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Report on Fiber Reinforced Concrete

Reported by ACI Committee 544

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

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

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

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

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

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

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.

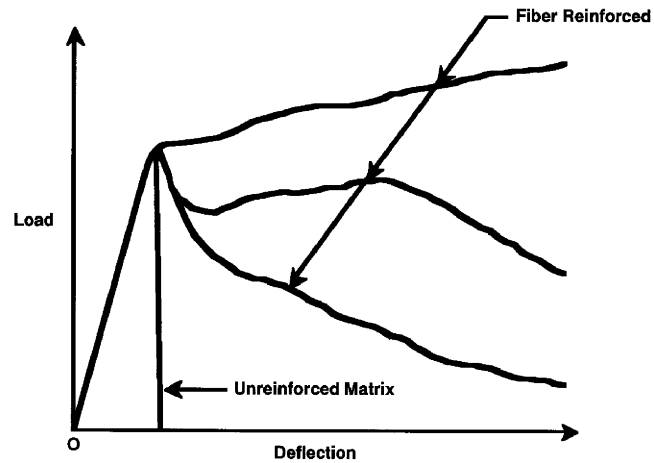

Fig. 1.1—Range of load versus deflection curves for unreinforced matrix and fiber reinforced concrete.

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 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

ASTM International
1916 Barr Harbor Dr.
West Conshohocken, PA 19103

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

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

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

1.8.1 *ACI committee documents*

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

1.8.2 *ACI Special Publications*

SP-155 Testing of Fiber Reinforced Concrete, edited by D. J. Stevens, N. Banthia, V. S. 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

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1.3 Romualdi, J. P., and Batson, G. B., "Mechanics of Crack Arrest in Concrete," *Journal of the Engineering Mechanics Division*, ASCE, V. 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., V. 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, Farmington Hills, Mich., 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* V. 70, No. 11, Nov. 1973, pp. 727-744.

1.11 RILEM Technical Committee 19-FRC, "Fibre Concrete Materials," *Materials and Structures*, Test Res., V. 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.

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CHAPTER 2—STEEL FIBER REINFORCED CONCRETE (SFRC)

2.1—Introduction

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

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

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

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

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