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Guide for Specifying, Proportioning, and Production of Fiber-Reinforced Concrete

Reported by ACI Committee 544

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Guide for Specifying, Proportioning, and Production of Fiber-Reinforced Concrete

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This guide covers specifying, proportioning, mixing, placing, and finishing of fiber-reinforced concrete (FRC). Much of the current conventional concrete practice applies to FRC. The emphasis in the guide is to describe the differences between conventional concrete and FRC and how to deal with them. Sample mixture proportions are tabulated. Guidance is provided in the mixing techniques to achieve uniform mixtures, placement techniques to assure adequate consolidation, and finishing techniques to assure satisfactory surface textures. A listing of references is provided covering proportioning, properties, applications, shotcrete technology, and general information on FRC.

Keywords: fiber; fiber-reinforced concrete; production; proportioning; specification.

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CHAPTER 1—INTRODUCTION AND SCOPE

1.1—Introduction

Fiber-reinforced concrete (FRC) is a composite material made of hydraulic cements, water, fine and coarse aggregate, and a dispersion of discontinuous fibers. In general, fiber length varies from 0.25 to 2.5 in. (6 to 64 mm). FRC may also contain supplementary cementitious materials and admixtures commonly used with conventional concrete.

The most common steel fiber diameters are in the range of 0.02 to 0.04 in. (0.5 to 1.0 mm) and a specific gravity of 7.85. Steel fiber shapes include round, oval, polygonal, and crescent cross sections, depending on the manufacturing process and raw material used.

Two general sizes of synthetic fibers have emerged: microsynthetic and macrosynthetic fibers. Microsynthetic fibers are defined as fibers with diameters or equivalent diameters less than 0.012 in. (0.3 mm), and macrosynthetic fibers have diameters or equivalent diameters greater than 0.012 in. (0.3 mm). Polypropylene fibers can be either microsynthetic or macrosynthetic, and have a specific gravity of 0.91. Nylon fibers, generally microfibers, have a specific gravity of 1.14.

Microsynthetic fibers are typically used in the range of 0.05 to 0.2% by volume, while steel fibers and macrosynthetic fibers are used in the range of 0.2 to 1% by volume, and sometimes higher in certain applications. For example, 2% by volume and higher of steel fibers is common for security applications such as vaults and safes. These dosages equate to 0.75 to 3 lb/yd^3 (0.44 to 1.8 kg/m^3) for microsynthetic fibers, 3 to 15 lb/yd^3 (1.8 to 9 kg/m^3) for macrosynthetic fibers, and 26 to 132 lb/yd^3 (15 to 78 kg/m^3) for steel fibers.

Glass fibers for use in concrete should be alkali-resistant (AR) glass to prevent loss of strength due to the high alkalinity of the cement-based matrix. Glass fibers need to contain a minimum of 16% by mass of zirconium dioxide (zirconia) to be considered as alkali resistant. AR glass fiber monofilaments are either 0.0005 or 0.0007 in. (13 or 18 μm) in diameter, with specific gravity of 2.7.

AR glass fiber chopped strands can be provided in two basic types: dispersible fibers and internal strands. Dispersible fibers quickly disperse into individual monofilaments when mixed into the concrete. These fibers are considered to be microfibers. The addition rate for this type of AR glass fiber is typically 0.5 to 1.5 lb/yd^3 (0.29 to 0.88 kg/m^3). This corresponds to a range from 0.01 to 0.03% by volume. This type of glass fiber is used mostly for plastic shrinkage crack control. Integral strands are bundles of monofilaments that stay integral as bundles through mixing and into the cured concrete. Integral strands are available in bundles of 50, 100, and 200 monofilaments. These strands are considered as macrofibers, and can be added at higher fiber contents, typically 4 to 8 lb/yd^3 (2.35 to 4.7 kg/m^3) corresponding to 0.09 to 0.17% by volume. Addition rates of up to 25 lb/yd^3 (14.7 kg/m^3) or 0.55% by volume have also been used with higher cement contents.

Natural fibers and synthetic fibers, such as carbon, acrylic, and aramid fibers, have been used in specialized FRC and are not discussed in this guide. The use of glass fibers in the spray-up process is also not discussed in this guide. Information on these fiber types may be found in ACI 544.1R.

The addition of fibers affects the plastic and hardened properties of mortar and concrete. Depending on the fiber material, length and diameter, deformation geometry, and the addition rate, many properties are improved, notably plastic shrinkage cracking, impact resistance, and toughness or ductility. Flexural strength, fatigue and shear strength, and the ability to resist cracking and spalling can also be enhanced by providing the composite material with some postcracking (residual) strength in either the plastic or hardened state. More detailed information on properties may be found in ACI 544.1R and 544.2R.

1.2—Scope

This guide covers specifying, proportioning, mixing, placing, and finishing of conventional FRC. The fiber types included in this guide are steel, glass, and synthetic. Not included are FRC produced using the shotcrete method, by extrusion, by slurry infiltration, by roller compaction, or by spray-up process.

1.3—Typical uses of FRC

When used in structural applications, fiber reinforcement is generally only used in a supplementary role to distribute cracking, to improve resistance to impact or dynamic loading, and to resist material disintegration. Under certain conditions stated in Section 11.4.6.1(f) of ACI 318-08, the use of steel fiber-reinforced concrete to resist shear forces without conventional shear reinforcing steel is permitted. In structural members where flexural tensile or axial tensile stresses will occur, such as in beams, columns, and suspended slabs, continuous conventional reinforcing steel is typically designed to resist the tensile forces. With a dosage rate of 76 to 84 lb/yd^3 (45 to 50 kg/m^3), however, more than 75 million ft^2 (7 million m^2) of suspended ground floor slabs without conventional reinforcing steel with span-depth ratios up to 20 that are reinforced with steel fibers have been successfully completed since 1990 in Europe, the U.S., and Canada (Destrée 2006).

In applications where the presence of continuous conventional reinforcement is not essential to resist tensile stresses, for example, pavements, overlays, some precast products, and shotcrete linings—the improvement in flexural toughness associated with the fibers can be used to reduce section thickness, improve performance, or both. The following are some examples of structural and nonstructural uses of FRC:

- *Airport and highway paving and overlays*—Both full-depth pavements and overlays on concrete and asphalt bases (white topping) (Johnston 1984; Loper and Henry 2003; Task Force 36 2001; Cole 1999);
- *Flooring*—Residential, commercial, and heavy industrial slabs-on-ground (Gervickas 2000; Suprenant and Malisch 1999; Roesler et al. 2004, 2006; ACI 360R);
- *Bridge decks*—For repairs, overlay resurfacing and "steel free" bridge decks where loads are resisted through an internal compressive arch in the slab and external tension tie (Melamed 1985; Newhook and Mufti 1996; Banthia and Bindiganavile 2001; Banthia et al. 2004, 2006; Banthia and Gupta 2006; Naaman and Chandrangsu 2004);
- *Shotcrete linings*—Underground support in mines and tunnels, slope stabilization and ground coverings, and structural repairs (Morgan and Heere 2000; Morgan and McAskill 1984; Tatnall and Brooks 2000; ACI 506.1R);
- *Precast products*—Segmental tunnel liners, vaults, safes, dolosse, equipment vaults, utility boxes, and septic tanks (Court 2003; Novak and Greenhalgh 2007); and
- *Explosive spalling and seismic-resistant structures*—Seismic upgrade applications and resistance to explosive spalling from fire (Henager 1983; Forrest et al. 1995; Tatnall 2002).

1.4—Specifying FRC

1.4.1 *General*—FRC is often specified by strength, either compressive or flexural, and fiber type (material) and content (dosage or percent by volume). This prescriptive method is appropriate for many applications, such as lower dosages of microsynthetic fibers for control of plastic shrinkage cracking, or where testing for fiber performance is not practical. For a performance specification, the compressive or flexural strength and flexural performance parameters should be specified. Flexural parameters include post-cracking residual strength f_{XXX}^{D} and toughness T_{XXX}^{D} as defined in ASTM C1609/C1609M, average residual strength (ARS) as defined in ASTM C1399, toughness as defined in ASTM C1550, and the equivalent flexural strength and toughness as defined by JSCE SF-4 (Japan Society of Civil Engineers 1983). These parameters are discussed in ACI 544.2R and in this chapter. It is noted that the postcracking performance parameters are dependent on many variables, such as specimen size, testing speed, and sawed versus molded specimens; therefore, ASTM C1399 and C1609/C1609M require a minimum specimen size that depends on the fiber length. ASTM C1609/C1609M advises users that the magnitude of the energy absorption capability of the specimen is dependent upon both the geometry of the test specimen and the loading configuration.

The flexural strength (modulus of rupture) is normally specified for slabs-on-ground, paving, and shotcrete applications, whereas compressive strength is specified for structural applications. A flexural strength of 500 to 800 psi (3.4 to 5.5 MPa) and a compressive strength of 4000 to 6000 psi (27.5 to 41.4 MPa) at 28 days are typical values. In general, the addition of fibers does not significantly decrease or increase compressive or flexural strength at low to moderate dosages, but can increase the strain at ultimate load and the postcracking residual strength and toughness. Therefore, specifying compressive or flexural strength provides general guidelines for concrete proportioning, but does not allow for assessment of improvements in properties, such as post-cracking load capacity and toughness, that are directly attributable to fibers and other improvements such as increased tensile strain capacity and resistance to cracking.

Toughness, which is the concrete property represented by the area under a load-deflection curve, a postcracking load, or strength, may be specified to help define the performance requirements of FRC intended for use where postcracking energy absorption or resistance to failure after cracking are important. The properties are important in applications such as structures subjected to earthquakes or explosive blasts, impact loads, cavitation loading, and other dynamic loads such as those that occur with pavements and industrial floors.

As noted in subsequent chapters, the manufacture and placing of FRC is similar to conventional concrete. ASTM C1116/C1116M covers the manufacture and delivery of FRC, and is similar to ASTM C94/C94M. Most existing concrete specifications can be used for placements of FRC with some added requirements to account for the differences in material and application techniques. Subsequent chapters point out those differences.

1.4.2 *Guidelines for specifying FRC using ASTM C1116/C1116M*—ASTM C1116/C1116M covers the manufacture of FRC by any method (with the exception of packaged, dry FRC materials), for example, transit mixing, central batch plant mixing, and continuous mixing. Packaged FRC materials for shotcrete are covered in ASTM C1480/C1480M. ASTM C1116/C1116M is similar to ASTM C94/C94M in that it allows ordering the concrete by one of three alternative methods, including:

- *Alternative 1*—The purchaser assumes responsibility for mixture proportions and specifies them, including cement content, maximum allowable water content, the type and amount of fibers to be used, and the type, name, and dosage of admixtures (if admixtures are to be used);
- *Alternative 2*—The purchaser requires the concrete supplier to assume responsibility for selecting mixture proportions, and specifies minimum flexural toughness or postcracking load or strength, flexural strength, or a combination of these, or, at the purchaser's option, compressive strength, but does not permit compliance on the basis of compressive strength alone; and
- *Alternative 3*—Similar to Alternative 2, except that a minimum allowable cement content is specified.

ASTM C1116/C1116M provides for four types of FRC: 1) Type I is steel FRC (SFRC) that contains stainless steel, alloy steel, or carbon steel fibers; 2) Type II is glass FRC (GFRC) that contains AR glass fibers; 3) Type III is synthetic FRC (SynFRC) that contains synthetic fibers with documented long-term performance in concrete; and 4) Type IV is natural FRC (NFRC) that contains natural fibers with documented long-term performance in concrete. ASTM C1116/C1116M has extensive information and guidance for the purchaser on the nature of FRC and the ordering requirements for it. Any level of performance related to toughness or post-cracking behavior may be specified using Alternatives 2 and 3. An FRC specifier should obtain a copy of ASTM C1116/C1116M, as this document provides extensive and valuable guidance.

1.4.3 *Hybrids*—Combinations of fiber sizes, fiber materials, or both have been increasingly introduced to the market. These combinations are known as hybrid fibers. In well-designed hybrid composites, there is positive interaction between the fibers, and the resulting hybrid FRC performance exceeds the sum of the individual fiber performances. This phenomenon is termed "synergy." Many fiber combinations may provide synergy (Banthia and Gupta 2004; Banthia and Soleimani 2005); the most commonly recognized include:

- *Hybrids based on fiber constitutive response*—One type of fiber is stronger and stiffer and provides reasonable first-crack strength and ultimate strength, while the second type of fiber is relatively flexible and leads to improved toughness and strain capacity in the post-cracking zone;
- *Hybrids based on fiber dimensions*—One type of fiber is smaller so that it bridges microcracks and therefore controls their growth and delays coalescence. This leads to a higher tensile strength of the composite. The second fiber is larger and is intended to arrest the propagation of macrocracks, therefore resulting in a substantial improvement in the fracture toughness of the composite;
- *Hybrids based on fiber function*—One type of fiber is intended to improve the fresh and early-age properties, such as ease of production and plastic shrinkage crack control, while the second fiber leads to improved mechanical properties. Some of these hybrids are commercially available with a low (~0.1% by volume) dosage of polypropylene fiber that is combined with a higher (~0.25% by volume) dosage of steel fiber. These hybrids include the combination of microsynthetic fibers with steel macrofibers, or microsynthetic fibers with macrosynthetic fibers. These systems are typically provided with the different fibers prepacked in proprietary blends ready to add to the concrete mixture. There is no easy way to specify these hybrids using ASTM C1116/C1116M, except to specify a particular hybrid product, and then use the performance criteria as described in 1.4.2.

CHAPTER 2—NOTATION AND DEFINITIONS

2.1—Notation

This section not used.

2.2—Definitions

aspect ratio, fiber—the ratio of length to diameter of a fiber in which the diameter may be an equivalent diameter. (See also **fiber, equivalent diameter**.)

fiber, equivalent diameter—diameter of a circle having an area equal to the average cross-sectional area of a fiber.

tex—the mass in grams of 1 km (3280 ft) of strand or roving.

CHAPTER 3—MATERIALS

3.1—General

When ASTM C1116/C1116M is used to purchase FRC, the cement, aggregates, fibers, and admixtures are automatically required to meet the appropriate ASTM specifications. When purchasing fiber-reinforced shotcrete, the specifier should require the aggregates to meet the requirements of ASTM C1436. ASTM C1116/C1116M defaults to common materials, such as Type I cement. If different material specifications are desired, they should be named in the project specifications or purchase order.

3.2—Fibers

3.2.1 *Steel fibers*—ASTM A820/A820M covers five types of steel fibers for SFRC, and should be referenced when specifying steel fibers. It covers types commonly used in concrete, and it is necessary to specify the fiber's type, length, diameter, or aspect ratio, straight or deformed, and a minimum ultimate tensile strength if a strength of more than 50,000 psi (345 MPa) is desired. Fibers are commonly available with strengths up to 160,000 psi (1100 MPa), and in excess of 300,000 psi (2068 MPa) on special order.

Steel fibers should be clean and free of rust, oil, and deleterious materials. Steel fibers in the common length range of 0.5 to 2.5 in. (13 to 64 mm) should preferably have an aspect ratio in the range of 30 to 100.

3.2.2 *Synthetic fibers*—ASTM C1116/C1116M covers synthetic fibers for use in FRC and shotcrete, and should be referenced when specifying synthetic fibers. It covers all available types commonly used in concrete or shotcrete. Under this specification, it is necessary to specify the type of material required, such as polyolefin, nylon, or other, and whether micromonofilament, macromonofilament, or fibrillated fibers are required. The length, and sometimes the diameter, of fiber should also be specified. Many synthetic fibers are available in lengths from 0.25 to 2.5 in. (6 to 64 mm). For macrosynthetic fibers, the tensile strength and elastic modulus should also be specified.

3.2.3 *AR glass fibers*—ASTM C1666/C1666M covers AR glass fibers for use in concrete. AR glass fibers are commonly used in lengths of 0.5 to 1.5 in. (13 to 38 mm). Under this specification, it is necessary to specify the type or types permissible, and the tex or length required. The required minimum tensile strength of AR glass fiber monofilaments is 145,000 psi (1 GPa), and can range up to 246,000 psi (1.7 GPa).

3.2.4 *Hybrid fibers*—Hybrid fiber products are comprised of the fibers described in Section 1.4.3. The ratios of blends and sizes used are typically proprietary.

3.3—Admixtures

All admixtures meeting ASTM specifications for use in concrete or shotcrete are suitable for use in FRC. Air-entraining admixtures are recommended for FRC exposed to freezing-and-thawing conditions, and applications where deicing salts are used. Calcium chloride and chlorides from other sources should be limited to amounts permitted to be added to conventional structural concrete as per ACI 318.

3.4—Storage of fibers

Care should be taken to ensure that fibers are stored in a manner that will prevent their deterioration or the intrusion of moisture or foreign matter. If fibers deteriorate or become contaminated, they should not be used.

CHAPTER 4—MIXTURE PROPORTIONING

4.1—General

As with conventional concrete, FRC mixtures employ a variety of mixture proportions depending on the application. They should be specially proportioned for a project or selected to be the same as a mixture used previously. In either case, they should be adjusted for yield, workability, and other factors as noted in Section 1.4.2.

4.2—Slump

FRC slump requirements may be somewhat different from those of conventional concrete. Acceptable slump of FRC should be determined by the following method, and its use should be specified in the contract documents.

The slump test may be specified in the contract documents to serve as a control test for consistency of FRC from batch to batch. In addition to the slump test described in ASTM C143/C143M, it may be appropriate to also gather information on unit weight, yield, and air content as described in ASTM C138/C138M and C173/C173M or C231. Other methods for measuring workability of FRC are summarized in ACI 544.2R.

Table 4.1—Range of mixture proportions for normalweight macrofiber-reinforced concrete

Maximum aggregate size	3/8 in.* (9.5 mm)	3/4 in. (20 mm)	1-1/2 in. (38 mm)
Mixture parameters			
Cementitious material, lb/yd^3 (kg/m^3)	600 to 1000 (356 to 593)	500 to 900 (297 to 534)	470 to 700 (279 to 415)
w/c	0.35 to 0.45	0.35 to 0.50	0.35 to 0.55
Percent of fine to coarse aggregate	45 to 60	45 to 55	40 to 55
Fiber content, volume %	0.3 to 2.0	0.2 to 0.8	0.2 to 0.7

*Includes shotcrete mixtures.

In general, the slump for FRC determined from ASTM C143/C143M should be at least 1 in. (25 mm), but not greater than 7 in. (175 mm). Factors that influence the measured slump include the fiber type, length, aspect ratio, amount, cement content, fine aggregate content, aggregate shape, and grading. When these factors change, such as in self-consolidating concrete, a different range may be acceptable. In any case, the specified maximum water-cement ratio (*w/c*) should be maintained.

4.3—Proportioning methods

4.3.1 *General*—In many cases, no changes are necessary to conventional concrete mixture proportions when adding fibers at low to moderate dosages. Adding fibers at less than approximately 0.25% by volume will typically not require adjustment to conventional mixtures as far as cementitious content and fine and coarse aggregate ratios are concerned. Depending on the fiber type and amount, it may be required to adjust the water content, or preferably to add or increase water-reducing admixture quantities to maintain workability, slump, and *w/c*. Guidance for proportioning concrete mixtures can be found in ACI 211.1, 211.2, and 211.4R.

4.3.2 *Steel FRC*—Procedures for proportioning steel FRC mixtures, with emphasis on good workability, are available (Schrader and Munch 1976; Schrader 1989; Ounanian and Kesler 1976; ACI 544.1R). Some typical previously used proportions are shown in Table 4.1.

In many projects, steel fibers have been added without any changes to the conventional mixture proportions used by ready mixed concrete suppliers for the required concrete compressive strength. Where fibers are above approximately 0.33% by volume, some mixture adjustments may be required. In these instances, more paste may be needed to provide better workability. Therefore, fine-to-coarse aggregate ratio is adjusted upward accordingly. Guidance on combined aggregate grading for macrofiber FRC provided in Table 4.2 is taken from ACI 544.1R. The tendency for wet steel fibers to ball during mixing increases with increases in the maximum size aggregate, the coarse-to-fine aggregate ratio, the fiber aspect ratio, and the amount and the rate of addition of fibers to the mixer (Tatnall 1984). It also depends on the method of addition of fibers to the mixer, geometry of the fiber, and whether or not they are collated.

Table 4.2—Recommended combined aggregate grading for macrofiber-reinforced concrete* (ACI 544.1R)

U.S. standard sieve size	Percent passing for maximum size of 3/8 in. (10 mm)	1/2 in. (13 mm)	3/4 in. (19 mm)	1 in. (25 mm)	1-1/2 in. (38 mm)
2 in. (51 mm)	100	100	100	100	100
1-1/2 in. (38 mm)	100	100	100	100	85 to 100
1 in. (25 mm)	100	100	100	94 to 100	65 to 85
3/4 in. (19 mm)	100	100	94 to 100	76 to 82	58 to 77
1/2 in. (13 mm)	100	93 to 100	70 to 88	65 to 76	50 to 68
3/8 in. (10 mm)	96 to 100	85 to 96	61 to 73	56 to 66	46 to 58
No. 4 (5 mm)	72 to 84	58 to 78	48 to 56	45 to 53	38 to 50
No. 8 (2.4 mm)	46 to 57	41 to 53	40 to 47	36 to 44	29 to 43
No. 16 (1.1 mm)	34 to 44	32 to 42	32 to 40	29 to 38	21 to 34
No. 30 (600 μm)	22 to 33	19 to 30	20 to 32	19 to 28	13 to 27
No. 50 (300 μm)	10 to 18	8 to 15	10 to 20	8 to 20	7 to 19
No. 100 (150 μm)	2 to 7	1 to 5	3 to 9	2 to 8	2 to 8
No. 200 (75 μm)	0 to 2	0 to 2	0 to 2	0 to 2	0 to 2

*Combined grading for shotcrete should be in accordance with ACI 506R or ASTM C1436.

In early applications, coarse aggregate larger than 0.75 in. (19 mm) was not recommended for steel FRC. Based on work by Tatro (1987), however, many successful placements have used aggregates as large as 1.5 in. (38 mm) (Rettberg 1986).

Another method of improving SFRC workability is to use supplementary cementitious materials (SCMs) such as fly ash, slag, and silica fume in addition to or as a partial replacement of cement.

4.3.3 *Glass FRC*—Low dosages of AR glass fibers, less than 1.5 lb/yd^3 (0.88 kg/m^3), can be added without changing conventional concrete mixture proportions. Higher fiber contents may require adjustments to maintain good workability and compaction of the concrete. Higher cement contents, smaller aggregate size, and the use of SCMs and water-reducing admixtures are usually required when higher fiber contents are used.

4.3.4 *Microsynthetic FRC*—Low dosages of microsynthetic fibers, less than 3 lb/yd^3 (1.8 kg/m^3), can generally be added without changing conventional concrete mixtures. For higher volumes, adjustment of the fine-to-coarse aggregate ratio may be required. Procedures for proportioning microsynthetic FRC mixtures are available in ACI 544.1R.

4.3.5 *Macrosynthetic FRC*—Proportioning macrosynthetic FRC is similar to proportioning steel fibers. As the fiber volumes increase to greater than 0.5% by volume, adjustments to aggregate ratios and use of water-reducing admixtures become more necessary.

4.3.6 *Hybrid FRC*—Proportioning of these mixtures can follow the general aforementioned recommendations with the added recommendations of the fiber supplier.

CHAPTER 5—FORMWORK AND CONVENTIONAL REINFORCEMENT

5.1—Formwork

Design and construction of formwork should be done according to ACI 347. Normalweight FRC with a fiber content up to 2% volume has a density in the same range as normalweight conventional concrete (144 to 150 lb/ft^3 [2306 to 2403 kg/m^3]). Stiff fibers, such as steel, glass, or some macrosynthetic fibers, have a tendency to protrude from sharp corners of formed concrete. These may be hazardous to personnel. To minimize this, sharp corners and edges may be chamfered. Alternately, a rounded corner or edge may be formed by applying pressure-sensitive tape, or caulking to the inside of sharp corners and edges of the form. On formed surfaces, use of a form vibrator will cause fibers to back away from the form, leaving them covered by approximately 0.125 in. (3 mm) of concrete. ACI 347 provides further information.

5.2—Conventional reinforcement

Fabricating and placing conventional reinforcing steel should be in accordance with ACI 301. FRC is routinely used in conjunction with conventional reinforcing steel. Consideration should be given to the spacing of bars, spacing of wires in welded wire reinforcement, and fiber dosage. Unless otherwise shown in full-scale tests, the fiber length for stiff fibers, such as steel, glass, or some macrosynthetic fibers, should not exceed 1/2 the clear spacing between bars, welded wire reinforcement, or other embedded materials.

CHAPTER 6—BATCHING, MIXING, DELIVERY, AND SAMPLING

6.1—General

Batching, mixing, delivery, and sampling of FRC should be in accordance with ASTM C1116/C1116M and applicable portions of ACI 304R, as modified and supplemented by the following.

Appropriate equipment and a suitable technique should be provided for dispersing fibers in the mixer. Many fiber manufacturers have developed equipment to automatically dispense and account for the required amount of fibers and add them to the batch stream. Devices such as conveyor belts, chutes, loss-in weight dispensers, blowers, and pneumatic tubes can be used to add fibers to the mixer on the job site or at the batch plant. Figures 6.1 through 6.6 illustrate many of these devices.

The batching procedure is critical to obtaining a good blend of fibers with the concrete. Several methods have been used with success; information to assist the contractor in the choice of a suitable procedure is discussed in ACI 544.1R, or may be obtained from fiber manufacturers.

Many manufacturers of synthetic fibers and fiber blends have developed special packaging that allows for adding the complete bag of fibers into the mixer, where the moisture and mixing action disintegrates the package. These package systems are designed to provide uniformly dispersed fibers throughout the mixture. Any FRC that is not properly batched and that develops dry fiber balls or a significant number of wet fiber balls (which includes fibers and matrix) should be discarded and removed from the site.

Fibers should be dispersed uniformly throughout the mixture. Reducing the batch size, increasing mixing time, or both, may be necessary when a uniform dispersion is not achieved.

Fig. 6.1—Manual synthetic fiber feeder system.

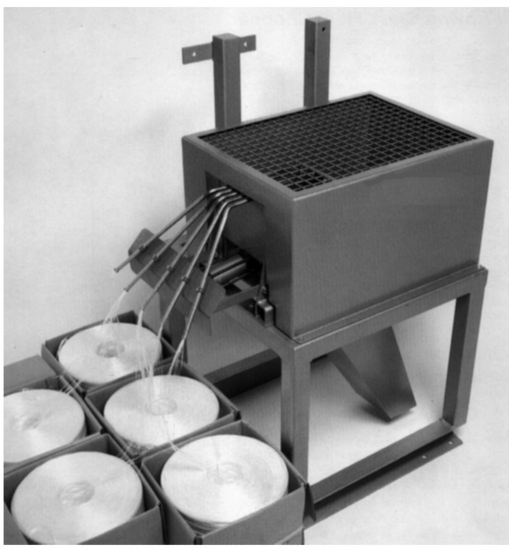

Fig. 6.2—Multi-strand glass roving chopper/feeder.

Fig. 6.3—Glass roving chopper and negative-mass dispenser on continuous mixer.

Fig. 6.4—Loss-in-mass macrofiber dispenser.

6.2—Mixing

Generally fibers should be added to a concrete mixture. Methods 1 and 2 describe procedures used to mix FRC by adding the fibers to a fluid mixture. Microsynthetic fibers and macrofibers with aspect ratios less than about 50 can generally be added to a fluid mixture without balling problems to achieve uniform dispersion. Rigid macrofibers with aspect ratios greater than 60 may require a fiber blower or collation of the fibers into bundles of fibers to prevent balling.

6.2.1 *Method 1*: *Adding fibers last to a transit mixer*—The wet mixture to be used is prepared first without the fibers. The slump of the concrete before fiber addition should be 1 to 3 in. (25 to 76 mm) greater than the final slump desired, depending on the fiber type and dosage. The mixture would typically be prepared using the *w/c* found to give the best results and to meet the project specifications. The use of mid- or high-range water-reducing admixtures can be advantageous, but is not essential.

With mixers operating at normal charging speed, the individual fibers, ball-free (that is, as a rain of individual fibers), or the special-packaged or collated fiber bundle of fibers should be added to the mixer. Clumped fibers should be avoided in this step, as clumps, once introduced to the mixer, tend to remain clumps. The mixer drum should rotate fast enough to carry the fibers away as they enter the mixer. After all the fibers have been introduced into the mixer, it should be slowed to the rated mixing speed and mixed for a minimum of 40 revolutions, or until the mixture is satisfactory.

This method has been used successfully by a number of ready mixed concrete producers and contractors. The use of an auxiliary conveyor belt and manual addition of fibers from scaffolding has also produced good results with a variety of fiber types. It has been found, however, that introducing synthetic fibers to self-consolidating concrete earlier in the batching process prevents fibers from floating in the mixtures, and promotes better distribution of the fibers. Fibers should be added before the final addition of admixtures.

Fig. 6.5—Adding fibers to transit truck mixer with conveyor.

Fig. 6.6—Blower/pneumatic tubes adding fibers to transit truck mixer.

6.2.2 *Method 2*: *Adding fibers to aggregates*—In a batch plant set up to charge a central mixer or transit mixers, the fibers or special packages should be added to the aggregates on a conveyor belt during aggregate addition and mixed in the normal manner. This method does not require the same care as Method 1 concerning where the fibers land in the mixer, but fibers should not be allowed to pile up and form clumps on their way to the mixer. If possible, the fibers should go into the mixer with the aggregates, or, if this is not possible, after the aggregates are introduced to the mixer.

As an alternative, individual fibers may be added to the aggregate weigh hopper in the plant after the aggregates have been weighed. A conveyor belt normally facilitates this alternative. Fibers then flow with the aggregates into the mixer.

6.2.3 *Method 3*: *Adding AR glass fibers by chopping directly into the mixer or onto a conveyor*—AR glass fibers are available in roving form, which comprise parallel, continuous strands (usually between 28 and 56 strands) wound into a bobbin. Roving strands can easily be cut by simple chopping devices. The chopping device is mounted over the mixer or conveyor, and the roving strands are cut to the desired length directly into the mixer or conveyor. Fiber content is controlled either by a preset timer or by loss-in weight of the roving. The rate of fiber dispensing can be varied by changing the speed of the chopping device.

6.3—Causes of fiber balling

The following discussion of possible causes of fiber balling may be useful in designing a plant or mixing sequence for FRC or correcting the problem in a mixing operation. Most fiber balling occurs before the fibers get into the mixture. Once the fibers get into the mixture ball-free, they generally stay ball-free. This means that when balls form, it is because fibers were added in such a way that they fell on each other and stacked up (in the mixer, on the belt, or on the vanes). This typically happens when the fibers are added too fast at some point in the procedure. The mixer should carry the fibers away into the mixture as fast as they are added. Balls can form by hanging up on a rough loading chute at the back of a truck mixer. Fibers should not be allowed to pile up or slide down the vanes of a partially filled drum.

Other potential causes of balling are adding too many fibers to a mixture (more than about 2% by volume or even 1% of a fiber with a high aspect ratio); adding fibers too fast to a harsh mixture (the mixture is not fluid enough or workable enough, and the fibers do not get mixed in fast enough; therefore, they pile up on each other in the mixer); adding some fibers first to the mixer (the fibers have nothing to keep them apart, they fall on each other and form balls); and using equipment with worn-out mixing blades. The most common causes of wet fiber balls is overmixing and using a mixture with too much coarse aggregate (more than 55% of the total combined aggregate by absolute volume).

6.4—Delivery

The delivery of FRC is specified in ASTM C1116/C1116M, and all precautions and procedures used for conventional concrete delivery should be adopted.

6.5—Sampling

Sampling of FRC should follow the applicable portions of ASTM C172 or C1140.

6.6—Production quality assurance and quality control

Quality assurance and quality control of the production, delivery, and placement of FRC should generally follow the guidelines developed in ACI 121R. A reference to ASTM C1116/C1116M should be added to the list of recommended references in ACI 121R.

CHAPTER 7—PLACING AND FINISHING

7.1—General

All of the conventional methods for placing conventional concrete have been successfully used to place FRC, including chutes, buckets, buggies, conveying, pumping, tremie, and shotcreting. After placement of the FRC, manual movement of the FRC should always be handled by a hoe-like tool (come-along). Tined rakes should not be used. In general, FRC should be consolidated with mechanical

Fig. 7.1—Placing slab-on-ground from transit mix truck with laser screed machine.

vibrators, such as vibrating screeds; however, lower volume addition rates of microsynthetic FRC have been successfully placed without vibration. The basic guide for placing concrete, ACI 304R, should be used for placing and finishing FRC, along with the different techniques noted in the following sections. Figure 7.1 illustrates placing FRC for a slab-on-ground application. Information for placing FRC with the shotcreting method is available in ACI 506R and 506.1R.

7.2—Placing

Some FRCs that contain macrofibers can appear relatively stiff and unworkable compared with conventional concrete. The use of mechanical vibrators or water-reducing admixtures, however, allows placement of seemingly unworkable concrete. The material exhibits apparent cohesion and tends to resist movement during consolidation if an attempt is made to handle it without vibration or water-reducing admixtures. Batch plant operators and truck drivers should be instructed not to add additional water to the mixture based on its appearance and their experience with conventional concrete. FRC containing microfibers generally allows placement without the aforementioned methods.

7.3—Transporting and handling equipment

Transporting and placing of FRC can be accomplished with most conventional equipment that is properly designed, maintained, and clean.

7.3.1 *Transit trucks*—Discharging from transit truck mixers is usually accomplished with little trouble. A mixture that is too stiff or a truck that is in poor condition will prevent the mixture from being easily discharged from the drum onto the chute. A well-proportioned mixture usually slides down the chute by itself, but may need to be pushed by the truck operator. The truck can be driven up on blocks or a ramp to help discharge.

7.3.2 *Concrete buckets*—Concrete buckets should have steep hopper slopes, be clean and smooth inside, and have a minimum gate opening dimension of 12 in. (300 mm). Some fibers may bridge smaller gate openings, and the mixture will not fall out of its own weight. A remedy for bridging and an aid to placement is to provide a vibrator at the bucket when discharging. To facilitate placement of stiff mixtures, a form vibrator can be attached to the side of the bucket and activated when the gate is opened. Another procedure is to weld pieces of pipe to the bucket exterior. Internal vibrators can then be placed into the pipes to assist in emptying the bucket.

7.3.3 *Powered buggies*—The buckets of the buggies should be smooth and clean inside. Occasional manual help may be required to discharge the concrete, but well-proportioned concrete will generally easily slide into place.

7.3.4 *Pumping*—Pumping has been used to transport microfiber- and macrofiber-reinforced concrete and shotcrete on many projects (Tatnall 1984). A mixture that will pump satisfactorily without fibers will generally pump well when fibers are added. Combined aggregate gradings recommended for macrofiber reinforced concrete in Table 4.2 are also compatible with good pumping properties. A few important points about pumping FRC should be considered:

1) A pump capable of handling the volume and pressures should be used;

2) A large-diameter line should be used for fibers 2 in. (50 mm) and longer (preferably at least 5 in. [125 mm]), although some flexible macrosynthetic FRC has been successfully pumped through small-diameter lines;

3) The amount of flexible hose should be minimized where possible;

4) The chutes from the concrete truck should be about 12 in. (300 mm) above the grate on the hopper of the pump; this will reduce any potential for the FRC to restrict the flow of the concrete through the grate. The grate on the hopper

should not be removed when pumping FRC. A small vibrator attached to the hopper grate can facilitate the flow of FRC through the grate. Some pump manufacturers have developed hopper grates specifically for FRC;

5) Gap grading of combined aggregates should be avoided, as macrofibers will tend to be pushed out of the mixture in the line, causing plugs; and

6) Pumping a fibrous mixture that is too wet should not be attempted. Pump pressures can cause the fluid paste and fine mortar to squeeze out ahead of the rest of the mixture, resulting in a mat of fibers and coarse aggregate without mortar. It should be noted that this is the result of a mixture that is too wet, not too dry. A maximum 7 in. (175 mm) slump is recommended. The same type of plugging can occur with conventional concrete, with a plug that consists of coarse aggregate devoid of paste and fine mortar. Additional information on pumping is available in ACI 304.2R. Ounanian and Kesler (1976) describe proportioning of steel FRC for pumping.

7.4—Finishing

FRC can be finished with conventional equipment, but minor refinements in techniques and workmanship may be needed. For flat-formed surfaces, no special attention is typically needed. To provide consolidation and bury surface fibers, open slab surfaces should be struck off with a vibrating screed or laser screed. Where a laser screed is used, the operator should adjust the magnitude of vibration and control the speed of the retracting leveling head to ensure adequate consolidation of the concrete and embedment of the fibers. Magnesium floats in the form of a bullfloat, channel radius float, or highway straightedge should be used to establish a surface and close tears or open areas. Wood floats tend to tear the surface and expose macrofibers, and are not recommended. Float finishes and hard steel trowel finishes for FRC flat slabs should follow the recommendations found in ACI 302.1R. Either walk-behind or ride-on trowels may be used to finish FRC. Fiber-free surfaces are desirable, but some fibers may be exposed on the surface. The timing of finishing operations is important in achieving the desired result. Finishing operations should not begin with mechanical equipment until the surface has stiffened so that footprints are barely perceived on the surface. With walk-behind trowels, float blades should be used first. The blades should be as flat as possible against the surface. Where ride-on trowels are used, pans should be used in the initial finishing operations. After the floating operation, the float blades or pans are removed, and either combo or finish blades are installed on the machine. As with floating, the blades on both pieces of equipment should be kept as flat as possible for as long as possible. The tilting of the blades at too great an angle will expose fibers on the surface. Where a texture is required for flatwork, a broom, roller, and tines may be used. The broom and tines should be held at a small angle to the horizontal surface to prevent lifting and exposing fibers. For best results, the texturing equipment should be pulled in one direction only. The equipment should never be pulled in the opposite direction or across the established pattern. Burlap drags are not recommended for surface texturing because they tend to pick up and expose fibers.

Mechanical placing equipment, such as laser screeds, slip form pavers, slip form barriers, and curb and sidewalk machines, is well-suited to placing and finishing FRC. The mechanical vibration normally provided with these machines is generally sufficient to consolidate the FRC and ensures that fibers are not exposed at the surface.

7.5—Hot and cold weather requirements

Placement of FRC should be done according to the recommendations of ACI 305R for hot weather, and ACI 306R for cold weather.

7.6—Repair of defects

The repair of defects, such as voids and honeycombing, is done in much the same manner as for conventional concrete. Further information on repair of defects in concrete construction may be found in ACI 546R. Where removal of some FRC is required, however, the removal operation can be significantly more difficult because of the greater toughness of the FRC.

Removal of FRC with jackhammers is generally hindered because the material may not fracture easily. Sawing may be a more effective method of cutting and removing FRC.

7.7—Contraction joints

Sawed contraction joints in flat slabs are more easily made, particularly when using macrofibers, than cast or tooled joints. New, clean saw blades are recommended for crisp saw cuts. The sawing can be done shortly after final set, but timing of the sawing is critical so as not to pull up macrofibers. A 5 ft (1.5 m) long cut should be attempted and evaluated for spalling or raveling before the contractor cuts the entire section of the slab. If fibers are pulled up, the sawing should be delayed until no fibers are exposed when sawing. At joints where it is desired to have a controlled shrinkage crack occur below the sawed portion of the joint, it has been found that for higher contents of macrofibers and thicker slabs, the saw cut may have to extend to 1/3 of the way through the slab to activate the crack. Otherwise, the depth of saw cutting and filling of the contraction joints should follow the recommendations found in ACI 302.1R.

CHAPTER 8—CURING AND PROTECTION

8.1—General

Curing of FRC and protection from freezing or excessively hot or cold temperatures should be done the same way as for conventional concrete. Guidance can be found in ACI 308R. Many times FRC is placed in thin sections (for example, as overlays), and may have a high cementitious content and be vulnerable to plastic shrinkage cracking. This may occur when the rate of surface evaporation is high. In such conditions, placements should be shaded from the sun and sheltered from wind to prevent this type of damage. Guidance can be found in ACI 305R.

CHAPTER 9—REFERENCES

9.1—Referenced standards and reports

The standards and reports listed below were the latest editions at the time this document was prepared. Because these documents are revised frequently, the reader is advised to contact the proper sponsoring group if it is desired to refer to the latest version.

American Concrete Institute

121R	Guide for Concrete Construction Quality Systems in Conformance with ISO 9001
211.1	Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete
211.2	Standard Practice for Selecting Proportions for Structural Lightweight Concrete
211.4R	Guide for Selecting Proportions for High-Strength Concrete with Portland Cement and Fly Ash
301	Specifications for Structural Concrete
302.1R	Guide for Concrete Floor and Slab Construction
304R	Guide for Measuring, Mixing, Transporting, and Placing Concrete
304.2R	Placing Concrete by Pumping Methods
305R	Hot Weather Concreting
306R	Cold Weather Concreting
308R	Guide to Curing Concrete
318	Building Code Requirements for Structural Concrete
347	Guide to Formwork for Concrete
360R	Design of Slabs-on-Ground
506R	Guide to Shotcrete
506.1R	Guide to Fiber-Reinforced Shotcrete
544.1R	Report on Fiber Reinforced Concrete
544.2R	Measurement of Properties of Fiber Reinforced Concrete
546R	Concrete Repair Guide

ASTM International

A820/A820M	Specification for Steel Fibers for Fiber-Reinforced Concrete
C94/C94M	Specification for Ready-Mixed Concrete
C138/C138M	Test Method for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete
C143/C143M	Test Method for Slump of Hydraulic-Cement Concrete
C172	Practice for Sampling Freshly Mixed Concrete
C173/C173M	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
C1116/C1116M	Specification for Fiber-Reinforced Concrete
C1140	Practice for Preparing and Testing Specimens from Shotcrete Test Panels
C1399	Test Method for Obtaining Average Residual-Strength of Fiber-Reinforced Concrete
C1436	Specification for Materials for Shotcrete
C1480/C1480M	Specification for Packaged, Pre-Blended, Dry, Combined Materials for Use in Wet or Dry Shotcrete Application
C1550	Test Method for Flexural Toughness of Fiber-Reinforced Concrete (Using Centrally Loaded Round Panel)
C1609/C1609M	Test Method for Flexural Performance of Fiber-Reinforced Concrete (Using Beam with Third-Point Loading)
C1666/C1666M	Specification for Alkali Resistant (AR) Glass Fiber for GFRC and Fiber-Reinforced Concrete and Cement

These publications may be obtained from these organizations:

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

ASTM International
100 Barr Harbor Dr.
West Conshohocken, PA 19428-2959
www.astm.org

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Guide for Specifying, Proportioning, and Production of Fiber-Reinforced Concrete

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