This report describes the technology and uses of fiber reinforced shotcretes using steel and polypropylene fibers. Mechanical properties, particularly ductility, toughness, impact strength, and flexural strength are improved by the fiber addition, and these improvements are described along with other typical properties and proportions of typical mixes. Batching, mixing, and application procedures are described, including methods of reducing rebound and equipment used to apply fiber reinforced shotcrete. Applications of fiber reinforced shotcrete in North America, Europe, and Scandinavian countries are described. These include rock slope stabilization work, construction and repair of mine and tunnel linings, bridge arch strengthening, and dome-shaped structures. Available design information is briefly discussed and design references are listed.

Keywords: fiber reinforced concretes; fibers; linings; metal fibers; mines; mixture proportioning; placing; polypropylene fibers; shotcrete; slope protection; stabilization; steel strength; toughness; tunnel linings.

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**CHAPTER 1—INTRODUCTION**

**1.1—Definition of fiber reinforced shotcrete**

Fiber reinforced shotcrete 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 to be discrete fiber-type reinforcing elements in this report.

**1.2—Fiber types**

Fibers for shotcrete can be made of steel, glass, synthetic and natural materials. For purposes here, only steel and polypropylene will be considered since they represent by far the most commonly used types.

One parameter used to characterize a fiber is its aspect ratio, defined as the fiber length divided by its diameter or an equivalent fiber diameter.\(^*\)

Typical aspect ratios range from about 30 to 150 for length dimensions of 0.25 to 3 in. (6 to 75 mm). For shotcrete, common lengths are 0.75 to 1.5 in. (20 to 40 mm).

Typical fiber diameters are:
- Steel—0.010 to 0.030 in. (0.25 to 0.76 mm)
- Synthetic—0.008 to 0.02 in. (0.20 to 0.5 mm)

Additional information on fibers may be found in ACI 544.1.

ASTM A 820 is a specification defining the required properties of steel fibers.

**1.3—General**

The inclusion of fibers in concrete and shotcrete generally improves material properties including ductility, toughness, flexural strength, impact resistance, fatigue resistance, and, to a small degree, compressive strength. The type and amount of improvement is dependent upon the fiber type, size, strength and configuration, and the amount of fiber. Of the two types, steel fiber reinforced shotcrete accounts for the largest usage, having applications in mine and tunnel linings, rock slope stabilization, thin shell dome construction, refractory linings, dam construction, repair of surfaces, and fire protection coatings.\(^1,2\)

Polypropylene fiber shotcrete has also been used.\(^3\) Its use has been reported in thin shell domes, repair of surfaces, and as a component in stucco-type overlayer systems. Polypropylene fiber shotcrete’s use has grown significantly over the last decade.

A report by the U.S. Bureau of Mines\(^4\) presents a comprehensive comparison of glass, steel, and fibrillated polypropylene fiber reinforced shotcrete properties used in underground applications. It states:

“Results indicate that all of the commercially available fiber gunite materials tested can provide a beneficial sealant, spill prevention, or roof stability control attributes for underground mining environments when applied by an experienced crew using a well-maintained gun, in accordance with product manufacturers’ recommendations and when used for the designated purpose.\(^5\)”

A compilation of international experience on shotcrete, particularly for rock support, was prepared by the International Tunnelling Association.\(^5\) It compares fiber reinforced and plain shotcrete; the report dwells primarily on steel fiber but has some data on synthetic fibers.

**1.4—Historical background**

Fiber reinforced shotcrete using steel fibers was first placed in North America early in 1971 in experimental work under the direction of D. R. Lankard of Battelle Memorial Institute’s Columbus Laboratories.\(^6\) Steel fiber reinforced shotcrete was proposed for underground support under the direction of H. W. Parker at the University of Illinois in 1971.\(^7\) Additional trials were made under the direction of M. E. Poad for the U.S. Bureau of Mines in an investigation of new and improved methods of using shotcrete for underground support.\(^8\) Subsequently, R. A. Kaden of the U.S. Corps of Engineers supervised the first practical application of steel fiber reinforced shotcrete in a tunnel adit at Ririe Dam, Idaho, in 1973.\(^9\) Since that time, steel fiber reinforced shotcrete has been placed in Germany (Stahlfaserspritzbeton), Sweden (Stalfiberarmerad Sprubeton), England, Norway, Finland, Switzerland, Poland, South Africa, Australia, Canada, and Japan.

Shotcrete using polypropylene fibers was first placed in Europe in 1968.\(^10\)

**1.5—Tests for fiber reinforced concrete and shotcrete**

Properties of fiber reinforced concrete are generally measured by tests advocated in ACI 544.2R; these are equally applicable to shotcrete. ASTM tests directly applicable to fiber reinforced concrete and shotcrete are mentioned in ACI 544.2R. One of these, ASTM C 1018, is the most important because it evaluates the post-cracking performance of fiber reinforced concrete and shotcrete.
CHAPTER 2—STEEL FIBER REINFORCED SHOTCRETE

2.1—General
Steel fiber reinforced shotcrete is essentially a conventional shotcrete to which steel fibers have been added. It is placed using the same mixing and placing equipment used for conventional shotcrete. Some specialized equipment and nozzles have been developed to aid in metering and adding individual fibers and for shooting, but special equipment is generally not required for mixing and placing. It can be placed by either the wet-mix or dry-mix process.

Steel fiber reinforced shotcrete incorporates steel fibers up to 2 percent by volume of the total mix. Improvements in flexural strength, ductility, and toughness are sufficient to enable it to be used as a replacement for steel mesh reinforced shotcrete in certain instances, such as rock slope stabilization, mine and tunnel linings, and thin shell structures. The improvements in toughness and flexural strength are evaluated by ASTM C 1018 and are evident in the mode of failure; large deformations are required to cause complete separation of steel fiber reinforced shotcrete, and it continues to carry a significant load after cracking. This post-crack resistance has been cited as providing ductility to the shotcrete11,12 and works to an advantage in applications where there may be relatively large deformations such as in mine linings and tunnel linings.

2.2—Fiber types
Steel fibers are manufactured by at least three processes: 1) cutting cold drawn wire, 2) slitting steel sheet, and 3) extracting them from a pool of molten steel (metal-extraction). Wire fibers with bent or deformed ends have a higher pullout resistance than straight fibers and may be used in smaller quantities to achieve similar properties. The ultimate tensile strength of fibers varies from 50,000 to over 300,000 psi (345 to 2070 MPa). Fiber sizes range from $\frac{1}{2}$ in. x 0.010 in. to 2 1/2 in. x 0.016 in. (19 to 32 x 0.40 mm). A popular fiber size range for shotcrete is $\frac{1}{2}$ in. to 1 1/4 in. length x about 0.016 in. diameter (19 to 32 x 0.40 mm). This size range is easily handled and is normally shot through a 2-in.-diameter hose.

Steel fibers are used in applications at ambient temperatures and in some high temperature applications, up to 1500 F (815 C) for elements heated from one side only. Stainless steel fibers are used in refractory concrete, both cast and shotcreted, for high temperature applications up to 3000 F (1650 C) for elements heated from one side only. Stainless steel fibers are manufactured by at least three processes: 1) cutting cold drawn wire, 2) slitting steel sheet, and 3) extracting them from a pool of molten steel (metal-extraction). Wire fibers with bent or deformed ends have a higher pullout resistance than straight fibers and may be used in smaller quantities to achieve similar properties. The ultimate tensile strength of fibers varies from 50,000 to over 300,000 psi (345 to 2070 MPa). Fiber sizes range from $\frac{1}{2}$ in. x 0.010 in. to 2 1/2 in. x 0.016 in. (19 to 32 x 0.40 mm). A popular fiber size range for shotcrete is $\frac{1}{2}$ in. to 1 1/4 in. length x about 0.016 in. diameter (19 to 32 x 0.40 mm). This size range is easily handled and is normally shot through a 2-in.-diameter hose.

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2.3—Typical material properties
Unless otherwise indicated herein, data is for steel fiber reinforced shotcrete.

2.3.1 Flexural and compressive strengths—Typical 28-day flexural strengths as determined from beam specimens vary from about 600 to about 1500 psi (4.1 to 10.3 MPa) with typical values of 800 to 1100 psi (5.5 to 7.6 MPa).15 These flexural strengths were determined using 4 x 4 x 14-in. (100 x 100 x 350-mm) beams sawed from test panels and tested on a 12-in. (305-mm) span in accordance with ASTM C 78. In one investigation, the U.S. Bureau of Mines reported flexural strengths of 4617 psi (31.9 MPa) for fibrous shotcrete and 2244 psi (15.5 MPa) for the plain, control shotcrete using regulated-set cement and 2 percent by volume of fibers.16 These were 360-day strengths determined by ASTM C 78 as described above. BESAB, a shotcrete equipment manufacturer and applicator in Sweden, reported flexural strengths of about 2900 psi (20 MPa) on material placed with a special wet process nozzle using fibers with an aspect ratio of 100 at 1 to 2 percent by volume.

Placement of the shotcrete tends to orient the fibers in a plane parallel to the surface being shot.12 This orientation is of benefit to the flexural properties of the shotcrete layer.

Table 2.3.1—Typical steel fiber reinforced shotcrete mixes (Reference 15, p. 52)

<table>
<thead>
<tr>
<th>Material</th>
<th>Fine aggregate mix, lb/ft³ (kg/m³)</th>
<th>3/8 in. (9 mm) aggregate mix, lb/ft³ (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>753 to 940 (446 to 558)</td>
<td>750 (445)</td>
</tr>
<tr>
<td>Blended sand—1/4 in. (6 mm) maximum</td>
<td>2830 to 2500 (1679 to 1483)</td>
<td>1485 to 1175 (880 to 697)</td>
</tr>
<tr>
<td>3/8 in. (9 mm) aggregate</td>
<td>—</td>
<td>1180 to 1475 (700 to 875)</td>
</tr>
<tr>
<td>Steel fiber</td>
<td>66 to 265 (39 to 157)</td>
<td>66 to 250 (39 to 150)</td>
</tr>
<tr>
<td>Accelerator</td>
<td>Varies</td>
<td>Varies</td>
</tr>
<tr>
<td>Water-cement, by weight</td>
<td>0.40 to 0.45</td>
<td>0.40 to 0.45</td>
</tr>
</tbody>
</table>
2.3.3 **Toughness**—The amount of energy required to cause failure of fiber reinforced concrete by complete separation varies with the type and amount of fiber. Typical values of flexural toughness for small beams (4 x 4 x 14 in. (100 x 100 x 350 mm)) are in the range of 10 to 20 times that obtained for plain concrete. This is reported as toughness or as a toughness index.

The test procedure for flexural toughness is ASTM C 1018. There is currently considerable discussion on the methods of interpreting results from ASTM C 1018 for fiber reinforced shotcrete. The discussion in the Appendix of ASTM C 1018 assists. However, there is agreement that the addition of steel fibers, and to a lesser degree polypropylene, greatly increases toughness values.19

2.3.4 **Pullout strength**—Tests have been made using pullout anchors that are embedded in the shotcrete as it is gunned. The pullout anchors, similar to those described in ASTM C 900, were discs about 1 in. (25 mm) in diameter, embedded about 1 1/4 in. (30 mm) deep. In plain shotcrete, pullout test results show a linear relationship to compressive strength. For steel fiber reinforced shotcrete, a similarity in the magnitude and shape of strength-time curves for pullout and flexural strength (ASTM C 78) has been reported.12 Tests on fibrous concrete placed on an open pit mine slope in Canada gave results shown in Table 2.3.4.

2.3.5 **Tensile strain at 90 percent ultimate load (strain-to-failure)**—Kaden9 made rapid load flexural tests of shotcrete specimens (4 x 4 x 12 in.; 100 x 100 x 305 mm) and found significantly increased strain-to-failure in the steel fibrous material. Tensile strain in the outer beam fibers at 90 percent of ultimate load ranged from 320 to 440 microstrain for steel fibrous shotcrete at 28 days versus 192 microstrain for plain shotcrete.

2.3.6 **Bond strength**—BESAB reports bond strengths of about 145 psi (1 MPa) to granite for steel fiber reinforced shotcrete placed by the wet process.20 A bond strength of about 0.04 \( f_{d} \) (540 psi, 3.7 MPa) was reported for in situ tests at the Peachtree Center Station, Atlanta, subway on a rough-surfaced granitic gneiss. These values were obtained by pulling off a 2 x 2-ft (610 x 610-mm) steel plate embedded in a flat (not arched) shotcrete layer and calculating the bond strength.21 This is compared to 0.1 \( f_{d} \) (135 psi, 0.9 MPa) for similar laboratory tests.21 In other tests, a core drill was used to isolate a cylindrical specimen that was then pulled from the rock. Here, tensile bond strengths of 0.02 \( f_{d} \) (130 psi, 0.9 MPa) were obtained for fiber reinforced shotcrete compared to 0.03 to 0.05 \( f_{d} \) (220 to 375 psi, 1.5 to 2.6 MPa) for plain shotcrete.21

2.4—**Mix compositions**

2.4.1 **General**—Most steel fiber reinforced shotcrete placed to date has used the dry process. Early applications used a fine aggregate mix having a sand:cement ratio of 2.4:1 by weight or about 940 lb of cement per yd\(^3\) (560 kg/m). Mixes containing \( \frac{3}{8} \) and \( \frac{3}{4} \)-in. (9 and 19-mm) aggregate and less cement have been used more recently, and this has helped to reduce shrinkage. The amount of fiber has varied from about 0.3 percent by volume to about 2 percent by volume (66 to 265 lb/yd\(^3\); 39 to 157 kg/m). The proportions of typical mixes are shown in Table 2.3.1. The fiber amounts shown in Table 2.3.1 are before gunning. Since the fiber rebound is generally greater than the aggregate rebound, there is usually a smaller percentage of fiber in the applied shotcrete.11

| Table 2.3.4—Fourteen day pullout strengths\(^{15}\) |
|---------------------------------|------------------|
| **Mix**                        | **Pullout strength, psi (MPa)** |
| Plain shotcrete*               | 1000 (6.9)       |
| Fibrous shotcrete†             | 1800 (12.4)      |

\(^{*} f_{d} \) here is the compressive strength of the concrete as tested.

---

2.5—**Batching and mixing**

2.5.1 **General**—Batching and mixing for the dry process is often done by mixing the dry ingredients, complete with fibers, in a transit mixer. This is then delivered to the hopper (gun) of the shotcrete machine. The material has also been mixed the same as normal shotcrete with the fibers being added to a mixing hopper by a screw auger or in a separate air stream. Fiber feeders, nozzles with the provision for fiber addition, and special mixers are also available (Section 2.6.2). Prebagging has been found to be very useful, particularly in mines where a mixer and bulk materials would aggravate space problems. Batching and mixing of steel fiber reinforced mixes with loose, bulk fibers need some care to avoid the formation of fiber balls.

2.5.2 **Dry-mix**—Good results were obtained in a turbine mixer (a stationary, cylindrical, flat-bottomed pan with revolving mixing arms) for U.S. Bureau of Mines tests. The sand was placed in the mixer first, and the fibers were added through a 2 1/2-in. (63-mm) mesh screen to break up any fiber clumps. After transfer to a transit mixer and transport to a remote job site, the cement was added from sacks. A screen over the machine hopper, already a part of the equipment, was used to intercept any fiber balls that were formed.
For a larger project, the Snake River rock slope stabilization, the contractor charged the materials in 5 yd\(^3\) (3.8 m\(^3\)) batches into a large hopper using a front-end loader and from there into transit mixers via a conveyor. The ingredients were added in the following order: all the sand; one-half of the fibers; all the cement plus the accelerator; and one-half of the fibers. This technique, where 500 lb (225 kg) of loose bulk fibers were added at one time, would normally work only for short fibers with a low aspect ratio such as those used on this project—\(\frac{1}{2}\) x 0.010-in. (13 x 0.25-mm) fibers with an aspect ratio of 50. Fibers were added through a 4 x 4-in. (100 x 100-mm) crusher screen.

The important parts of the batching and mixing procedure that differ from mixing plain shotcrete are:

1) Fibers that show a tendency to clump should be added through a screen or by a shaker or apparatus that separates them and adds them so that they do not reclump. This means adding them to a rotating mixer, a conveyor belt, or a screw conveyor that is carrying the fibers away fast enough so that the fibers do not stack up on each other.

2) Mixing should avoid bending the fibers. Badly bent fibers cause poor compaction and reduced strengths. A paddle (pugmill) mixer with small counter-rotating paddle wheels has caused severe bending and subsequent formation of fiber balls.\(^{12}\)

3) A screen should be put over the shotcrete hopper to divert any fiber clumps.

Williamson\(^{22}\) reported that a screw-type mixer-conveyor was used along with a metering fiber feeder to mix shotcrete for spraying experimental domes at Champaign, Ill., by the U.S. Army Corps of Engineers. The fibers were mixed in the screw conveyor and the mix discharged directly into the gun hopper. The U.S. Bureau of Mines has also added the fibers to a screw conveyor prior to discharging into the gun hopper on a rotating barrel-type shotcrete machine.

It has been found that a good electrical ground to the gun and nozzle dramatically reduces the fiber clumping and plugging that might otherwise occur.

Collated fibers, bundled together with a quick-dissolving glue, are available for the dry-mix process. They are added directly to the mixer after the aggregate has been added. They come apart after addition of the water at or near the nozzle.

2.5.3 Wet-mix—Wet-mix shotcrete uses a wet mix similar to that used for cast-in-place concrete applications. The experience gained from mixing steel fiber reinforced concrete for cast-in-place applications may be used to help batch and mix fiber reinforced mixes for wet shotcreting. (See ACI 544.1R—Chapter 3, “Preparation of Fiber Reinforced Concrete.”)

There are some precautions that should be taken to prevent the formation of fiber balls when adding loose bulk fibers to the wet-mix. The fibers should not be added too quickly. They should be added clump-free and should be carried away before they pile up on one another. It may be necessary to pass them through a screen or shaker screen. They should not be allowed to hang up or pile up on their way to or inside the mixer. A good method is to introduce the fibers to the fine aggregate on a conveyor belt during the addition of aggregate.

Where fibers are added directly to a transit mixer, the fibers should land on the mix, not on the mixing vanes where they can form clumps. The drum must rotate fast enough to carry away the fibers as they enter the mix.

Collated fibers, fibers with a very low aspect ratio (usually less than about 40) and some large diameter fibers may be added directly into a completed mix without causing a clumping problem. Over-mixing should be avoided, in any event, as too much mixing of these or any fiber may result in fiber ball formation. Worn mixing blades or harsh mixes may also result in fiber balls. Therefore, a screen should be put over the pump hopper to intercept fiber balls.

2.6—Installation

2.6.1 General—Applying steel fiber reinforced shotcrete is basically the same as applying plain shotcrete. Information on good application techniques is included in ACI 506.R. Specification requirements suitable for use in contracts are included in ACI 506.2.

2.6.2 Equipment—Existing shotcrete equipment has been used to apply steel fiber reinforced shotcrete with little or no modifications. The modifications, when made, are generally to reduce plugging by eliminating restrictions such as 90-deg elbows or abrupt changes in hose size. If line size is reduced, a long, tapered reducer should be used. When plugging occurs, it is usually at the outlet from the gun where a sudden size reduction or change in direction is a common feature. Larger hose sizes, 2 in. (50 mm) in diameter and up, work better. Generally, the hose diameter should be a minimum of two times the fiber length. However, 1-in. (25-mm) fiber has been gunned through 1-in. (25-mm) hose, and fiber reinforced refractories using 1-in. (25-mm) fiber are shot regularly through 1\(\frac{1}{2}\)-in. (38-mm) hose.

Other modifications have included: removing elastomeric wear linings at elbows, adding vibrators or revolving wiper arms to the hopper screen, and adding vanes in the hopper or changing the wheel size on segmented rotor gun types to speed up material delivery. Sometimes a stronger rotor motor is needed. If no hopper screen is present, one should be added to divert fiber clumps that would otherwise plug the gun. Fig. 2.6.2.1 shows modifications made to a gun hopper for the Snake River rock slope stabilization project.\(^{15,23}\)

Fiber reinforced shotcrete has been successfully applied with every kind of delivery equipment, from the original single or dual chamber feed wheel type to the more recent revolving barrel and segmented rotor types now in common use. It has been placed by wet-mix using a pressurized chamber-type machine, squeeze-pump-type pumps, and positive displacement pumps.

Some special equipment has been devised to separate and meter steel fibers in a separate air stream and add them at the nozzle for both wet- and dry-mix. This equipment enables the use of high aspect ratio fibers (up to about 125), avoids
putting the fibers through the gun, and eliminates the fiber balling problem.

Specialized equipment is available for feeding steel fibers separately to the dry-mix shotcrete mix or for feeding prefibrated mixes to the gun. Fig. 2.6.2.2 and 2.6.2.3 show examples.

2.6.3 Rebound considerations

2.6.3.1 General—The factors affecting rebound encompass a wide range of items and conditions. Generally, it has been noted that a greater percentage of fibers than aggregate rebound from the wall. Ryan24 reports fiber retention of 40 percent overhead and 65 percent on vertical surfaces. Parker12 reported fiber retention of 44 to 88 percent (average 62 percent) for coarse aggregate mixes gunned onto vertical panels. In the Atlanta Research Chamber tests, the average rebound in a 10-min test where 2500 lb (1130 kg) of mix was shot was 22 percent for a 3-in.- (75-mm)-thick placement. The fiber content before gunning was 3.3 percent by weight of the dry material, while the fiber content in the rebound material was 4.6 percent.21

Some investigators and applicators have reported that steel fiber reinforced shotcrete showed less total rebound than plain shotcrete. Others have reported no difference from the fiber mixes.

An example of less rebound was reported for a trial in Nevada conducted by Fenix and Scisson, Inc. In that work, 4 yd$^3$ (3 m$^3$) of a steel fiber mix consisting of 700 lb (317 kg) cement, 2700 lb (1225 kg) sand, and 150 lb (68 kg) $1/2 \times 0.010$-in. (13 x 0.25-mm) fiber per yd placed 6-in. (150-mm) thick had a total estimated rebound of 10 percent. A control batch applied under identical conditions by the same personnel had an estimated rebound of 31 percent. The work was done in a tunnel and included vertical and overhead surfaces.15

On the other hand, Parker12 reported average rebounds of 18.3 and 17.7 percent for a nonfiber mix and a fiber mix, respectively, and concluded from that and other data that the mere presence of fibers in a mix does not affect rebound appreciably. Instead, other factors appear to be more important than fiber.

Reference 4 states:

“Due to rebound, the effective amount of fibers is reduced to about only 50 to 70 percent of the amount in the mix in dry-mix shotcrete. For wet-mix shotcrete, the amount of fiber rebound is approximately 5 to 10 percent.”

2.6.3.2 Factors affecting rebound of fibers—Quantitative data on rebound of steel fiber reinforced shotcrete with the dry-mix process were obtained in a study that systematically investigated variables one at a time and used high-speed photography to observe the shotcrete airstream.12

The photography showed that many of the steel fibers were in the outer portion of the airstream and that many of them were blown away radially from near the point of intended impact shortly before or after they hit. Some fibers were blown up into the air and floated down. It was obvious that the fibers were mostly blown away by the remnant air currents and that the effect was not one of the fibers simply bouncing off the surface. If lower air pressure or less air is used, the amount and velocity of the remnant air currents is less and the rebound of fiber is correspondingly less.

Reference 19 presents data on the effect of five steel fiber geometries on rebound and other shotcrete characteristics. It shows ranges of fiber rebound of:

- dry-mix 35 to 78 percent
- wet-mix 12 to 18 percent
2.6.3.3 Conditions that reduce rebound—Parker’s study\textsuperscript{12} concluded that the rebound process differed during establishment of an initial critical thickness (Phase 1) and subsequent gunning into fresh shotcrete (Phase 2).

During Phase 1, anything that promotes adherence of material on the wall should reduce rebound. This includes the following mix conditions: a higher cement content; more fines in the mix (fly ash or very fine sand); smaller maximum size aggregate; proper wetness of aggregates so that particles are well-coated with cement; and a finer gradation.

After the initial critical thickness is established, Phase 2 rebound is reduced by any condition or set of conditions that makes the shotcrete on the wall softer or more plastic, at least until it tends to drop off. Thus, for maximum reduction of Phase 2 rebound, shotcreting as wet as possible, that is, the wettest stable consistency, is one of the most beneficial and easiest conditions to control.

A large number of measures can be used to reduce rebound of steel fiber reinforced shotcrete in dry-mix. The most effective of these measures (which also applies to plain shotcrete) seems to be reduction of the air pressure, air velocity, or amount of air at the nozzle; use of more fines and smaller aggregate; use of shorter, thicker fibers; predampening to get the right moisture content; and shotcreting at the wettest stable consistency.\textsuperscript{12,15}

2.7—Applications

Applications of fiber reinforced shotcrete have been made to rock slopes, mines, tunnels, dams, powerhouse, bridge arches, thin shell dome structures, rock caverns for oil storage, houses, boat hulls, landslides for stabilization, and deteriorated concrete surfaces for repair.

2.7.1—Slope stabilization

2.7.1.1 Corps of Engineers, Snake River rock slope stabilization\textsuperscript{9,23}—A large application of steel fiber reinforced shotcrete was completed in January 1974, near Little Goose Dam along the Snake River in the State of Washington. The shotcrete was used to stabilize a deteriorating section of rock slope above the Camas Prairie Railroad. The work included scaling, installing rock bolts, and applying shotcrete a minimum of 2\(\frac{1}{2}\)-in. thick (63-mm). The area involved was about 1550-ft (460-m) long and varied from 15 to 45-ft (5 to 14-m) high for a total of 6900 yd\(^2\) (5800 m\(^2\)).

2.7.1.2 Joint Nordic Program (Nordforsk), oil refinery, Brofjorden, Sweden\textsuperscript{25}—A large application was also made at an oil refinery at Brofjorden, on the west coast of Sweden (Fig. 2.7.1.2).

About 5380 yd\(^2\) (4500 m\(^2\)) of rock surface was stabilized. A layered construction was used: \(\frac{1}{4}\) to \(\frac{3}{8}\) in. (5 to 10 mm) of plain shotcrete followed by \(\frac{1}{8}\) in. (30 mm) of steel fiber reinforced shotcrete covered with a top layer of \(\frac{1}{4}\) to \(\frac{3}{8}\) in. (5 to 10 mm) of plain shotcrete.

2.7.2—Selected underground applications

2.7.2.1 Corps of Engineers, Ririe Dam, tunnel adit, Idaho\textsuperscript{9}—In December 1972, steel fiber reinforced shotcrete was used to line a 40 ft (12 m) length of an exploratory tunnel adit on the right abutment of Ririe Dam, Idaho. Thickness was 3 in. (75 mm) and the 34-day flexural strength of cast beams was 910 psi (6.3 MPa) (ASTM C 78 test method). The lining survived a blasting operation with minor cracking.

2.7.2.2 British Columbia Hydro-Peace River Site C tunnels\textsuperscript{26}—At the Site C Project, a proposed earthfill dam and powerhouse on the Peace River in northeastern British Columbia, steel fiber reinforced dry-mix shotcrete was used to line several hundred feet of exploratory tunnels and a test chamber. These fibers replaced the originally designed wire mesh. The work was done in 1981 and 1982.

A thickness of 2 in. (50 mm) was specified. The shotcrete used was a premixed type supplied in bags. The average composition of this mix is given in Table 2.7.2.2.

2.7.2.3 Atlanta subway tunnel lining\textsuperscript{21}—Another tunnel application, of limited size, was made in the Metropolitan Atlanta Rapid Transit Authority (MARTA) subway. Here, a 200-ft (61-m) length of the subway tunnel was lined with 4 to 6 in. (100 to 150 mm) of steel fiber reinforced shotcrete by the dry-mix process. Examination after 18 months of use showed the lining to be in satisfactory condition.

2.7.2.4 U.S. Bureau of Mines, coal mine applications—Underground rooms at the U.S. Bureau of Mines’ experimental mine at Bruceton, Pa., were enlarged, rock bolted, and lined with steel fiber reinforced shotcrete.\textsuperscript{27} Fiber shotcrete was also used to coat bulkheads, seals, and stoppings formed by Bernold steel.\textsuperscript{28}

Shotcrete has been shown by testing to provide good fireproofing protection for urethane foam.\textsuperscript{29}

2.7.2.5 Bolidens Gruv AB, mines and ore shaft, Sweden\textsuperscript{20}—Steel fiber reinforced shotcrete has been used in a number of mines in Sweden. At the Bolidens Gruv AB mine near Kristineberg, the material was used to line and stabilize a gravity ore transfer shaft that was deteriorating from the impact of the ore. The shaft was filled with ore so that the top surface of the ore became the working platform for the shotcreting operation (Fig. 2.7.2.5).
The thickness varied from 4.0 to 20 in. (100 to 500 mm).

2.7.2.6 **British Rail, arch and tunnel relining, England**—Steel fiber reinforced shotcrete was used for strengthening tunnels and brick arches under bridges for British Rail in England. It is applied up to 6-in. (150-mm) thick. A $\frac{1}{2}$-in. (13-mm) flash coat is used to cover exposed fibers (Fig. 2.7.2.6). One advantage found in the use of fiber reinforced shotcrete in rail tunnel work is that the scaffolding required for mesh installation can be eliminated and traffic interruption is minimized.

2.7.2.7 **Swedish State Power Board, Ringhals Nuclear Power Station**—An emergency cold water tunnel at the Ringhals Nuclear Power Station in Sweden was lined with steel fiber reinforced shotcrete using the wet process equipment. It was used in conjunction with rock bolts (Fig. 2.7.2.7).

2.7.2.8 **Roadway tunnels, Japan**—The Japanese have used steel fiber reinforced shotcrete in at least three vehicular tunnels. In the Miyanoshita Tunnel, it was used to repair concrete lining damaged by rock pressure. In the Itaya Tunnel, it was placed 4-in. (100-mm) thick to repair the original, 50-year-old lining that had deteriorated from icing conditions. In a tunnel near Hakodate, Hokkaido, it was placed as a trial lining. All of these applications used the wet-mix and a squeeze-type pump.

2.7.3 **Dome structures**—Two construction methods have been used to build dome-shaped structures using steel fiber reinforced shotcrete. In the first method, polyurethane foam is sprayed on the underside of an inflatable membrane of the desired shape (from inside the inflated shape) to a thickness of about 4 in. (100 mm). After the foam hardens, the shotcrete is applied to the underside of the foam 1 1/2 to 3-in. (38 to 76-mm) thick or more. The resulting structure is very efficient thermally and can support heavy roof loads, compared to conventional structures. Uses are for homes, offices, warehouses and the storage of grain, potatoes, and other agricultural products.

The second construction method reverses the foam and shotcrete so that the shotcrete is on the outside. Small domes of this type were made as experimental shelters for protection against small fire arms and grenades.

2.7.4 **Other applications**—Other steel fiber reinforced shotcrete applications have included lining of an oil storage cavern at Skarvik, Sweden, using the wet process; residences

### Table 2.7.2.2—Shotcrete mix composition

<table>
<thead>
<tr>
<th>Component</th>
<th>lb/yd³</th>
<th>kg/m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type 10 cement</td>
<td>740</td>
<td>439</td>
</tr>
<tr>
<td>10-mm aggregate</td>
<td>610</td>
<td>362</td>
</tr>
<tr>
<td>Concrete sand</td>
<td>1927</td>
<td>1143</td>
</tr>
<tr>
<td>Fine blend sand</td>
<td>376</td>
<td>223</td>
</tr>
<tr>
<td></td>
<td>3653</td>
<td>2167</td>
</tr>
<tr>
<td>Steel fibers</td>
<td>100</td>
<td>59</td>
</tr>
<tr>
<td></td>
<td>3753</td>
<td>2226</td>
</tr>
</tbody>
</table>

Fig. 2.7.2.5—Technique for lining of ore shaft at Bolidens Mine, Sweden.

Fig. 2.7.2.6—Brick railway bridge near Birmingham, England; reinforced with about 6 in. (150 mm) of steel fiber reinforced shotcrete.

Fig. 2.7.2.7—Emergency cold water tunnel lining at Ringhals Nuclear Power Station, Sweden.
of sandwich wall construction at Rainworth, England; lightweight and chimney repairs in Sweden; resurfacing of a rocket flame deflector at Cape Canaveral, Fla.; coal mine strengthening and sealing of stoppings by National Coal Board, England; stabilization of the Tuve landslide in Sweden; and forming boat hulls similar to ferrocement, using fibers and fibers plus mesh.

2.8—Available design information

2.8.1 General—Design of steel fiber reinforced shotcrete for structural uses is similar to design of plain shotcrete. Although design with fiber reinforced shotcrete and conventional shotcrete is basically the same, the material properties can be significantly different, thereby allowing considerable difference in shotcrete thickness and amount of reinforcement. At present, limited data are available for the design of fiber reinforced shotcrete structures. Most design data that are available are for ground support such as tunnel linings.

Shotcrete in ground support has been most successful in treating problems associated with loosening ground and air slaking.

At present, the design of thin shotcrete linings is based on empirical rules and/or analytical models of shotcrete-rock behavior. Empirical design is based on actual tunnel experience. The analytical models have been developed from observation of shotcrete performance under service conditions and from large scale testing in the laboratory and in the field.

2.8.2 Precautions—The scope of this report prevents a detailed treatment of the design of shotcrete for ground support. However, it is appropriate to list some available references relating to design and engineering properties of shotcrete and to list some general precautions.

Shotcrete may be used as sole support of underground excavations but only in cases where a good shotcrete-rock bond can be obtained, when the shotcrete is thick enough to act as a structurally continuous lining, or when air slaking is the only ground problem. In any other cases, shotcrete should be employed together with some other support elements (i.e., rock bolts, steel ribs, etc.).

The prevention or reduction of water flow from the ground because of the sealing action of the shotcrete may lead to a buildup of hydraulic forces and possibly to stability problems in the ground. Therefore, it is advisable to provide for drainage of such water.

A thin shotcrete lining applied over irregular rock surfaces has been found to be inadequate as the sole support of underground excavations in the following cases: 11
1. Drill and blast openings 20 ft (6.1 m) or more in diameter.
2. Zones where blocks are bounded by smooth to slick joint surfaces, the overbreak is prominent, and block sizes are typically 4 ft (1.2 m) or more in width.
3. Vertical side walls more than 10 ft (3 m) in height.

2.8.3 Empirical design, plain shotcrete—Several different empirical rules for estimating shotcrete thicknesses for tunnel support are presented in a publication by Mahar. 11 These rules include tables of thicknesses based on case histories in which shotcrete did or did not fail. Various thicknesses, depending on conditions, were formulated by Alberts, 33 Kobler, 34 Cecil, 35 and Heuer. 36 Other researchers who used rock quality designation (RQD) and rock structure rating (RSR) to refine empirical rules include Deere 37 and Wickham. 38

2.8.4 Design based on analytical models, plain shotcrete—A second method of estimating shotcrete thickness for initial support involves use of analytical models of shotcrete behavior.

A suggested method of determination of shotcrete thickness for a flat-roof tunnel by using models and analyses is shown in Mahar 11 and Cecil. 35 A thickness of not less than 2 in. (50 mm) is used because of possible deterioration of thinner layers from shrinkage, cracking, construction activity, or water seepage.

Design of shotcrete as a circular ring following the ultimate strength concepts of reinforced concrete design is illustrated by Peng. 39 Rabcewitz’s methods, widely used in the New Austrian Tunnelling Method, are illustrated in a series of articles. 40,41

2.8.5 Analytical models based on laboratory and field tests, fiber reinforced shotcrete—Analytical models for steel fiber reinforced shotcrete based on large scale laboratory tests were formulated by Fernandez-Delgado of the University of Illinois and published in ACI SP-54. 42 Additional data on the same general subject (i.e., adhesion, flexure, and punch loads in arched and flat configurations for steel fiber reinforced shotcrete) also appear in ACI SP-54. 43

The work was continued in large scale field tests in the Atlanta Research Chamber, and the results were applied to the design of liners for underground openings. 44 The models include analysis for wedges displacing through the liner and thrust coefficients for analysis of thicker, continuous arch configurations.

2.8.6 Additional data, fiber shotcrete—Data on the performance and design of steel fiber reinforced shotcrete compared to mesh reinforced shotcrete anchored on 4-ft (1.2-m) centers is given in a report by Morgan. 45 The report indicates that the two cases are equivalent and that fiber reinforced shotcrete provided good residual load capacity with large deformations, i.e., 2 in. (50 mm). Additionally, tests made by British Columbia Hydro on the proposed Site C project on the Peace River confirm that in similar tests on mesh and fiber reinforced panels, first and second cracks generally occur at higher loads in the steel fiber reinforced shotcrete than in the mesh reinforced shotcrete. After cracking, both types exhibited similar load-carrying capabilities. 26 Additional data on engineering properties were generated by Poad, Serbousek, and Goris. 8
CHAPTER 3—SYNTHETIC FIBER REINFORCED SHOTCRETE

3.1—Polypropylene fiber reinforced shotcrete

3.1.1 Types of fibers—Polypropylene fibers that have been used in shotcrete range typically from 1/2 to 2 in. (12 to 50 mm) and may be straight or of a fibrillated configuration.

3.1.2 Production aspects—The methods of adding polypropylene fibers to a mix are similar to those for steel fibers described in Section 2.5. Generally, they do not have the same susceptibility to clumping as steel fibers. However, balling may be experienced at larger addition rates such as 10 to 12 lb/yd³ (6 to 7 kg/m³).

In terms of addition rates, typical values have about 1.5 lb/yd³ (0.9 kg/m³), which is approximately 0.1 percent by volume. However, some applications have used up to 10 lb/yd³ (6 kg/m³) to achieve improved performance.

3.1.3 Properties—It is generally recognized that polypropylene fibers will affect shotcrete properties in a manner similar to steel fibers—see Section 2.3—but not to the same degree.

Reference 19 states that, at normal addition rates of 1 to 2 kg/m³ (1.7 to 3.4 lb/yd³):

“Synthetic fibers contribute to the stability of shotcrete material having excessively low mechanical properties by modifying rheological behavior of the fresh concrete and of the concrete during hardening (improved cohesion and shearing strength). Contributions to improved the hardened properties are negligible.”

However, tests at higher addition rates show improved properties.

3.2—Shotcrete using other synthetic fibers

There are limited data available on the use of other synthetic fibers in shotcrete.

CHAPTER 4—REFERENCES

4.1—Specified and/or recommended references

The documents of the various standards-producing organizations referred to in this document are listed below with their serial designation.

American Concrete Institute (ACI)

544.1R State-of-the-Art Report on Fiber Reinforced Concrete

544.2R Measurement of Properties of Fiber Reinforced Concrete

506. R Guide for Shotcreting

506.2 Specification for Materials, Proportioning, and Application of Shotcrete

547R State-of-the-Art Report on Refractory Concrete

American Society of Testing and Materials (ASTM)

A 820 Steel Fiber for Fiber Reinforced Concrete

C 78 Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)

C 900 Test Method for Pullout Strength of hardened Concrete

C 1018 Test Method for Flexural Toughness and First Crack Strength of Fiber Reinforced Concrete

C 1116 Specification for Fiber Reinforced Concrete and Shotcrete

The above publications may be obtained from the following organizations:

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

48333-9094

American Society for Testing and Materials
100 Barr Harbor Drive
West Conshohocken, PA

19428

4.2—Cited references


4.3—General references