DESIGN CONSIDERATIONS

The designer may best view SFRC as a concrete with increased strain capacity, impact resistance, energy absorption, fatigue endurance and tensile strength. The increase in these properties will vary from nil to substantial depending on the type and quantity of fibers used.

Several approaches to the design of members with SFRC are available. These are based on conventional design methods generally supplemented by special procedures for the fiber contribution. Additional information can be found in "Design Considerations for Steel Fiber Reinforced Concrete," ACI 544.4R.

In applications where the presence of continuous tensile reinforcement is not essential to the safety and integrity of the structure, e.g., floors on grade, pavements, overlays, ground support and shotcrete linings, the improvements in flexural strength, impact resistance, toughness, and fatigue performance can be used to reduce section thickness, improve performance, or both.

Guidance for the design of floors-on-grade is available from fiber manufacturers, the Battelle Memorial Institute [25], the CUR Recommendation 10 [26], and the FAA [27]. These methods take advantage of the improvements to properties described above.

APPLICATIONS

The applications of SFRC will depend on the ingenuity of the designer and builder in taking advantage of the improvements to the mechanical properties of this composite material. The uniform dispersion of fiber throughout the concrete provides isotropic strength properties and the ability to re-distribute stresses not common to conventionally reinforced concrete.

Cast-in-Place SFRC

Many cast-in-place SFRC applications involve slabs-on-grade, either in the form of pavements or industrial floors. As early as 1983, 22 airport paving projects had been completed in the United States, and over 200 million square feet (18.6 million square meters) of industrial flooring have been constructed throughout the world.

An example of SFRC industrial floors is the 1.5 million sq. ft. (140,000 sq.m.) Chrysler Jefferson North Assembly Plant in Detroit, Michigan. These floors are 5 and 6.5 inches (127 and 165 mm) thick, and contain 0.38 volume percent, or 50 lbs. per cu. yd. (30 kg. per cu.m.) of 2.4 in. (60 mm) long deformed fibers. The owner reports substantial savings from this contractor proposed alternate to the original design [28].

In 1984, 500,000 sq. ft. (46,000 sq. m.) of 4 in. (100 mm) thick SFRC was placed as a replacement of the upstream concrete facing placed in 1909 at the Barr Lake Dam near Denver, Colorado. The SFRC mixture contained 0.6 volume percent, or 80 lbs. per cu. yd. (47 kgs. per cu.m.) of 2.4 in. (60 mm) long deformed fibers, and 1-1/2 in. (38 mm) maximum size aggregate. The SFRC was pumped to a slip-form screed to pave the 47 feet (14 m) high, 2.5 to 1 slope facing. [29].

Other applications of cast-in-place SFRC include:

- Repairs and new construction on major dams and hydraulic structures to provide resistance to cavitation and large debris impact [22].
- Repairs and rehabilitation of marine structures such as piling and cassions [19].
- Bonded overlays in industrial floors and highways.
- Both conventional and latex-modified SFRC bridge deck overlays in the U.S. and Canada.
- Slip-formed, cast-in-place tunnel linings.
- Impact resistant turbine test facility encasement.

Precast SFRC

Many precast applications for SFRC make use of the improvement in properties such as impact resistance or toughness. Other precast applications use steel fibers to replace conventional reinforcing in utility boxes and septic tanks. Some recent applications are cited:

- Dolosse: 30,000 cu.yd. (22,900 cu.m.) of SFRC were placed in over 1,500 - 42 ton (38 MT) dolosse by the Corps of Engineers in Northern California. SFRC was specified in lieu of conventional reinforcing bars to improve the wave impact resistance of the dolosse [30].

- Vaults and Safes: Since 1984, most of the vault and safe manufacturers in North America have used SFRC in precast panels that are then used to construct vaults. Wall thicknesses have been reduced by up to two-thirds over the cast-in-place methods and still are tough enough to resist penetration.

- Mine Crib Blocks: These units, made with conventional concrete masonry machinery, are routinely supplied throughout the world for building roof support structures in coal mines. Steel fibers are used to increase the compressive toughness of the concrete to allow controlled crushing and thus prevent catastrophic failures [31].

- Precast Garages: SFRC is used in Eruope to precast complete automobile garages for single family residences.

Shotcrete

The first practical application of steel fiber reinforced shotcrete (SFRS) was a trial use for rock slope stabilization in 1974 along the Snake River in Washington [32]. Since that time, many applications have been made in slope stabilization, in ground support for hydroelectric, transportation and mining tunnels, and in soldier pile retaining walls as concrete lagging.

A recent example of SFRS use in tunnels is the twin highway tunnels at Cumberland Gap between Kentucky and Tennessee in Eastern United States [33]. These tunnels are 4,100 ft. long (1,250 m) 40 ft. wide (12.2 m) and 30 ft. high (9.1 m) running 40 ft. (12.2 m) apart through Cumberland Mountain which is mostly quartz sandstone, shale, siltstone, mudstone and coal. These tunnels were constructed by S.A. Healy/Lodigiani-JV using the principles of the NATM approach to excavation and ground support. This technique involves allowing the ground to deform slightly after excavation so that it can relieve stresses and essentially support itself. In order to succeed, this approach requires a thin, ductile initial lining to provide initial support in blocky, fractured rock. This lining must be able to support localized roof falls and be able to deform with the ground. The ability of SFRS to carry substantial load after cracking is the ideal material for this lining.

Specifications required the 4 inch thick (100 mm) SFRS in the initial linings to have a flexural strength of 700 psi (4.8 MPa), and a Residual Flexural Strength of 420 psi (2.9 MPa) at 7 days. The Residual Flexural Strength was defined as the strength capacity of the ASTM C 1018 test beam after deforming to 5.5 times the first-crack deformation, or to 0.013 inches (0.33 mm) in this case.

Quality control testing of one series of 606 ASTM C 1018 test beam specimens (202 sets) show the following mean results:

Flexural Strength:	870 psi	(6.0 MPa)
Standard Deviation:	73 psi	(0.5 MPa)
Residual Flexural Strength:	507 psi	(3.5 MPa)
Standard Deviation:	82 psi	(0.6 MPa)

These results are considered outstanding when the method for obtaining specimens is considered. 30 by 30 by 1-inch thick (76 by 76 by 25 cm) test panels were shot from production SFRS at the face of the tunnel excavaions, and moved from the face to a curing shed outside within 8 hours in the bucket of a rubber-tired front end loader. Beam specimens were sawed from the panels at an age of 4 days and then cured in water.

The Contractor selected a wet-process SFRS mixture which included silica fume, high range water reducers and 90 lbs. per cu. yd. (53 kgs. per cu.m.) of 1.2 inch (30 mm) long, bent-end steel wire fibers primarily for the economics involved versus reinforcement with welded wire fabric, but safety was a major concern. The SFRS was applied with robotic shotcrete machines which allowed tunnellers to always be protected by the shotcrete lining in the tunnel. If WWF had been used, they would have been exposed to unsupported ground while placing the mesh. Over 39,000 cubic yards (29,800 cubic metres) of SFRS was placed in the initial lining requiring over 3.5 million pounds (1.6 million kgs.) of steel fibers. Both tunnels were holded through in 1992 without a lost time accident.

In addition to ground support, SFRS applications include thin-shell domes shot on inflatable forms, artificial rockscapes, repair and reinforcing of structures such as lighthouses, bridge piers and abutments, port facilities, channel linings, and lining oil storage caverns. Additional references and more information may be found in "State-of-the-Art Report on Fiber Reinforced Shotcrete," ACI 506.1R.

SIFCON - Slurry Infiltrated Fiber Concrete

Slurry Infiltrated Fiber Concrete (SIFCON) is a type of fiber reinforced concrete in which formwork molds are filled to capacity with random-oriented steel fibers and the resulting fiber network is infiltrated by a cement-based slurry. Infiltration is usually accomplished by gravity flow aided by light vibration.

SIFCON composites differ from conventional SFRC in at least two respects: they contain a much larger volume fraction of fibers (up to 12 volume percent) and they use a matrix consisting of very fine particles. As such they can be made to exhibit outstanding strengths and ductilities as listed below:

- Compressive: strengths to 20 ksi (140 MPa), and strain capacities to 10 percent.
- Tensile: strengths to 6 ksi (41 MPa), and strains to 2 percent.
- Moduli of Rupture: up to 13 ksi (90 MPa).
- Shear: strengths of up to 4 ksi (28 MPa).

Since SIFCON is not inexpensive, only applications requiring very high strength and toughness have so far benefitted from its use. These include impact and blast resistant structures, refractories, protective revetments and taxiway and pavement repairs.

Refractories

Steel fibers have been used as reinforcement in monolithic refractories since 1970. Steel fibers have been added to refractory concretes to provide improvements in resistance to cracking and spalling in applications where thermal cycling and thermal shock have limited the service life of the refractory. The presence of fibers acts to control the cracking in such a way that cracks having relatively large openings are less frequent and crack-plane boundaries are held together by fibers bridging the crack-plane. Fracture toughness is a method of characterizing this property, and a convenient technique used involves the measurement of a flexural toughness index (ASTM C 1018) [12].

Both carbon steel and stainless steel fiber reinforced refractories have shown excellent performance in a number of applications including ferrous and nonferrous metal production and processing, petroleum refining, rotary kilns used for producing portland cement and lime, coal-fired boilers and municipal incinerators.

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- ASTM documents cited may be obtained from ASTM, 1916 Race Street, Philadelphia, PA 19103-1187.

Table 1 Recommended Combined Aggregate Gradations for Steel Fiber Reinforced Concrete [22,23]

PERCENT PASSING FOR MAXIMUM SIZE OF:

US STANDARD SIEVE SIZE in.	(mm)	3/8" 10 mm	1/2" 13 mm	3/4" 19 mm	1" 25 mm	1-1/2" 38 mm
2	51	100	100	100	100	100
1-1/2	38	100	100	100	100	85-100
1	25	100	100	100	94-100	65- 85
3/4	19	100	100	94-100	76- 82	58- 77
1/2	13	100	93-100	70- 88	65- 76	50- 68
3/8	10	96-100	85- 96	61- 73	56- 66	46- 58
# 4	5	72- 84	58- 78	48- 56	45- 53	38- 50
# 8	2.4	46- 57	41- 53	40- 47	36- 44	29- 43
# 16	1.1	34- 44	32- 42	32- 40	29- 38	21- 34
# 30	0.6	22- 33	19- 30	20- 32	19- 28	13- 27
# 50	0.3	10- 18	8- 15	10- 20	8-20	7- 19
# 100	0.15	2 - 7	1 - 5	3 - 9	2 - 8	2 - 8
# 200	0.08	0 - 2	0 - 2	0 - 2	0 - 2	0 - 2

Note: Aggregates should be well graded from the largest to the smallest size. Aggregate should not vary from near the maximum allowable percent passing one sieve to near the minimum allowable percent passing the next sieve size.

Peter Tatnall,
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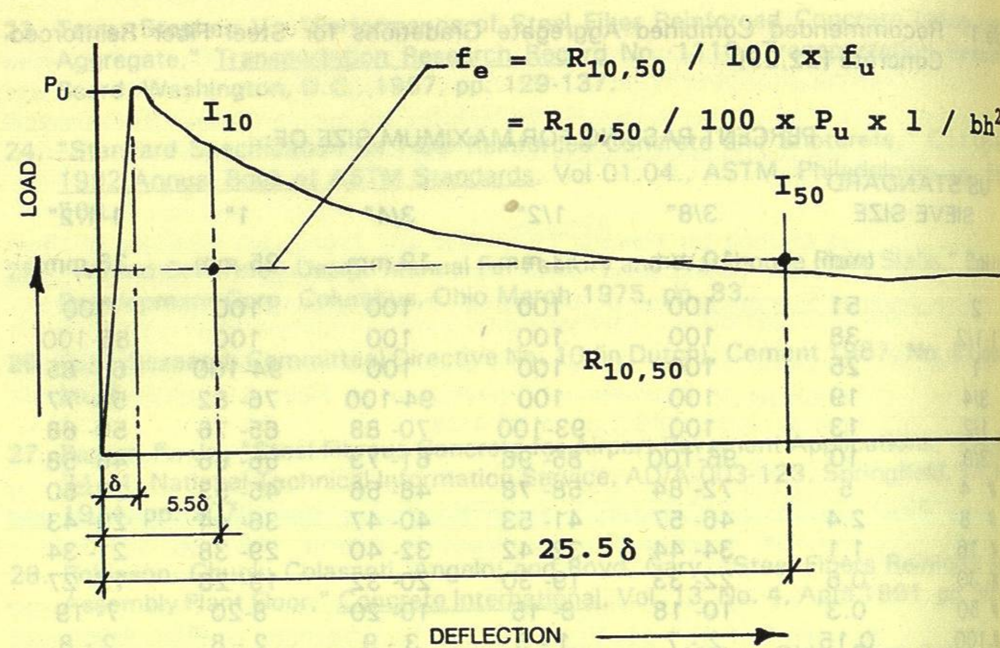

Fig. 1 (a). ASTM C 1018 Toughness

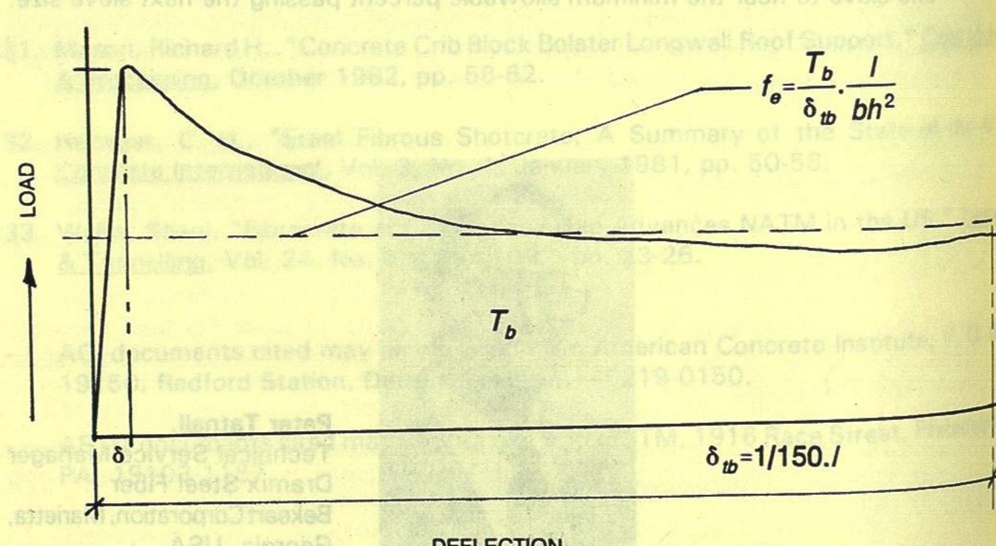

Fig. 1 (b). JCI (JSCE) SF-4 Toughness