrete both in the plastic stage and in the hardened final product.

The average fiber spacing is a function of fiber cross-sectional area, fiber volume, and fiber orientation. The average fiber spacing is derived from the number of fibers crossing a unit area in an arbitrary composite cross section. It affects both the rheological properties of the mix and, to a certain extent, the mechanical properties of the hardened concrete. When mixing and casting FRC, the deformation and flow characteristics depend on fiber spacing. More energy is required to distribute concrete throughout numerous narrow fiber spaces than throughout a few large spaces. The ability of fibers to act as crack arrestors is influenced in part by the distance a crack can travel before it intercepts a fiber.

The fiber specific surface (FSS) is the predominant factor determining crack spacing and crack width. The greater the specific fiber surface, the closer the crack spacing and the narrower the crack width. The FSS is a function of the single fiber surface area and the number of fibers in a unit volume of concrete, i.e., the fiber count.

For any given volume percentage of fibers of equal length that can ideally be assumed uniformly distributed in a concrete mix the number of individual fibers per unit volume of concrete varies inversely with the square of the individual fiber diameter. Put more simply, the number of fibers which theoretically occupy and are distributed in a unit volume of concrete matrix, termed the fiber count (FC), can be determined from the relationship [4.84]:

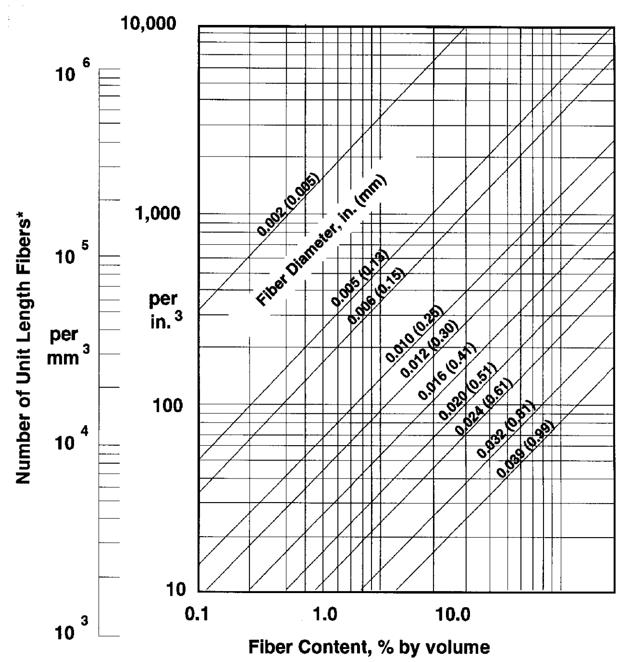

Fig. 4.18—Fiber count or specific surface as a function of fiber volume and geometry

$$FC = \left[\frac{0.0127(V)}{L(d^2)}\right]$$

or in terms of fiber denier,

$$FC = \left[\frac{50.8(V)(SG)(10^3)}{L(P_0MD)}\right]$$

where:

V = fiber content, percent by volume,
L = fiber length, in.,
d = equivalent fiber diameter, in., and
P_0MD = post-mix fiber denier, i.e., after dispersion of bundled or collated fiber.

To determine how many more (or fewer) fibers of different equivalent diameter will occupy a unit volume of concrete matrix it can be shown that the fiber count, *FC*, varies inversely as the square of the fiber diameter as:

$$FC_1 = (d_2/d_1)^2 FC_2$$

where:

FC_1 and FC_2 = fiber count (no. of fibers/ unit volume) for fiber types 1 and 2, respectively.
d_1 and d_2 = equivalent fiber diameter for fiber types 1 and 2, respectively.

Similarly, using the definition of specific surface as the total surface area of fibers per unit volume of matrix, it is shown below that the specific surface of fibers of unit length and constant volume percentage varies inversely with the fiber diameter:

$$FSS_1 = (d_2/d_1)FSS_2$$

where:

FSS_1 and FSS_2 = fiber specific surface for fiber types 1 and 2, respectively.

d_1 and d_2 = equivalent fiber diameter for fiber types 1 and 2, respectively.

Similar expressions have been derived for fiber count (*FC*) or fiber specific surface (*FSS*) as a function of weight dosage rate, volume, specific gravity, denier, and diameter [4.84] as shown below:

$$FC = \left[\frac{7.5(DRT)(10^{-4})}{L(d^2)(SG)}\right] = \left[\frac{0.0127(V)}{L(d^2)}\right] = \left[\frac{3.0(DRT)(10^3)}{L(P_0MD)}\right] = \left[\frac{50.8(V)(SG)(10^3)}{L(P_0MD)}\right]$$

$$FSS = \left[\frac{2.36(DRT)(10^{-3})}{d(SG)}\right] = \left[\frac{0.04(V)}{d}\right] = \left[\frac{4.71(DRT)}{[(P_0MD)(SG)]^{1/2}}\right] = \left[\frac{80(V)(SG)^{1/2}}{(P_0MD)^{1/2}}\right]$$

where:

FC = fiber count, fibers/in.^{3} (divide FC by 16,390 for mm^3 basis)

FSS = fiber specific surface, surface area/in.^{3} (divide FSS by 16,390 for mm^3 basis)

DRT = dosage rate of fiber, lbs/yd^3

V = fiber content, percent by volume

L = fiber length, in.

d = equivalent fiber diameter, in.

P_0MD = post-mix denier

4.5.2—*Graphical solution*

Figure 4.18 is a nomograph [4.84] that gives the fiber count, *FC*, or the fiber specific surface, *FSS*, of unit length fibers as a function of fiber volume and equivalent diameter.

For example, if a specified volume percentage of fibers is entered along the base of the graph, the abscissa, and a specified equivalent fiber diameter in inches is chosen on the diagonal lines on the graph, then the vertical axis, the ordinate of the graph, gives the fiber count on a unit volume basis. In this procedure, as in previous equations, it is assumed that fibers have a cylindrical shape and circular cross section. Fiber count and specific surface for lengths of fiber of other than unit length, one inch (25 mm), can be found by dividing the values found on the ordinate of the graph by the actual fiber length in the appropriate units.

4.6—Applications of SNFRC

Commercial use of SNFRC currently exists worldwide, primarily in applications of cast-in-place concrete (such as slabs-on-grade, pavements, and tunnel linings) and factory manufactured products (such as cladding panels, siding, shingles, and vaults) [4.85]. Currently, there are two different synthetic fiber volume contents used in applications today. They are 0.1 to 0.3 percent, which is referred to as low-volume percentage, and 0.4 to 0.8 percent, which is referred to as high-volume percentage. There are also two different physical fiber forms. They are monofilament and fibers produced from fibrillated tape. Most synthetic fiber applications are at the 0.1 percent by volume level to control plastic shrinkage cracking. Uses include precast products, shotcrete, and cast-in-place elements. Typically, the fiber length is $^3/_4$ to $2^1/_2$ in. (19 to 64 mm) with the predominance of demand for $^3/_4$ or $1^1/_2$ in. (19 or 38 mm) long fibers.

4.6.1—*Applications of carbon FRC*

Due to the current high cost of the carbon fiber, its application has been limited. Suggested applications for carbon fiber reinforced concrete [4.86] include: corrugated units for floor construction, single and double curvature membrane structures, boat hulls, and scaffold boards. The use of carbon fiber in combination with other fiber types has been discussed as a means of reducing the overall cost.

Carbon FRC has been successfully used in construction of free access floor systems used in computer rooms and office automation system rooms [4.14]. Lightweight carbon FRC with microballoons as aggregate has been applied in the construction of the Al Shaheed Monument in Iraq [4.10]. Carbon FRC curtain walls have been installed in the construction of a 37 story office building in Tokyo, Japan, reportedly resulting in substantial savings in both time and money [4.44].

Proponents of carbon FRC suggest that reduction in the minimum dimensions of pipes and boards can be obtained with the use of carbon fibers. Ignoring economics, structural applications appear promising. Optimization of manufacturing processes for carbon fibers may bring costs down.

4.6.2—*Applications of polypropylene and nylon FRC*

To date, most commercial applications of polypropylene FRC [4.85, 4.88] and nylon FRC have used low denier, low volume percentage (0.1 percent), monofilament (in the case of polypropylene and nylon) or fibrillated fibers (in the case of polypropylene). These fibers have been applied to non-structural and non-primary load bearing applications.

Current applications include residential, commercial, and industrial slabs on grade, slabs for composite metal deck construction, floor overlays, shotcrete for slope stabilization and pool construction, precast units, slip form curbs, and mortar applications involving sprayed and plastered portland cement stucco.

4.7—Research needs

In addition to the ongoing pursuit of the goal of developing cost effective fibers with material properties and fiber geometries that are best suited to particular applications or FRC fabrication technologies, there is a need for further research in the following areas:

1. Determine the effect of the addition of various fiber types on control joint spacing for concrete flatwork.

2. Continue to determine effectiveness of fibers as temperature and shrinkage reinforcement.

3. Develop standardized test procedures for impact and fatigue loading to demonstrate performance differences among various fiber types.

4. Develop composite applications and design parameters using conventional reinforcement in FRC concrete for structural applications.

5. Determine the fire resistant properties of fiber reinforced composites.

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CHAPTER 5—NATURAL FIBER REINFORCED CONCRETE (NFRC)

5.1—Introduction

Discontinuous short fibers are widely used in both types of FRC all over the world. In this chapter, attention is focused on the use of naturally occurring fibers for reinforcing concretes, mortars, and cements. Concretes reinforced with naturally occurring fibers are generally termed natural fiber reinforced concrete (NFRC).

Many natural reinforcing materials can be obtained at low levels of cost and energy using locally available manpower and technical know-how. Such fibers are used in the manufacture of low fiber content FRC and occasionally have been used in the manufacture of thin sheet high fiber content FRC.

These fibers are typically referred to as unprocessed natural fibers (UNF).

However, other natural fibers are available that have been processed to enhance their properties. These fibers are derived from wood by chemical processes such as the kraft process. Kraft pulp fibers are used in sophisticated manufacturing processes, such as the Hatschek process, to produce thin sheet high fiber content FRC. These fibers are typically referred to as processed natural fibers (PNF) and concretes made from them as processed natural fiber reinforced concretes (PNFRC).

Although historically many fibers have been used to reinforce various building materials, until recently little scientific effort has been devoted to the use of natural fibers for reinforcement. The use of some of the best known natural fibers such as sisal, coconut, sugarcane bagasse, plantain (banana), palm, etc., have mostly been limited to the production of fabrics, ropes, mats, etc.

In this report, the various types of natural fibers available for reinforcing concretes, the mix proportions, the method of mixing, handling and placing, and the properties of fresh and hardened natural fiber reinforced concretes are described. Additionally, some of the applications of the NFRC are presented.

5.2—Natural fibers

5.2.1—*Unprocessed natural fibers*

Unprocessed natural fibers are available in reasonably large quantities in many countries and represent a continuously renewable resource. UNFs require relatively small amounts of energy and technical know-how for their production compared to some other types of fibers. In the historical context, the use of raw natural fibers in construction substantially preceded the advent of conventional reinforced concrete. Straw-reinforced, sun-dried mud bricks for wall construction, and horse hair in mortar,

Table 5.1— Typical properties of natural fibers

Fiber type	Coconut	Sisal	Sugar cane Bagasse	Bamboo	Jute	Flax	Elephant grass	Water reed	Plantain	Musamba	Wood fiber (kraft pulp)
Fiber length, in.	2-4	N/A	N/A	N/A	7-12	20	N/A	N/A	N/A	N/A	0.1-0.2
Fiber diameter, in.	0.004-0.016	N/A	0.008-0.016	0.002-0.016	0.004-0.008	N/A	N/A	N/A	N/A	N/A	0.001-0.003
Specific gravity	1.12-1.15	N/A	1.2-1.3	1.5	1.02-1.04	N/A	N/A	N/A	N/A	N/A	1.5
Modulus of elasticity, ksi	2750-3770	1880-3770	2175-2750	4780-5800	3770-4640	14,500	710	750	200	130	N/A
Ultimate tensile strength, psi	17,400-29,000	40,000-82,400	26,650-42,000	50,750-72,500	36,250-50,750	145,000	25,800	10,000	13,300	12,000	101,500
Elongation at break, percent	10-25	3-5	N/A	N/A	1.5-1.9	1.8-2.2	3.6	1.2	5.9	9.7	N/A
Water absorption, percent	130-180	60-70	70-75	40-45	N/A	N/A	N/A	N/A	N/A	N/A	50-75

Note: N/A = properties not readily available or not applicable.
Metric equivalents: 1 in. = 25.4 mm; 1 ksi = 1000 psi = 6.895 MPa

Table 5.2— Mechanical properties of several types of fibers

Type of fiber	Average diameter, in.	Average length, in.	Absorption after 24 hr, percent	Average fiber density (SG)	Average tensile strength, psi	Average bonding strength, psi	Average elongation, percent
Bagasse	0.020	1.38	122.5	0.639	3,570	36	N/A
Coconut	0.027	11.02	58.5	0.580	8,825	40	2.600
Jute	0.004	15.75	62.0	1.280	53,500	20	N/A
Maguey	0.014	15.75	63.0	1.240	54,400	N/A	N/A
Lechuguilla	0.014	15.75	102.0	1.360	54,100	N/A	N/A
Banana	0.011	3.70	276.0	0.298	10,960	35	3.000
Guaney (palm)	0.017	17.44	129.9	1.195	50,000	40	2.880
Bamboo	Variable	Variable	51.0	0.720	54,680	45	1.800

Note: N/A = Not available
Metric equivalents: 1 in. = 25.4 mm; 1 psi = 0.006895 MPa

are typical examples of how natural fibers were used long ago.

In the late 1960s, a systematic evaluation of the engineering properties of natural fibers, and of cement composites made with these fibers was undertaken. The results of these investigations indicated that these fibers could be used successfully to make thin cement sheets for walls and roofs. Appropriate manufacturing processes were subsequently developed for commercial production in various countries of Central America, Africa, and Asia. Products made with portland cement and unprocessed natural fibers such as coconut coir, sisal, sugarcane bagasse, bamboo, jute, wood, and vegetable fibers have been tested for their engineering properties and possible use in buildings in at least 40 different countries [5.1-5.9]. Although the results were encouraging, some deficiencies were found in their durability. These seem to have resulted from the reaction between the cement paste and the fibers and swelling of the fibers in the presence of moisture. A number of researchers are now investigating remedial measures for improving durability.

5.2.2—*Processed natural fibers*

Processed natural fibers have been used in commercial production for the manufacture of thin-sheet fiber reinforced cement products since the mid-1960s initially as an adjunct to asbestos and since the early 1980s as a sole reinforcing fiber. Experimental use of these fibers greatly precedes their large scale commercial use. The first experiment with the use of wood pulp as a replacement for asbestos in asbestos cement dates back to World War I. The Norwegian fiber cement industry was forced to manufacture wood pulp reinforced cement sheets for commercial use during this period because they were unable to obtain their usual supplies of asbestos due to the war.

5.2.3—*Mechanical properties of natural fibers*

5.2.3.1 *Mechanical properties of unprocessed natural fibers*—Information on mechanical properties of unprocessed natural fibers is available [5.5-5.40]. In this section, a brief summary of the results of research to determine the mechanical properties of various types of unprocessed natural fibers is presented. The types of fibers for which the mechanical properties have been evaluated are given in Table 5.1. A brief description for some of the more commonly found natural fibers is presented below.

a. *Coconut fiber.* A mature coconut has an outer covering made of fibrous material. This part of the coconut, called the husk, consists of a hard skin and a large amount of fibers embedded in a soft material. The fibers can be extracted simply by soaking the husk in water to decompose the soft material surrounding the fibers. This process, called retting, is widely used in the less developed countries. Alternatively, a mechanical process [5.10] can be used to separate the fibers. Coconut cultivation is restricted to the tropical regions of Africa, Asia, and Central America.

b. *Sisal fiber*. In Australia, sisal fibers have been successfully used for making gypsum plaster sheets [5.7]. A considerable amount of research has been carried out in Sweden for developing good quality concrete products reinforced with sisal fibers [5.9]. These fibers are stronger than most of the other natural fibers, as can be seen from Table 5.1.

c. *Sugar cane bagasse fiber.* Sugar cane is cultivated in both tropical and sub-tropical regions. Sugar cane bagasse is the residue remaining after the extraction of the juice and contains about 50 percent fiber and 30 percent pith with moisture and soluble solids constituting the remaining 20 percent. In order to obtain good quality fibers, the pith and other solids are removed from the fibers. The properties of bagasse fibers depend, to a very large extent, on the variety of the sugar cane, its maturity, and on the efficiency of the milling plant. The properties given in Table 5.1 are considered to be typical.

d. *Bamboo fiber*. Bamboo belongs to the grass family and can grow to a height of 50 ft (15 m) with diameters varying within the range of 1 to 4 in. (25 to 100 mm). It grows naturally in tropical and sub-tropical regions. Dried bamboo stems are commonly used for building temporary structures such as scaffolding. They may also be fabricated to form a continuous reinforcing material for concrete. Bamboo fibers are strong in tension (Table 5.1) and can be used as a reinforcing material. However, they have a high water absorption capacity, low modulus of elasticity, and special equipment may be needed to extract them from the stems.

e. *Jute fiber*. Jute is grown mainly in India, Bangladesh, China, and Thailand. It is grown solely for its fiber, which is traditionally used for making ropes and bags to transport grains and other materials ranging from cement to sugar. Strong in tension (Table 5.1), jute fiber can also be used in a cement matrix. The process of obtaining jute fibers is very simple. Mature plants are cut and soaked in water for about 4 weeks, which completely decomposes the bark. The fibers thus exposed are then stripped from the stem, washed, and dried.

f. *Flax*. Flax is a slender and erect plant grown mainly for its fiber. Both the tensile strength and the modulus of elasticity of flax are extremely high [5.13] compared to those of other natural fibers, as may be seen from Table 5.1.

g. *Other vegetable fibers*. Of the various vegetable fibers, only a few have been found to be potentially suitable as reinforcing materials. The mechanical properties of the more promising fibers, namely elephant grass, water reed, plantain, and musamba, are listed in Table 5.1. Investigations have also been carried out to explore the possibility of using other natural fibers such as palm fiber and akwara fiber as reinforcing materials for concrete [5.14]. These fibers are usually removed manually from the stem of the plant.

5.2.3.2 *Mechanical properties of processed natural fibers*—Processing of plant materials to extract the fibers is referred to as pulping and the principal plant materials used for pulping are trees. Pulping involves breaking of the bond between fibers in solid softwoods and hardwoods.

Pulping processes are classified as either full-chemical, semi-chemical, or mechanical depending on the nature of the defiberization process. Mechanical pulps are made essentially by grinding the wood to separate the fibers, while in chemical pulps the wood is chipped into approximately 1 inch cubes and cooked in alkalis to dissolve the material that holds the fi-

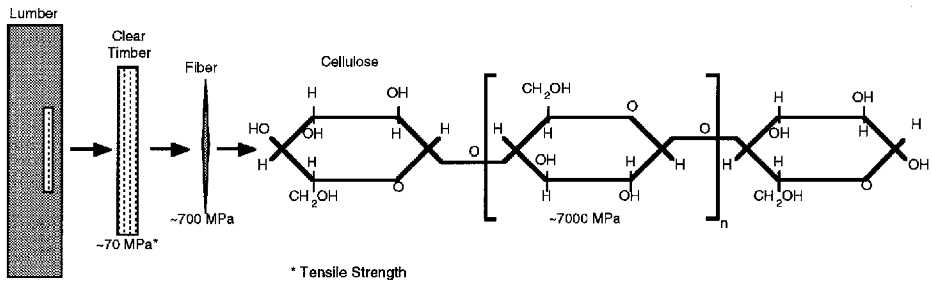


Fig. 5.1—A schematic representation of the substructure of a tree

bers together. Semi-chemical pulps are made with a combination of chemical cooking, which softens the fiber, followed by mechanical treatment to separate the fibers.

It has been found that those components of the wood that are removed in the chemical process are susceptible to alkalis and are responsible for the degradation of unprocessed natural fiber reinforced cements and concretes. Thus chemical (kraft) pulps are more commonly used for the reinforcement of cement. Typical mechanical properties of kraft pulps are also included in Table 5.1.

Figure 5.1 briefly illustrates the structure of wood. A piece of clear timber may attain a tensile strength of approximately 10 ksi (69 MPa). But lumber pieces often contain defects. Individual fibers which constitute the reinforcing unit of timber may have tensile strengths as high as 100 ksi (690 MPa) or more [5.33]. Cellulose, the primary chemical constituent of natural fibers, exhibits a tensile strength of approximately 930 ksi (6400 MPa). Among commercial trees, softwoods are the source of the so-called long fibers with typical lengths ranging from 0.1 to 0.3 in. (2 to 7 mm). Softwood fibers have widths ranging from 15 to 80 microns. Hardwoods yield fibers that, on the average, are about $^1/_3$ to $^1/_2$ the length and about $^1/_2$ the width of softwood fibers. Even within the same tree species, fiber strengths can vary considerably.

5.3—Unprocessed natural fiber reinforced concrete

5.3.1—*Materials and mixing*

5.3.1.1 *Mix proportions*—Mix proportions for unprocessed natural fiber reinforced concrete cannot be generalized since there are a variety of natural fibers that can be used in conjunction with the other standard ingredients such as cement, pozzolans, fine aggregates, water, and admixtures.

The types of natural fibers that can be used with these standard ingredients include: bagasse, sisal, jute, coconut, banana, and palm. A brief description for each of the constituents which is used for obtaining fiber reinforced concrete is outlined below.

5.3.1.2 *Cement*—A cement that meets the ASTM standard specification C 150 or C 595 can be used. The type of cement recommended is Type I, although Type III (high-early strength) cement can be used in order to reduce hardening retardation caused by the glucose present in most natural fibers.

5.3.1.3 *Aggregates*—The aggregates should meet the gradation requirements specified by ASTM C 33, Standard Specification for Concrete Aggregates.

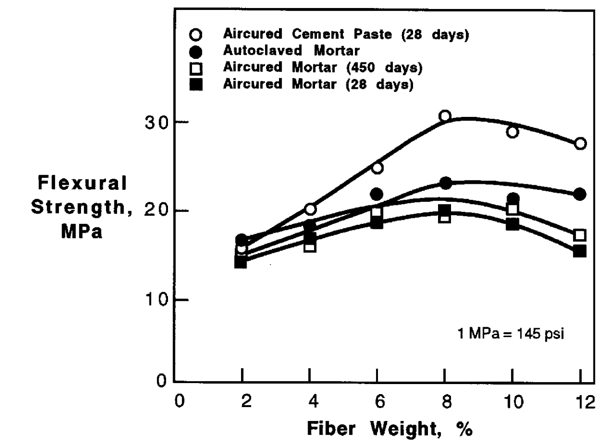
5.3.1.4 *Water and admixtures*—The water to be used for the mix should be clean and of good quality. Admixtures such as accelerating agents may be used in order to decrease the influence of the glucose retardant. If mild steel rebars are not used as additional reinforcement, calcium chloride could be used. Water-reducing admixtures and high-range water-reducing agents can be added in order to increase the workability when plastering. The use of organic-microbiocide is encouraged, for the prevention of bacterial attack of organic fibers.

5.3.1.5 *Fibers*—The length of fibers may vary from 1 to 20 in. (25 to 500 mm). Because fibers are natural materials, they are not uniform in diameter and length. Typical values of diameter for unprocessed natural fibers vary from 0.004 to 0.03 in. (0.10 to 0.75 mm) [5.2]. The mechanical properties of fibers are summarized in Table 5.2.

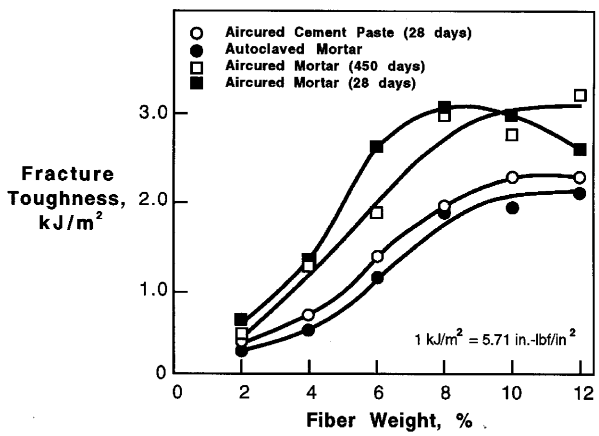
5.3.1.6 *Methods of mixing*—The two methods of mixing and placing are (1) wet mix and (2) dry-compacted mix. In the wet mix, a low volume fraction of fibers is used. The water to be added to the mix has to take into account the high natural water content in the natural fibers. The mixing procedure must comply with ASTM C 94 process and portions of ACI 304 recommendations. Trial batches are recommended and a batching plant is required. The recommended mixing procedure is to add cement with water and additives to form a slurry. Then the fine aggregates are added. Finally, fiber is added and dispersed into the slurry. The sampling is to be done according to ASTM Practice C 172 and C 685. For compressive and flexural strength testing, ASTM C 39 and C 78 are to be followed.

The dry-compacted mix is generally used for industrial or semi-industrial projects. In the dry-compacted mix, the volume fraction of fiber used is about 10 times the volume fraction used in wet mix. The fibers are in a saturated-surface-dry condition for this type of mix. Trial batches are recommended. The recommended mixing procedure is to add fibers in saturated-surface-dry condition to the cement and aggregates and then add a very limited amount of water. Mixing can be done by hand, although mixing according to ASTM C 94 is recommended. For compressive and flexural strength, ASTM C 39 and ASTM C 78 are to be followed. The dry mix samples are cast followed by the application of pressure since very little or no water is added to the mix.

The volume percentage of unprocessed natural fibers used in a mix varied from 3 to 30 percent depending on the type of fiber used and the manufacturing procedure. Typical mix proportions for coconut fiber reinforced concrete for both the wet mix and the dry-compacted mix are presented in Table 5.3.



(a) Flexural Strength



(b) Flexural Toughness

Fig. 5.2—Flexural strength and toughness versus fiber weight fraction for cements and mortars reinforced with wood fiber (Kraft pulp)

5.3.2—*Properties of unprocessed natural fiber reinforced concrete*

5.3.2.1 *General*—The properties of unprocessed natural fiber reinforced concrete, like those of any fiber reinforced concrete, are affected by a large number of factors. The major ones are listed in Table 5.4. Clearly, the type and length of fibers, as well as the volume fraction, are the most significant factors. Test results [5.10] show that for natural fibers the minimum fiber addition to provide some improvement in the mechanical properties of the cement composite is about 3 percent by volume. The impact resistance is increased in most cases regardless of the fiber volume fraction, but other properties are not improved significantly and remain similar to plain concrete. The properties of fresh and hardened unprocessed natural fiber reinforced concretes are briefly discussed in the following sections.

5.3.2.2 *Fresh concrete*—The addition of unprocessed natural fibers to concrete leads to reduced workability due to the increased surface area and water absorption of the fibers. It is important, however, that the mix be workable. A mix that is too stiff or too dry could lead to an inadequately compacted final product which is likely to contain voids and/or honeycombs. A mix that is too wet will, on the other hand, lead to unnecessary strength reduction.

The other important aspect is “balling” of fibers. The extent to which balling may occur in a given mix is determined by the type and length of fibers used, the volume fraction of fibers, and the maximum size of the aggregate. Balling should not be allowed to occur as it has a detrimental effect on the strength. Certain mixing methods can be employed to minimize the balling effect. Normally, the progressive addi-

Table 5.3— Mix proportions for wet mix and dry-compacted mix

Ingredient	Wet mix	Dry-compacted mix
Cement, lb/yd^3	925-1000	880-925
Coconut fiber, lb/yd^3	30	370
Sand, lb/yd^3	2500	2500
Water -in fiber, lb/yd^3 -added, lb/yd^3	3.5 (estimate of natural condition) 630	460 (estimate of saturated-surface-dry condition) 800
Additives -Calcium chloride, lb -Microbiocide, oz -Water reducers	 35 1.9 none	 35 2.1 none

Metric equivalents: 1 lb/yd^3 = 0.593 kg/m^3; 1 lb = 0.454 kg; 1 oz = 28.35 g

Table 5.4— Factors affecting properties of natural fiber reinforced concretes

Factors	Variables
Fiber type	Coconut, sisal, sugarcane bagasse, bamboo, jute, wood, vegetables (akwara, elephant grass, water reed, plantain, and musamba)
Fiber geometry	Length, diameter, cross-section, rings, and hooked ends
Fiber form	Mono-filament, strands, crimped, and single-knotted
Fiber surface	Smoothness, presence of coatings
Matrix properties	Cement type, aggregate type and grading, additive types
Mix proportioning	Water content, workability aids, defoaming agents, fiber content
Mixing method	Type of mixer, sequence of adding constituents method of adding fibers, duration and speed of mixing
Placing method	Conventional vibration, vacuum dewatering for sprayed-up member, vacuum-press dewatering for slurry-dewatered member, extrusion and guniting
Casting technique	Casting pressure
Curing method	Conventional, special methods

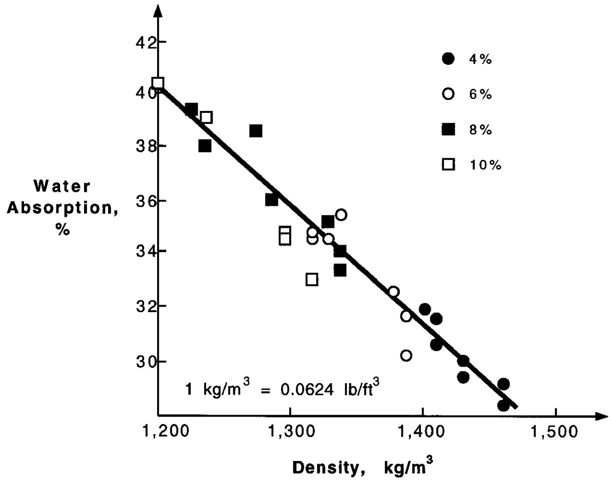


Fig. 5.3—Relationship between water absorption and density of slurry-dewatered softwood Kraft fiber-cement composites at different weight fractions

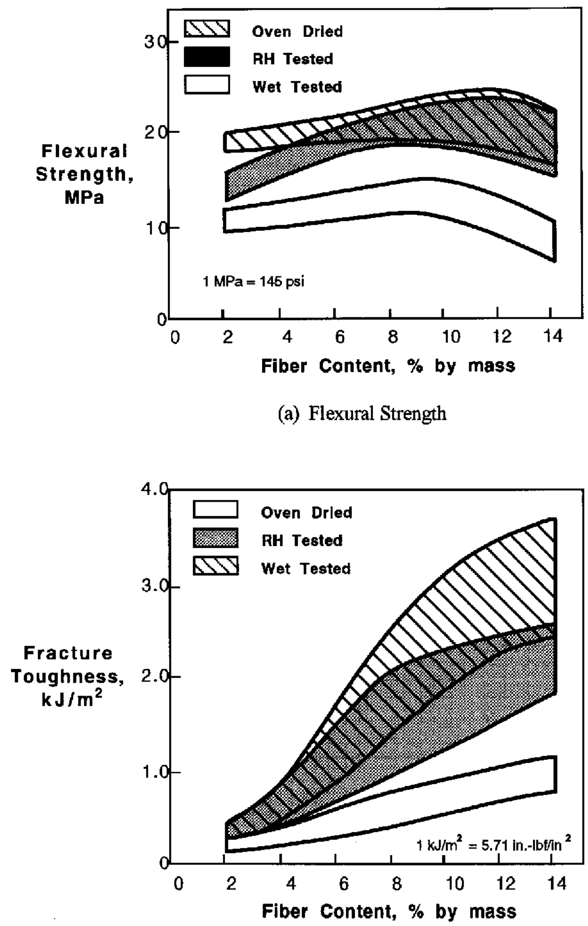


Fig. 5.4—Effects of moisture content on flexural strength and toughness of wood reinforced cement at different fiber contents

tion of fibers at the end of the mixing process, after the other ingredients have been mixed, reduces the balling effect. Also, the use of high-range water-reducing admixtures is found to substantially increase workability without adversely affecting strength.

Depending upon the amount of fibers and the method of mixing (dry batch or wet batch), unit weight may be reduced to 94 lb/ft^3 (1500 kg/m^3) (compared to normal concrete which is 145 to 155 lb/ft^3 (2300 to 2500 kg/m^3). The workability of the dry-compacted mix is normally poor.

5.3.2.3 *Hardened concrete*—One of the important properties of the hardened composite is its strength. Since the unreinforced cement mortar matrix possesses adequate strength for many applications, but is brittle, it is customary to study the influence of fibers on the increased ductility that can be achieved. Apart from strength, other aspects such as deformation under load (stiffness), durability, cracking characteristics, energy absorption, water tightness, and thermal properties should also be evaluated. The most important contribution of the fibers can be rationally evaluated by determining the fracture toughness of the composite [5.14].

Table 5.5 shows the strength characteristics of a typical composite, reinforced with jute fibers [5.11]. From this table it can be seen that, in general, compressive strength is not significantly affected by the addition of fibers, while tensile and flexural strength and toughness are all substantially increased. Furthermore, for a particular fiber there exists an optimum value for both volume fraction and fiber length. Detailed information on the behavior of composites made with jute, coconut, sisal, bagasse, bamboo, flax, and some other vegetable fibers can be found in references 5.11-5.22.

As mentioned earlier, a successful construction material should possess desirable serviceability characteristics in addition to strength. A number of investigators have studied various natural fiber reinforced concretes to understand their behavior in terms of permeability, water absorption, thermal conductivity, sound transmission, linear expansion, and combustibility. Typical results of these properties, are given in Tables 5.6 and 5.7 [5.17, 5.21].

Unfortunately, the amount of available test data on the durability of unprocessed natural fiber reinforced concrete are limited. The following observations can, nevertheless, be made, based on the existing literature [5.13].

a. Unprocessed natural fiber reinforced concrete is more vulnerable than other fiber reinforced concretes in terms of durability. The highly alkaline pore-water in the concrete seems to deteriorate the fibers.

b. Durability can be substantially improved by replacing 40 to 50 percent of the cement with silica fume, since the addition of silica fume reacts with lime and considerably reduces the alkalinity of the pore-water.

c. Improved durability can be achieved by coating the fiber with suitable chemicals such as formic and stearic acid.

5.3.2.4 *Placing and finishing*—The placing and finishing of the unprocessed natural fiber reinforced concrete is dependent on the method of mixing used (wet mix or dry-compacted mix). Placing of the wet mix may be achieved by using conventional equipment. Internal or external vibrators should be used. Other properties such as workability can be measured by the slump test or the K-slump tester as per the

Table 5.5— Effect of fiber length and volume fraction on strength parameters of jute-fiber reinforced cement composites

Mix ratio cement/sand	Fiber volume fraction, percent	Fiber length,in.	Compressive strength, psi	Tensile strength, psi	Modulus of rupture, psi	Flexural toughness, in.-lb	Compressive Young's modulus, ksi	Tensile Young's modulus, ksi
1:0	0	—	4560	175	410	0.3	2250	1400
	1	1.0	5175	200	540	4.9	2050	1450
	2	1.0	4350	285	650	7.7	1800	1700
	3	1.0	5430	300	555	6.6	1850	1600
	4	1.0	5075	245	480	6.1	1900	1650
	2	0.5	4435	250	565	5.8	2200	1500
	2	0.7	4160	340	600	7.4	1600	1450
	2	1.5	4520	255	640	7.3	1700	1350
1:1	0	—	5570	295	610	0.5	2150	2250
	2	0.5	5430	365	815	7.8	2050	2600
	2	0.7	4705	315	730	8.9	2050	1950
	2	1.0	4750	315	650	9.7	1800	2100
	2	1.5	4055	305	580	7.2	1250	2550
1:2	0	—	5070	305	545	0.4	1750	2600
	2	0.5	4055	335	645	7.3	1450	3300
	2	0.7	4165	360	670	8.9	1950	3250
	2	1.0	4710	295	570	7.1	2050	2300
	2	1.5	3620	235	545	6.6	2200	2400

Metric equivalents: 1 in. = 25.4 mm; 1 ksi = 1000 psi = 6.895 MPa; 1 in.-lb = 0.113 Nm

Table 5.6— Comparison of the properties of elephant-grass fiber reinforced roofing sheets with those reinforced with asbestos fibers

Properties	Cement sheets reinforced with elephant-grass fibers	Cement sheets reinforced with asbestos fiber
Consistency at 25 percent water, percent	15	11
Impact strength, ft-lb	2.08	2.98
Flexural strength, psi	1500	2600
Impermeability	Excellent	Excellent
Water absorption, percent	16.3	20.6
Coefficient of thermal conductivity, BTU/(ft x h x degrees F)	0.191	0.208
Sound transmission of 833 Hz signal, percent	22 when dry 30 when wet	26 when dry 40 when wet
Combustibility (BS 476-Part 4)	Non-combustible	Non-combustible
Linear expansion, percent	0.22	0.24
Density, lb/ft^3	110	96

Metric equivalents: 1 ft-lb = 1.356 J; 1 psi = 0.006895 MPa; 1 BTU/(ft x h x degrees F) = 1.731 W/(m x degrees K); 1 lb/ft^3 = 16.019 kg/m^3

Table 5.7— Comparison of the physical properties of coconut-fiber reinforced roofing sheets with those of asbestos roofing sheets

Characteristics and properties	Coconut-fiber reinforced roofing sheets	Asbestos roofing sheets
Pitch of corrugation, in.	5.75	5.75
Depth of corrugation, in.	1.9	1.9
Length of sheets, in.	59-79	59-118
Width of sheets, in.	39	41
Weight, lb/ft^2	2.4-2.5	2.8
Breaking load for a span of 24 in., lb/ft	3.4	—
Breaking load at a span of 40 in., lb/ft	1.3	3.4
Thermal conductivity, kcal/mm/m	0.009	0.024
Water permeability through finished surface in 24 hours	almost nil	—
Acid resistance as per I.S.: 5913-1970, ksi	236	235

Metric equivalents: 1 in. = 25.4 mm; 1 lb/ft^2 = 4.88 kg/m^2; 1 lb/ft = 14.595 N/m; 1 ksi = 6.895 MPa

ASTM recommended Penetration Test. Air content in the mix can be measured using ASTM C 231 or C 173.

For placing the dry-compacted mix, there is a need for a special type of formwork since the mix is dry and has to be compacted with some pressure within the formwork. Once the dry mix is placed inside the formwork, it is subjected to a confining pressure of about 30 to 70 psi (0.2 to 0.5 MPa). This confining pressure is applied for a period of about 24 hours. Care should be taken not to apply a larger pressure than needed, since water (which is critical for hydration) may be squeezed out. The air content of the mix can be obtained using ASTM C 231 or ASTM C 173. The unit weight can be obtained using ASTM C 130.

5.4—Processed natural fiber reinforced concrete

5.4.1—*Production methods*

The slurry-dewatering technique is commonly used for the production of processed fiber reinforced cements and concretes. In this method, the fibrous cement product is formed from a dilute slurry (about 20 percent solids) of fiber-cement or fiber-mortar. The excess water is removed from the slurry through the application of vacuum dewatering and pressure [5.35]. The product is then cured in air or in an autoclave to develop its strength and other mechanical properties. Industrial production of this composite now occurs in Europe, Australia, North America, South America, Asia, and South Africa using kraft wood fibers with good results.

Hand methods can also be used by methods similar to that used in the manufacture of sisal/gypsum plaster composites [5.50]. In this case, the fiber is rolled by hand into a slurry of cement and fine sand and compacted by rolling with a toothed roller. Clearly this method is slow and labor intensive and is not used in countries where labor is in short supply and expensive. This method is not appropriate for manufacture of kraft wood pulp reinforced boards since the fibers are not long enough.

5.4.2—*Properties of the hardened processed natural fiber reinforced concretes*

The performance of PNFRCs in both the short and long term depends on the methods used for their curing and their mix proportions. The mix proportions used for commercial products are not readily available.

Figures 5.2a and 5.2b show typical effects of kraft pulp fiber weight fraction on the flexural strength and toughness (area underneath the flexural load-deflection curve) of cementitious materials with different mix proportions that have been cured in different conditions. The results (all obtained at 50 percent R.H.) are indicative of improvements in flexural performance of cementitious materials resulting from kraft pulp fiber reinforcement.

In the case of slurry-dewatered wood fiber reinforced cement, it has been reported [5.37] that the density of the composite decreases and its water absorption capacity increases with increasing fiber content. The overall density of the composite reflects the changing proportions of the constituent fiber and the matrix. The void volume of the composite also increases, but in a non-linear fashion, as the fiber content increases. The amount of water absorbed by wood fiber reinforced cement depends on the density of the composite, Fig. 5.3 [5.35].

As far as the long-term durability of wood fiber reinforced cement composites is concerned, it should be noted that kraft pulps have relatively low lignin contents. Noting the susceptibility of lignin to alkaline attack, kraft pulps possess better durability characteristics than mechanical wood fibers in the highly alkaline cementitious environment [5.38].

Studies on processed natural fiber reinforced cement have shown that increase in moisture content tends to decrease the flexural strength and increase the flexural toughness of the composites. Figures 5.4a and 5.4b compare the flexural strength and toughness values, respectively, of slurry-dewatered kraft pulp reinforced cement with different fiber contents tested in wet or oven-dried conditions, or in an environment of 50 percent R.H. Increase in moisture content seems to weaken the bonding of matrix to fibers, thus encouraging fiber pull-out rather than rupture at cracks. The weakened bond reduces flexural strength, while the frictional energy consumed during pull-out tends to increase the fracture toughness of the composite [5.37].

Further details on the performance of air-cured composites are given in References 5.42 and 5.43. Autoclave-cured composites are dealt with in detail in Reference 5.41. The long-term performance of both autoclaved-cured and air-cured processed natural fiber cements is given in References 5.45 to 5.49.

5.5—Practical applications

In Africa, sisal fiber reinforced concrete has been used extensively for making roof tiles, corrugated sheets, pipes, silos, and gas and water tanks [5.22]. Elephant grass fiber-reinforced mortar and cement sheets are being used in Zambia for low-cost house construction [5.23], while wood and sisal fibers are being used for making cement composite panel lining, eaves, soffits, and for sound and fire insulation.

Kraft pulp fiber reinforced cement has found major commercial applications in the manufacture of flat and corrugated sheet, non-pressure pipes, cable pit, and outdoor fiber reinforced cement paste or mortar products for gardening [5.33-5.39, 5.41-5.49]. The durability of these products in outdoor exposure has been demonstrated with nearly 10 years of commercial use of these materials.

5.6—Summary

Naturally available reinforcing materials can be used effectively as reinforcement in portland cement concrete. Natural fiber reinforced concrete is suitable for low-cost construction, which is very desirable for developing countries. It is important for researchers, design engineers, and the construction industry to vigorously pursue the use of local materials. For economical engineering solutions to a variety of problems, natural fiber reinforced concrete offers a viable alternative that needs to be fully investigated and exploited.

Wood fibers derived from the Kraft process possess highly desirable performance-to-cost ratios, and have been successfully substituted for asbestos in the production of thin-sheet cement products, such as flat and corrugated panels and non-pressure pipes.

5.7—Research needs

The durability and performance of processed natural fiber reinforced cement is documented better than FRC made with unprocessed fibers. While the strength and elastic modulus of cement products reinforced with processed natural fibers (e.g., kraft pulp) seem to actually increase upon weathering, more research is needed regarding the potential for embrittlement under exposure to some aggressive environments.

The durability and moisture-sensitivity of unprocessed natural fibers are among the critical aspects of these composites that need to be further investigated. Research is needed to fully understand the mechanisms by which moisture and aggressive environments change the failure mechanisms and thus affect the strength and toughness characteristics of natural fiber reinforced composites. Potentials for the refinement of cementitious matrices in cellulose-cement composites to improve the durability characteristics also need further investigation. These refinements may be concerned with reducing the alkalinity and permeability of the matrix.

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