

# **Guide to Fiber-Reinforced Shotcrete**

Reported by ACI Committee 506



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## Guide to Fiber-Reinforced Shotcrete

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# Guide to Fiber-Reinforced Shotcrete

Reported by ACI Committee 506

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*This guide describes the technology and applications of fiber-reinforced shotcrete (FRS) using synthetic and steel fibers. Mechanical properties, particularly toughness, impact, and flexural strength, are improved by fiber addition, and these improvements are described along with other typical properties and benefits, such as control of shrinkage cracking. Proportions of typical mixtures, batching, mixing, and application procedures are described, including methods of reducing rebound and equipment used to apply FRS. Applications of FRS are described, including rock-slope stabilization work, construction and repair of tunnel and mining linings, fire explosive spalling-resistant linings, channel linings, pools and rockscapes, and structure repair. Available design information is briefly discussed, and design references are listed.*

**Keywords:** fiber-reinforced shotcrete; fibers; linings; mining; repair; steel fibers; synthetic fibers; tunnels.

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## CONTENTS

### Chapter 1—Introduction and scope, p. 506.1R-2

- 1.1—Introduction
- 1.2—Scope
- 1.3—Historical background

### Chapter 2—Notation and definitions, p. 506.1R-2

- 2.1—Notation
- 2.2—Definitions

### Chapter 3—Materials, p. 506.1R-2

- 3.1—General
- 3.2—Fibers
- 3.3—Other materials

### Chapter 4—Mixture proportions, p. 506.1R-3

- 4.1—General
- 4.2—Wet-process
- 4.3—Dry-process

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**Chapter 5—Production, p. 506.1R-4**

- 5.1—General
- 5.2—Batching and mixing
- 5.3—Application

**Chapter 6—Test procedures, p. 506.1R-4**

- 6.1—General
- 6.2—Fresh properties
- 6.3—Hardened properties

**Chapter 7—Performance of fiber-reinforced shotcrete, p. 506.1R-6**

- 7.1—Flexural strength
- 7.2—Compressive strength
- 7.3—Shear strength
- 7.4—Bond strength
- 7.5—Rebound considerations
- 7.6—Shrinkage crack control
- 7.7—Impact resistance
- 7.8—Thermal explosive spalling

**Chapter 8—Design considerations, p. 506.1R-8**

- 8.1—General
- 8.2—Empirical design
- 8.3—Comparable moment capacity

**Chapter 9—Specification and quality control considerations, p. 506.1R-9**

- 9.1—General
- 9.2—Performance specifications
- 9.3—Prescriptive specifications

**Chapter 10—Applications, p. 506.1R-9**

- 10.1—General
- 10.2—Ground support
- 10.3—Rehabilitation and repair
- 10.4—Architectural shotcrete
- 10.5—Explosive spalling resistance

**Chapter 11—References, p. 506.1R-11**

- 11.1—Referenced standards and reports
- 11.2—Cited references

**Appendix—Example of comparable moment capacity calculations, p. 506.1R-13****CHAPTER 1—INTRODUCTION AND SCOPE****1.1—Introduction**

Fiber-reinforced shotcrete (FRS) is mortar or concrete containing discontinuous discrete fibers that is pneumatically projected at high velocity onto a surface. Continuous meshes, woven fabrics, and long rods are not considered as discrete fiber-type reinforcing elements in this guide.

**1.2—Scope**

This document provides information on fiber-reinforced shotcrete using synthetic and steel fibers. Topics covered include materials used, mixture proportions, production of shotcrete, testing procedures, performance of FRS, design

considerations (including an example in the Appendix), specifications, and some examples of applications.

**1.3—Historical background**

FRS with steel fibers was first placed in North America early in 1971 in experimental work directed by Lankard, et al. (1971). Steel FRS (SFRS) was proposed for underground support by Parker in 1971 (Parker 1974). Additional trials were made by Poada in an investigation of new and improved methods of using shotcrete for underground support (Poada et al. 1975). Subsequently, the first practical applications of SFRS were made in a tunnel adit at Ririe Dam, ID in 1973 (Kaden 1977). Since that time, SFRS has been used throughout the world. Shotcrete using micropolypropylene fibers was first placed in Europe in 1968 (Hannant 1978). Macrosynthetic fibers for use in shotcrete were developed in the mid-1990s and have been used in mining and slope stabilization projects (Morgan and Heere 2000).

**CHAPTER 2—NOTATION AND DEFINITIONS****2.1—Notation**

|                 |                                                                                                                                                           |
|-----------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------|
| $A_S$           | = area of conventional steel per unit width                                                                                                               |
| $a$             | = $A_S f_Y / 0.85 f'_c b$                                                                                                                                 |
| $b$             | = unit width of section                                                                                                                                   |
| $d$             | = moment arm from loaded surface to center of reinforcement                                                                                               |
| $f_{600}^{100}$ | = post-cracking residual flexural strength of a 4 in. (100 mm) deep beam as determined at 0.02 in. (0.5 mm) deflection (Span/600) using ASTM C1609/C1609M |
| $f_Y$           | = yield strength of conventional reinforcement                                                                                                            |
| $f'_c$          | = compressive strength of shotcrete                                                                                                                       |
| $t$             | = FRS section thickness                                                                                                                                   |
| $\phi$          | = strength reduction factor, = 0.9 for flexure                                                                                                            |

**2.2—Definitions**

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

**denier**—measure of fiber diameter, taken as the mass in grams of 9000 m (29,528 ft) of the fiber.

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

**macrofiber**—a fiber with an equivalent diameter greater than or equal to 0.012 in. (0.3 mm) for use in concrete.

**microfiber**—a fiber with an equivalent diameter less than 0.012 in. (0.3 mm) for use in concrete.

**CHAPTER 3—MATERIALS****3.1—General**

FRS is conventional shotcrete with fibers added. Materials for use in FRS should conform to the requirements of ASTM C1436, which covers the typical materials used in shotcrete, including chemical and mineral admixtures, fibers, and the combined grading of aggregates for fine and coarse mixtures: Grading No. 1: No. 4 to No. 100 sieve (4.75 mm to 0.075 mm), and No. 2: 3/8 in. to No. 100 sieve (9.5 mm to 0.075 mm).

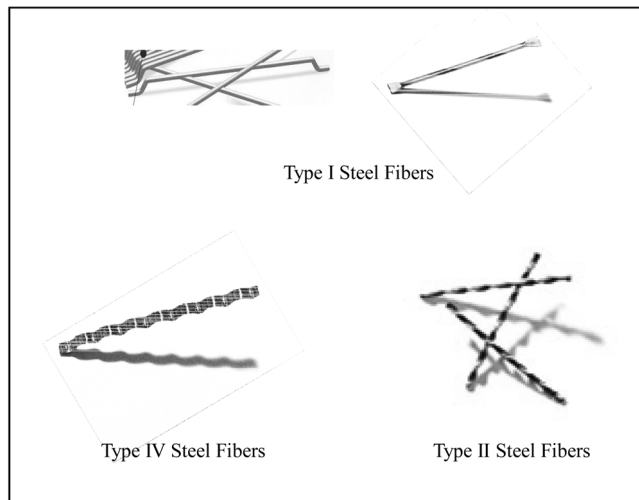


Fig. 3.1—Examples of steel fibers.

### 3.2—Fibers

Fibers for use in shotcrete can be made of steel, glass, synthetic polymers, and natural materials. Only steel and synthetic fibers are considered herein because they are the most commonly used. Figures 3.1 and 3.2 illustrate steel and macrosynthetic fibers being used in shotcrete.

Fibers for use in shotcrete are generally divided into two groups by their diameter. Fibers with equivalent diameters greater than 0.012 in. (0.3 mm) are known as macrofibers; fibers with diameters less than 0.012 in. (0.3 mm) are known as microfibers. The descriptor denier is often used to indicate the fineness of microfibers. A typical synthetic shotcrete microfiber has a denier of 6, which results in an equivalent diameter of 0.0012 in. (32  $\mu$ m). More information on fibers, denier, and equivalent diameters can be found in ACI 544.1R.

One parameter to characterize macrofibers is the aspect ratio. Typical aspect ratios of macrofibers for shotcrete range from 40 to 65 for common fiber lengths of 0.75 to 2 in. (19 to 50 mm), although steel fiber lengths are generally less than 1.5 in. (38 mm). Synthetic microfiber lengths vary from 0.25 to 2 in. (6 to 50 mm).

ASTM C1116/C1116M defines the required properties of FRS and fibers used in shotcrete.

**3.2.1 Macrofibers**—Macrofibers are defined as those fibers for use in shotcrete with equivalent diameters greater than 0.012 in. (0.3 mm). The majority of macrofibers used in shotcrete are either steel or synthetic fibers. Steel fibers used in shotcrete are generally between 0.75 to 1.4 in. (19 to 35 mm) in length and 0.016 to 0.03 in. (0.4 to 0.8 mm) in equivalent diameter. Synthetic macrofibers can be longer and vary between 1.5 to 2 in. (40 to 50 mm) long, with equivalent diameters similar to the steel fibers. The fibers should meet the requirements of ASTM C1436.

**3.2.2 Microfibers**—Microfibers used in shotcrete are normally polyolefin-based or nylon, and should meet the requirements of ASTM C1436. If the microfibers are used to resist explosive spalling in fires, then fibers should be polypropylene, with equivalent diameters less than 0.0013 in. (33  $\mu$ m) and less than 0.5 in. (12 mm) long (Tatnall 2002).

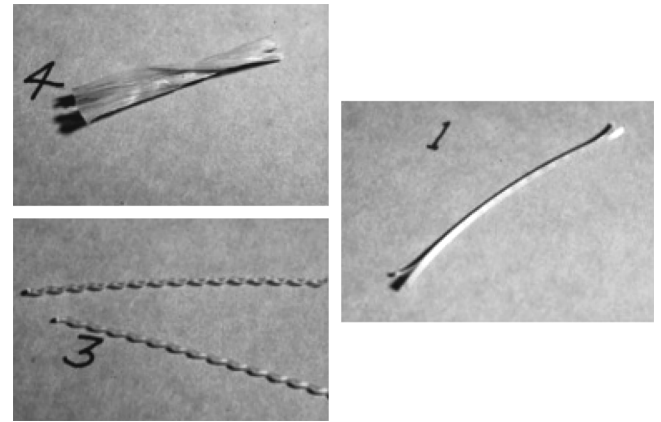


Fig. 3.2—Examples of macrosynthetic fibers.

### 3.3—Other materials

While the normal materials used in shotcrete are used in FRS, supplementary cementitious materials are often used, such as silica fume, slag, and fly ash. For applications that require vertical and overhead placement with macrofibers, these materials can help build thicker layers without sloughing and reduce fiber rebound. For shotcretes that contain more than about 0.3% by volume of fibers, the addition of water-reducing admixtures is common to maintain desired water-cementitious material ratios. Admixtures that meet the requirements of ASTM C1436 are normally acceptable for use in FRS.

## CHAPTER 4—MIXTURE PROPORTIONS

### 4.1—General

Proportioning shotcrete mixtures that contain fibers should follow the general guidelines outlined in ACI 506R. While FRS mixtures are normally proportioned to attain a specified compressive strength, many times an ultimate flexural strength and postcrack performance, such as residual strength(s), or an energy absorption, toughness, or both, are specified. Nonfibrous shotcrete proportioning methods should be used to attain compressive and flexural requirements (ACI 506R), and the recommendations from fiber suppliers selected for the type (material and shape) and quantity of fibers to attain postcrack performance requirements should be used.

### 4.2—Wet process

FRS for wet-process shotcrete is typically delivered to the pump in accordance with ASTM C1116/C1116M. Because rebound of macrofibers is typically less in wet-process shotcrete, fiber dosages are sometimes less than for dry-process shotcrete for the same postcrack performance. Steel fiber quantities used are in the range of 20 to 100 lb/yd<sup>3</sup> (12 to 60 kg/m<sup>3</sup>). Macrosynthetic fiber quantities are usually in the range of 8.5 to 15 lb/yd<sup>3</sup> (5 to 9 kg/m<sup>3</sup>). Microsynthetic fibers are normally used at dosages of 1 to 4 lb/yd<sup>3</sup> (0.6 to 2.4 kg/m<sup>3</sup>).

### 4.3—Dry process

Dry-process shotcrete can be delivered to the shotcrete machine in transit mix trucks, volumetric batcher, in

prepared prepackaged containers, or mixed on site. Because rebound of fibers in dry-process is normally greater than rebound of fibers for wet-process shotcrete, fiber quantities may be slightly higher than those indicated in Section 4.2 (Dufour et al. 2006). Therefore some macrosynthetic fibers do not lend themselves to successful shooting using the dry-process because they do not get coated with the cementitious paste and can tend to fly away in the shotcrete stream. Users should check with the fiber suppliers before using synthetic fibers when using the dry process.

## CHAPTER 5—PRODUCTION

### 5.1—General

Production of shotcrete follows closely the production procedures for producing concrete. Tolerances for batching materials should follow established provisions for concrete.

### 5.2—Batching and mixing

**5.2.1 Wet process**—Wet-process FRS should be batched and mixed in accordance with ASTM C1116/C1116M, which covers plant batching and mixing, transit truck mixing, and volumetric plant batching and mixing. Fibers may be added to a plant mixer by depositing them on top of aggregates just before they are introduced into the mixer. Various fiber dispensers have been developed to measure and add fibers to the mixture. When fibers are added to a transit mixer, they should be added at a rate of about 100 lb/minute (45 kg/minute) for steel fibers, and about 10 lb/minute (4.5 kg/minute) for synthetic fibers while the mixer is turning at maximum speed. When using a volumetric batcher, a dispenser is essential to obtaining the proper quantity of fibers in the mixture. If fibers are added to a transit mixer on site, adequate mixing time should be attained to ensure dispersion of the fibers. A minimum of 40 revolutions of the mixer after fiber addition should be recorded. Further guidance for production of FRS is available in ACI 544.3R.

**5.2.2 Dry process**—Dry-process shotcrete may be batched and mixed as for wet-process shotcrete except water is not added to the mixture. Adequate mixing should be ensured to achieve good fiber distribution. In many cases, packaged, dry, combined FRS mixtures are delivered to the project site. They are used for both dry-process FRS, and are sometimes placed in a mixer with water added to produce wet-process FRS. If used for FRS, these materials should meet the requirements of ASTM C1480/C1480M for Grade FR shotcrete.

### 5.3—Application

**5.3.1 Equipment for FRS**—Generally all the equipment used for nonfibrous shotcrete application are used in the application of FRS. Grates used over pump hoppers should be used with FRS, and some manufacturers offer grates designed to accommodate pumping FRS. As with nonfibrous shotcrete, dry-process FRS should be predampened. Predampening helps to reduce fiber rebound and fibers that fly away.

**5.3.2 Application**—All proper techniques of applying shotcrete, including safety requirements, as outlined in ACI 506R should be used to apply FRS. While fibers tend to orientate themselves in the plane of the shotcrete structure, some fibers

may protrude the surface. If this is objectionable, a thin coat on nonfibrous shotcrete may be applied to cover the fibers.

## CHAPTER 6—TEST PROCEDURES

### 6.1—General

Many test methods used for nonfibrous concrete and shotcrete may be applicable to FRS, such as ASTM C143/C143M, C138/C138M, C42/C42M, and C78. ASTM test methods directly applicable to FRS are mentioned in ACI 544.2R, and updated annually in *Shotcrete* magazine (Tatnall 2007). ASTM C1609/C1609M (a beam test) and ASTM C1550 (a flexural panel test) are important because they evaluate the postcracking flexural performance of fiber-reinforced concrete and FRS. A more detailed discussion of FRS testing follows.

### 6.2—Fresh properties

**6.2.1 Consistency and pumpability**—ASTM C143/C143M is typically used to measure the consistency of wet-process shotcrete from batch to batch. This method uses samples of FRS taken as the shotcrete is delivered to the pump. A standardized test method has not yet been developed to characterize the pumpability of a mixture.

**6.2.2 Unit density and air content**—ASTM C138/C138M may be used to determine the unit density and air content of FRS. ASTM C231 and C173/C173M may also be used to determine air content. For wet-process FRS, the samples are normally taken as the shotcrete is delivered to the pump. For dry-process FRS, samples should be taken from the shot section or panels shot for sampling purposes and tests can be conducted using the same test methods. For wet-process FRS, samples may also be taken from shot panels.

### 6.3—Hardened properties

**6.3.1 Strength**—Specimens of shotcrete, including FRS, for assessing the hardened properties should always be taken from sections that have been shot in-place or from panels shot for the purpose. Specimens made from concrete before it is shot will not reflect the compactive effort, mixing actions, and rebound effects on the final shotcrete structure. Panels shot for sampling should be prepared in accordance with ASTM C1140.

**6.3.1.1 Compressive strength**—Shotcrete specimens should be obtained and tested in accordance with ASTM C1604/C1604M.

**6.3.1.2 Flexural strength**—Shotcrete specimens should be obtained in accordance with ASTM C42/C42M. Flexural strength may be obtained using either ASTM C78 or C293, although C78 is the more common test method used. Typically, 4 x 4 x 14 in. (100 x 100 x 350 mm) specimens are used for flexural testing. See also Section 6.3.2.2.

**6.3.1.3 Shear strength**—The Japan Concrete Institute published a test method (JCI-SF 6) for determining the punching shear strength of fiber-reinforced concrete that may be used to assess FRS. Beam specimens are loaded in a jig to produce the punching action, and shear strength is reported as  $P_u/A_c$ , divided by two times the width and depth of the specimen.