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Guide for Specifying, Proportioning, Mixing, Placing, and Finishing Steel Fiber Reinforced Concrete

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This guide describes the current technology in specifying proportioning, mixing, placing, and finishing of steel fiber reinforced concrete (SFRC). Much of the current conventional concrete practice applies to SFRC The emphasis in the guide is to describe the differences between conventional concrete and SFRC and how to deal with them. Guidance is provided in mixing techniques to achieve uniform mixtures, placement techniques to assure adequate compaction, and finishing techniques to assure satisfactory surface textures. Sample mix proportions are tabulated. A listing of references is provided coveting proportioning, properties, refractory uses, shotcrete technology, and general information on SFRC.

Keywords: compacting; concrete construction; concrete finishing (fresh eoncrete); fiber reinforced concrete; metal fibers; mixing; mix proportioning; placing; specifications.

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CHAPTER 1 -- GENERAL

1.1 -- Scope

This guide covers specifying, proportioning, mixing, placing, and finishing of steel fiber reinforced concrete (SFRC).

1.2 -- Steel fiber reinforced concrete -- General

Steel fiber reinforced concrete is a composite material made of hydraulic cements, fine and coarse aggregate, and a dispersion of discontinuous, small steel fibers. It may also contain pozzolans and admixtures commonly used with conventional concrete.

In general, fiber length varies from 0.5 in. (12.7 mm) to 2.5 in. (63.5 mm). The most common fiber diameters are in the range of 0.017 in. (0.45 mm) to 0.04 in. (1.0 mm). Modem steel fibers have shapes which include round, oval, rectangular, and crescent cross sections, depending on the manufacturing process and raw material used.

The usual amount of steel fibers ran es from 0.25 percent by volume, i.e., 33 lb/yd^3 (20 kg/m^3), to 2 percent by volume, i.e., 265 lb/yd^3 (157 kg/m^3). The low end of the range applies to lightly loaded slabs on grade, some precast applications, and composite steel deck toppings. The upper end of the range is common for security applications (safes, vaults, etc).

The addition of steel fibers significantly improves many of the engineering properties of mortar and concrete, notably impact strength and toughness. Flexural strength, fatigue strength, and the ability to resist cracking and spalling are also enhanced. The extent of improvement in the concrete properties will vary based on the type and quantity of fibers used and the quality of the concrete matrix.

More detailed information on properties may be found in references listed in Chapter 8.

1.3 -- Typical uses of steel fiber reinforced concrete

Generally, when used in structural applications, steel fiber reinforced concrete should only be used in a supplementary role to inhibit cracking, to improve resistance to impact or dynamic loading, and to resist material disintegration. In structural members where flexural tensile or axial tensile stresses will occur, such as in beams, columns, suspended slabs (i.e., not slabs on grade), the reinforcing steel must be capable of resisting the tensile stresses.

A number of research documents have been published on the subject of using steel fibers for reinforcing structural members in combination with conventional reinforcing (Craig 1984; 1987; Craig et al. 1984; Jindal 1984; Batson, Terry, and Change 1984; Balaguru and Ezeldin 1987). This research shows that increased flexural strength, increased shear resistance, and fatigue endurance limits are attainable.

In applications where the presence of continuous reinforcements is not essential to the safety and integrity of the structure, e.g., pavements, overlays, and shotcrete linings, the improvements in flexural strength associated with the fibers can be used to reduce section thickness or improve performance, or both. The following are some examples of structural and nonstructural uses of SFRC:

- *Hydraulic structures* -- Dams, spillways, stilling basins, and sluiceways as new or replacement slabs or overlays to resist cavitation damage (Schrader 1989).
- *Airport and highway paving and overlays* -- Particularly where a thinner-than-normal slab is desired (Johnston 1984).
- *Industrial floors* -- For impact resistance and resistance to thermal shock (Vandenberghe and Nemegeer 1985).
- *Refractory concrete* -- Using high-alumina cement in both castable and shotcrete applications (Lankard 1978; Hackman 1980).
- *Bridge decks* -- As an overlay or topping where the primary structural support is provided by an underlying reinforced concrete deck (Melamed 1985).
- *In shortcrete linings* -- For underground support in tunnels and mines, usually with rock bolts (Morgan and McAskill 1988).
- *In shotcrete coverings* -- To stabilize aboveground rock or soil slopes, e.g., highway and railway cuts, and embankments (Henager 1981; Morgan 1988).
- *Thin shell structures* -- Shotcreted "foam domes" (Haber 1986).
- *Explosion-resistant structures* -- Usually in combination with reinforcing bars (Henager 1983).
- A possible future use in seismic-resistant structures (Henager 1977; Craig 1984).

1.4 -- Specifying steel fiber reinforced concrete

1.4.1 *General* -- Steel fiber reinforced concrete is usually specified by strength and fiber content. In certain applications, toughness parameters may be specified. These are defined in ASTM C 1018, and are further discussed in ACI 544.2R and in a subsequent paragraph.

The flexural strength is normally specified for paving applications while compressive strength is normally specified for structural applications. A flexural strength of 700 to 1000 psi (4.8 to 6.9 MPa) at 28 days and a compressive strength of 5000 to 7000 psi (34.5 to 48.3 MPa) are typical values. In general the addition of fibers does not significantly increase compressive strength but does increase the compressive strain at ultimate load. Therefore, specifying compressive strength will provide general guidelines for concrete proportioning, but will not allow for the assessment of improvement in properties, such as flexural strength and toughness, that are directly attributable to fibers and other improvements such as increased tensile strain capacity and resistance to cracking.

For normal weight concrete, fiber contents vary from as low as 50 lb/yd^3 (30 kg/m^3) to as high as 265 lb/yd^3 (157 kg/m^3), although the high range limit is usually about 160 to 200 lb/yd^3 (95 to 118 kg/m^3). The amount of fibers that can be used without unacceptable loss of workability of SFRC depends upon the placement conditions, the degree of congestion of conventional reinforcement, the fiber shape and aspect ratio (l/d) and the type and amount of water-reducing admixtures used. Fiber manufacturers and technical literature should be consulted for more specific information. Similar consideration applies for lightweight concrete.

Toughness, which is the concrete property represented by the area under a load-deflection curve, or a toughness index, which is a function of that area and the area up to first crack (the point at which the load-deflection curve becomes nonlinear) may be specified to help define the performance requirements of SFRC intended for use where post-cracking 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 loads, thermal shock, and other dynamic loads. ASTM C 1018 is the standard test for determining flexural toughness parameters and first crack strength. Flexural strength (modulus of rupture) may be determined by either ASTM C 78 or C 1018.

As noted in subsequent chapters, the manufacture and placing of SRFC is very similar to conventional concrete. ASTM C 1116, Standard Specification for Fiber Reinforced Concrete and Shotcrete, covers the manufacture of SFRC. Most existing concrete specifications can be used for the placement of SFRC with some added requirements to account for the differences in material and application techniques. The subsequent chapters point out those differences.

1.4.2 *Guidelines for specifying SFRC using ASTM C 1116* **--** ASTM C 1116 covers the manufacture of SFRC by any method, e.g., ready-mix, central batch plant mixing, and continuous mixing. It is similar to ASTM C 94 in that it allows ordering the concrete by one of three alternative methods. These are:

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, first-crack strength, or both, or at the purchaser's option, flexural strength or compressive strength requirements, but does not permit compliance on the basis of compressive strength alone.

Alternative 3: Similar to Alternative 2, except that a minimum allowable cement content is specified.

ASTM C 1116 has extensive information and guidance for the purchaser on the nature of SFRC and the ordering requirements for it. Any level of performance related to toughness may be specified when using Alternatives 2 and 3. It is recommended that an engineer specifying SFRC first obtain a copy of ASTM C 1116 and read it very carefully. The guidance in ASTM C 1116 is extensive and valuable. It is not practical to repeat here.

CHAPTER 2 -- MATERIALS

2.1 -- General

When ASTM C 1116, Standard Specification for Fiber Reinforced Concrete and Shotcrete, is used to purchase SFRC, the cement, aggregate, fibers, and other admixtures are automatically required to meet the appropriate ASTM specifications. If different material specifications are desired, they should be named in the project specifications or the purchase order.

2.2 -- Fibers

ASTM A 820 covers steel fibers for SFRC and should be referenced when specifying steel fibers. It covers all currently available types, so it is necessary to specify the fiber's length, diameter, and other features such as end anchorage provisions, collating,* deformations, and a minimum ultimate tensile strength, if a strength of more than 50,000 psi (345 MPa) is desired. Fibers are available with strengths up to 300,000 psi (2068 MPa).

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. (12.7 to 63.5 mm) should have an aspect ratio, i.e., fiber length divided by diameter (or equivalent diameters,† in the case of nonround fibers), in the range of 30 to 100.

* Collated steel fibers are fibers glued together in a clip with an adhesive that softens and allows the individual fibers to separate during mixing.

† The equivalent diameter of a fiber is the diameter of a round fiber having the same cross-sectional area A as the fiber in question: equivalent diameter = $\sqrt{4A/\pi}$.

2.3 -- Admixtures

- Calcium chloride and chlorides from other sources should be limited to amounts permitted to be added to conventional structural concrete as shown in ACI 318.
- Both regular and high-range (superplasticizer) water-reducing admixtures are suitable in SFRC and are commonly used.
- Air-entraining admixtures are recommended for SFRC exposed to freezing and thawing conditions.

2.4 -- Storage of fibers

Care should be taken to see that steel 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 3 -- MIXTURE PROPORTIONING

3.1 -- General

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

3.2 -- Workability and consistency measurements

Because of the unique properties of SFRC, workability measurements or slump requirements will be somewhat different from those of conventional concrete. Acceptable workability of SFRC should be determined by one of the following methods, and its use should be specified in the contract documents.

3.2.1 *Time of flow through the inverted slump cone* -- The inverted slump cone procedure (ASTM C 995) may be used to determine the workability of SFRC. This test apparatus consists of a conventional slump cone inverted, centered, and rigidly held by external supports so the the small end of the cone is 4 in. (100 mm) off the bottom of a 1 ft³ yield bucket (ASTM C 29). The slump cone is loosely filled with an uncompacted concrete sample. The test uses a vibrator conforming to ASTM C 31 or ASTM C 192 with a 1 ±1/8 in. (25 ±3 mm) diameter probe. The probe of the operating vibrator is allowed to fall under its own weight through the concrete in the slump cone to the bottom of the bucket until its end rests on the bottom of the bucket. The elapsed time from when the vibrator first makes contact with the concrete until the slump cone first becomes emptied is recorded as the inverted-slump-cone time. The inverted-slump-cone time for SFRC should preferably be not more that about 30 sec or less than about 10 sec.

These times may not suit all mixtures. Changes in fiber length and amount, cement content, sand content, air content, aggregate shape, and other factors may produce a different acceptable time. The test is not applicable to concrete that flows freely through the cone.

3.2.2 *Slump test* -- The slump test may be specified in the contract documents to serve as a control test for consistency of SFRC from batch to batch. (In addition to the slump test described in ASTM C 143, it may be appropriate also to perform the tests described in ASTM C 138 and either ASTM C 173 or ASTM C 231.)

In general, the slump for steel fiber reinforced concrete per ASTM C 143 should be at least 1 in. but not greater than 4 in. (25 mm to 100 mm.) However, the same factors that influence inverted-slump-cone time also influence the slump. When these factors are changed, a different range may be acceptable. In any event the specified maximum water-cement ratio should be maintained.

3.3 -- Proportioning methods

Procedures for proportioning of SFRC mixtures, with emphasis on good workability, are available (Schrader and Munch 1976; Schrader 1989; Ounanian and Kesler 1976; ACI 544.1R). Some typical proportions that have been used are shown in Table 3.1.

In many projects, steel fibers have been added without any changes to the conventional mixture proportions used by ready-mix suppliers for the required concrete compressive strength. Where very large numbers of fibers per unit volume are used, some adjustments may be required. To provide better workability of the concrete, more paste is needed in the mixture. Therefore, the ratio of fine to coarse aggregate is adjusted upward accordingly. To prevent wet fiber balls, avoid overmixing and using a mixture with too much coarse aggregate (more than about 55 percent of the total combined aggregate by absolute volume).

In early applications, coarse aggregate larger than ¾ in. (19 mm) was not recommended for SFRC. However, based on work by Tatro (1987), recent placements have successfully used aggregate as large as 1½ in. (38 mm) (Rettberg 1986).

Table 3.1 -- Range of proportions for normal weight steel fiber reinforced concrete

	3/8-in. maximum-sized aggregate	¾-in. maximum-sized aggregate	1½-in. maximum-sized aggregate
Cement, lb/yd³	600-1000	500-900	470-700
w/c, lb/lb	03.5-0.45	0.35-0.50	0.35-0.55
Percent of fine to coarse aggregate	45-60	45-55	40-55
Entrained air content, percent	4-8	4-6	4-5
Fiber content, volume percent			
Deformed fiber	0.4-1.0	0.3-0.8	0.2-0.7
Smooth fiber	0.8-2.0	0.6-1.6	0.4-1.4

1 lb/yd³= 0.5933 kg/m³; 1 in. = 25.4 mm; 1 steel fiber volume percent = 132.3 lb/yd³ (78.5 kg/m³).

Another method of improving SFRC workability has been to use pozzolans such as fly ash, slag, or silica fume in addition to or as a partial replacement of cement.

CHAPTER 4 -- FORMWORK AND REINFORCING STEEL

4.1 -- Formwork

Design and construction of formwork should be done according to ACI 347R. Normal weight SFRC with a fiber content up to 2 percent by volume has a density in the same range as normal weight conventional concrete-144 to 150 lb/ft^3 (2306 to 2403 kg/m^3). The fibers in steel fiber reinforced concrete have a tendency to protrude from sharp corners to formed concrete. These may be hazardous to personnel. To minimize this, sharp comers should be chamfered. Alternately, a rounded comer may be formed by applying a pressure-sensitive tape to the inside of sharp comers in the forms. On formed surfaces, use of a form vibrator will cause the fibers to back away from the form, leaving them covered by about 1/8 in. (3 mm) of concrete. Formwork must be designed for the additional stress caused by the vibration. Consult ACI 347R for further information.

4.2 -- Reinforcing steel

Fabricating and placing reinforcing steel should be in accordance with ACI 301. Steel fiber reinforced concrete is routinely used in conjuction with reinforcing steel. Consideration should be given to the spacing of bars and welded wire fabric. Unless otherwise shown in full-scale tests, the fiber length should not exceed the clear spacing between bars, welded wire fabric, or other embedded materials, including the cover of the reinforcing.

CHARTER 5 -- BATCHING, MIXING, DELIVERY, AND SAMPLING

5.1 -- General

Batching, mixing, delivery, and sampling of steel fiber reinforced concrete should be in accordance with ASTM C 1116 and applicable portions of ACI 304, as modified and supplemented by the following.

The contractor should supply appropriate equipment or develop a suitable technique for dispersing the fibers in the mixer, free of fiber balls. The equipment and/or method of adding the fibers to the mix should be reviewed and accepted by the engineer before any placement of SFRC takes place. Such devices as conveyor belts and chutes can be used to add fibers to the mixer on the jobsite or at the ready-mix plant.

The batching procedure is critical to obtaining a good blend of fibers with the concrete. Several methods have been used previously with success, and information to assist the contractor in the choice of a suitable procedure is discussed in ACI 544.1R or may be obtained from fiber manufactures. Any SFRC which is not properly batched and which develops dry balls of fibers or a significant number of wet fiber balls (which includes fibers and matrix) should be discarded and removed from the site.

At the request of the owner, the contractor should perform a full-scale trial batching, charging, and mixing operation with a minimum of SO percent of the planned operational batch size at least 8 days prior to the first SFRC placement, so that 7-day tests are possible. The owner's engineer should observe the operation and recommend adjustments in the mixture proportions at the time to help obtain a workable mixture at a low water-cement ratio. Additional batches may be necessary to verify the mixture adjustments and mixing efficiency. The contractor should conduct tests on the trial batches and the owner may elect to cast test specimens for his own information. At the time of the test batch, the contractor should have on hand a working vibrator of the type to be used in the actual placements. The behavior of the trial batch under this vibration should be observed to provide guidance for use in actual construction operations.

It is important that the fibers be dispersed uniformly throughout the mixture. Reducing the batch size or increasing the mixing time, or both, may be necessary if a uniform dispersion does not result.

5.2 -- Mixing

There are some important differences in mixing SFRC in a transit mixer or revolving drum mixer compared to conventional concrete. One of these is that, to obtain good dispersion of the fibers and to prevent fiber balling, the fibers should be added to a fluid mix.

Methods 1 and 2, which follow, describe procedures used to mix SFRC by adding the fibers to a fluid mix. These methods generally apply to uncollated, individual fibers. Certain types of individual half-round fibers up to 2.5 in. (63 mm) long, circular and rectangular fibers with an aspect ratio of less than 50, or fibers collated into bundles of about 30 fibers per bundle can generally be added to the mix as the last step of batching, with little or no likelihood of fiber balling.

Method l -- *Add fibers lust to transit mix truck:*

1. The wet mixture to be used is prepared first without the fibers. The slump of the concrete before fiber addition should be 2 to 3 in. (51 to 76 mm) greater than the final slump desired. Normally, the mixture would be prepared using the water-cement ratio found to give the best results and meeting the specifications for the job. The use of a high-range water-reducing admixture can be advantageous, but is not essential.

2. With the mixes operating at normal charging speed, add the fibers as described in the next step.

3. Add the individual fibers, ball-free (i.e., as a rain of individual fibers), to the mixer. A convenient way to do this is to dump the fibers through a 4 in. (100 mm) mesh screen into a hopper which opens onto a moving con-

veyor belt going to the mixer. It is important that no clumps be introduced, once a clump is introduced into the mixture, it will remain a clump. The drum must rotate fast enough to carry away the fibers as they enter the mixture. After all the fibers have been introduced into the mixer, the mixer should be slowed to the rated mixing speed and mixed for approximately 30 to 40 revolutions.

For small jobs, this method has been used successfully by a number of ready-mix concrete producers. The use of an auxiliary conveyor belt and manual addition of fibers has also produced good results with a variety of fiber types.

Method 2 -- *Add fibers to aggregate on a conveyor belt:*

In a plant set up to charge a central mixer or transit mixers, add the fibers to the aggregates on a conveyor belt during aggregate addition and mix in the normal manner. This method does not require the same care as Method 1 concerning where the fibers land in the mixer, but they should not be allowed to pile up and form balls on their way to the mixer. If possible, the operator should stretch out the addition of aggregate so that fibers go in with the aggregate and not by themselves. A fiber feeder or shaker is useful in reducing the time for fiber handling and addition. Method 2 has been used for the majority of fibrous concrete projects where larger quantities of concrete were mixed using bulk individual fibers.

5.3 -- Causes of fiber balling

The following listing of causes of fiber balling may be useful in designing a plant or mixing sequence for fibrous concrete or correcting the problem in a mixing operation. Most fiber balling occurs somewhere before the fibers get into the mixture. Once the fibers get into a mixture ball-free, they nearly always stay ball-free. This means that if 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, on the vanes, etc.) This normally happens when the fibers are added too fast at some point in the procedure. The mixer, whatever type, must carry the fibers away into the mixture as fast as they are added. Balls form by hanging up on a rough loading chute at the back of a mixer truck. Fibers should not be allowed to pile up or slide down the vanes of a partially filled drum; this will form balls.

Other causes of balling are adding too many fibers to a mixture (more than about 2 percent by volume or even 1 percent 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 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 are overmixing and using a mixture with too much coarse aggregate (more than 55 percent of the total combined aggregate by absolute volume).

CHAPTER 6 -- PLACING AND FINISHING

6.1 -- General

Conventional concrete equipment is adequate for the placing and finishing of nearly all steel fiber reinforced concrete. Internal or external vibrators (including vibrating screeds) can be used to reduce pockets of entrapped air voids.

On a number of projects where proper mixture proportions were used, successful placement of SFRC has been achieved using hand screeding of the slabs without the use of vibrators.

The basic guide for placing concrete, ACI 304, should be used for placing and finishing SFRC, along with the different techniques noted in the following sections.

6.2 -- Placing

Usually SFRC with a proper water-cement ratio appears relatively stiff and unworkable, compared to conventional concrete. However, use of vibrators or high-range water-reducing admixtures (HRWR) allows easy placing of such seemingly unworkable concrete. The material tends to “hang together” and resist movement during compaction if an attempt is made to handle it without vibration or an HRWR admixture. Also, at the lower end of fiber quantity, some types of fiber allow easy placing without the methods just mentioned. Generally, however, placing of SFRC with no vibration is discouraged because, without compaction, the concrete will be less dense, may have air voids, and may have less bond with any conventional reinforcement. Batch plant operators and transit truck drivers must be instructed not to add additional water to the mixture based on its appearance and their experience with conventional concrete.

Water-cement ratios for fibrous mixtures must be carefully controlled. It is very easy to add unnecessary water to the mixture and lose many of the beneficial properties obtained from the addition of fibers. Ratios on the order of about 0.35 to 0.50 are normal. Paving mixtures and some special structural applications may benefit from less workable, but much higher quality, concrete with the water-cement ratios in the range of 0.35 to 0.43. At the upper end of the water-cement spectrum, tests have shown that further addition of water causes an increase in slump without a change in workability under vibration. This water addition reduces the quality of the mixture without improving the placeability and it can give rise to excessive bleeding and segregation.

There are no special measures to take placing SFRC around reinforcing steel except to use vibration to properly consolidate it. In a very thin wall or beam form, e.g., 4 in. (100 mm) or less, which also contains bars or mesh, placement of the concrete may be difficult, especially with longer fibers. This is similar to the difficulties encountered in placing conventional concrete mixtures with larger aggregate in thin, congested sections. When SFRC mixtures are used in congested areas, a 3/8 in. (9 mm) maximum aggregate size should be specified to reduce placing difficulties.

6.3 -- Transporting and handling equipment

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

6.3.1 *Transit trucks* -- Discharging from transit trucks is usually accomplished with little trouble. Too stiff a mixture or a truck in poor condition will prevent the mixture from easily discharging from the drum onto the chute. A well-proportioned mixture usually just barely slides down the chute by itself and may need to be pushed by the truck operator. When an especially stiff mixture is used, the truck can be driven up on blocks or a ramp to help discharge.

6.3.2 *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). The fibers will bridge smaller gate openings and the mix 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 especially 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.

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

6.3.4 *Pumping* -- Pumping has been used to transport SFRC on a number of projects. A good fiber mixture generally has proportions of sand and admixtures which make it well-suited for pumping. Gradations suited to SFRC are also compatible with pumping. Although a mixture may appear stiff and unworkable, it may pump surprisingly well. Because of its composition, an SFRC mixture will move through the line without slugs and has been reported to pump more easily and with less trouble than conventional concrete. Some important points about pumping SFRC are (1) use a pump capable of handling the volume and pressures; (2) use a large-diameter line, preferably at least 6 in. (150 mm); (3) avoid flexible hose if possible; (4) provide a screen over the pump hopper to prevent any fiber balls from entering the line [about a 2 x 3 in. (50 x 75 mm) mesh is usually adequate]; and (5) do not try to pump a fibrous mix that is too wet. 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 must be noted that this is the result of a mixture that is too wet, not too dry. The same type of plugging can occur with conventional concrete, with the plug consisting 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 SFRC for pumping.

6.4 -- Finishing

Steel fiber reinforced concrete can be finished with conventional equipment, but minor refinements in techniques and workmanship are needed. For flat formed surfaces, normally no special attention is needed. The surface will normally be smooth and will not show fibers when the forms are stripped. If chamfers or rounds have been provided at the edges and in comers, the ends of fibers will not protrude at these points when forms are stripped. To provide added compaction and bury surface fibers, open slab surfaces should first be struck off with a vibrating screed. The screed should have slightly rounded edges and preferably should be metal. In areas where a screed is not practical, a jitterbug* or rollerbug can be used for compaction and to establish rough grade control. Care should be exercised when using a jitterbug or rollerbug not to overwork the surface, bringing excessive mortars to the surface. Magnesium floats can be used to establish a surface and close up any tears or open areas which are caused by the screed. Wood floats tend to tear the surface and should not be used.

Throughout all finishing operations, care must be taken not to overwork the surface. Overworking will bring excessive fines to the surface and may result in crazing, which normally shows up after the curing period. If excess bleeding occurs or excessive fines are at the surface, such materials should be screeded off and discarded.

After completion of any float work, the surface should be left until it can be worked further without damage. This is usually at about the time of initial set. Where a careful finish is not required for appearance or exact tolerance, no further work is needed after floating. If a texture is required, a broom or roller can be used prior to initial set. Burlap drags should not be used because they will lift up the fibers and tear up the surface. When additional finishing is needed, the next step should be done with magnesium floats. Power equipment or hand equipment may be used. When done by hand, the float should be held flat and not on edge. It should be moved with a sawing motion (short, quick, back-and-forth movements) as it is drawn across the surface. The magnesium float can be used to obtain a nearly perfect, flat surface, bury or cover all the fibers, and leave a slight texture. This can be followed by hard steel troweling if a smooth surface is desired. The trowel must be kept flat or the edge will cause fibers to spring out of the surface. Using these techniques, some excellent finishes of SFRC have been obtained.

* A grade tamper that forces aggregate and fibers below the surface.

Slipform pavers have been used on several projects, such as airport runways and taxiways, with excellent results.

The proper time to execute a broom finish following a screed finish or paving machine finish is just prior to application of curing compounds, when the water sheen has practically disappeared.

6.5 -- Hot and cold weather requirements

Placement of steel fiber reinforced concrete should be done according to the recommendations of ACI 305R for hot weather and ACI 306R for cold weather.

6.6 -- Repair of defects

The repair of defects such as voids and honeycombing is done in much the same manner as for plain concrete. However, if removal of some SFRC is required, the removal operation will be significantly more difficult because of the greater toughness of SFRC.

Removal by jackhammers is hindered because the material does not fracture easily. Sawing is a more effective method of cutting or removing steel fiber reinforced concrete.

6.7 -- Contraction joints

Contraction joints in slabs on ground are more easily made if they are sawed rather than cast or formed. The sawing can be done shortly after final set. 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 the saw cut should extend from one-third to one-half of the way through the slab. If it does not, the higher tensile strength of the SFRC tends to prevent cracking at the joint and random cracking occurs elsewhere in the slab. Use of SFRC may allow increased distances between construction joints and sawcuts of up to two times, compared to unreinforced concrete. Just how much the joint spacing may be increased depends on fiber content and type. The concrete proportions, floor thickness, and other relevant factors should be taken into consideration in selecting the distance between sawcut and construction joints.

A joint sealing compound should be used to seal the sawed joint to prevent water infiltration to the subgrade, and to prevent the corrosion of those fibers and fiber ends that become exposed in the saw cut and the crack below.

CHAPTER 7 -- CURING AND PROTECTION

7.1 -- General

Curing of steel fiber reinforced concrete and protection from freezing or excessively hot or cold temperatures should be done in the same way as for conventional concrete. One aspect deserves special attention. Since SFRC is often placed in thin sections, as overlays for example, and often has a high cement content, it is particularly vulnerable to plastic shrinkage cracking. This will occur when the rate of surface evaporation is high. In such conditions, placements must be shaded from the sun and sheltered from the wind to prevent this type of damage.

CHAPTER 8 -- REFERENCES

8.1 -- Recommended references

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

These publications may be obtained from the following organizations:

American Concrete Institute
P.O. Box 19150
Detroit, MI 48219

ASTM
1916 Race Street
Philadelphia, PA 19103

American Concrete Institute

301 Specifications for Structural Concrete for Buildings
304R Guide for Measuring, Mixing, Transporting and Placing Concrete
304.2R Placing Concrete by Pumping Methods
305R Hot Weather Concreting
306R Cold Weather Concreting
318 Building Code Requirements for Reinforced Concrete
347-R Guide to Formwork for Concrete
506.1R State-of-the-Art Report on Fiber Reinforced Shotcrete
544.1R State-of-the-Art Report on Fiber Reinforced Concrete
544.2R Measurement of Properties of Fiber Reinforced Concrete

ASTM

A 820 Standard Specification for Steel Fibers for Fiber Reinforced Concrete
C 29 Standard Test Methods for Unit Weight and Voids in Aggregate
C 31 Practice for Making and Curing Concrete Test Specimens in the Field
C 33 Standard Specification for Concrete Aggregates
C 78 Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)
C 94 Standard Specification for Ready-Mixed Concrete
C 138 Standard Test Method for Unit Weight, Yield

and Air Content (Gravimetric of Concrete)

C 143 Standard Test Method for Slump for Portland Cement Concrete

C 173 Standard Test Method for Air Content of Freshly Mixed Concrete by the Volumetric Method

C 192 Practice for Making and Curing Concrete Test Specimens in the Laboratory

C 231 Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method

C 995 Standard Test Method for Time of Flow of Fiber Reinforced Concrete Through Inverted Slump Cone

C 1018 Standard Test Method for Flexural Toughness and First-Crack Strength of Fiber Reinforced Concrete (Using Beam with Third-Point Loading)

C 1116 Standard Specification for Fiber Reinforced Concrete and Shotcrete

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Henager, C.H., 1983, "Use of Steel Fiber Reinforced Concrete in Containment and Explosive Resistant Structures," *Symposium Proceedings*, Interaction of Non-Nuclear Munitions with Structures, U.S. Air Force Academy, Colorado, May, pp. 199-203.

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This report was submitted to letter ballot of the committee and approved in accordance with ACI balloting procedures.