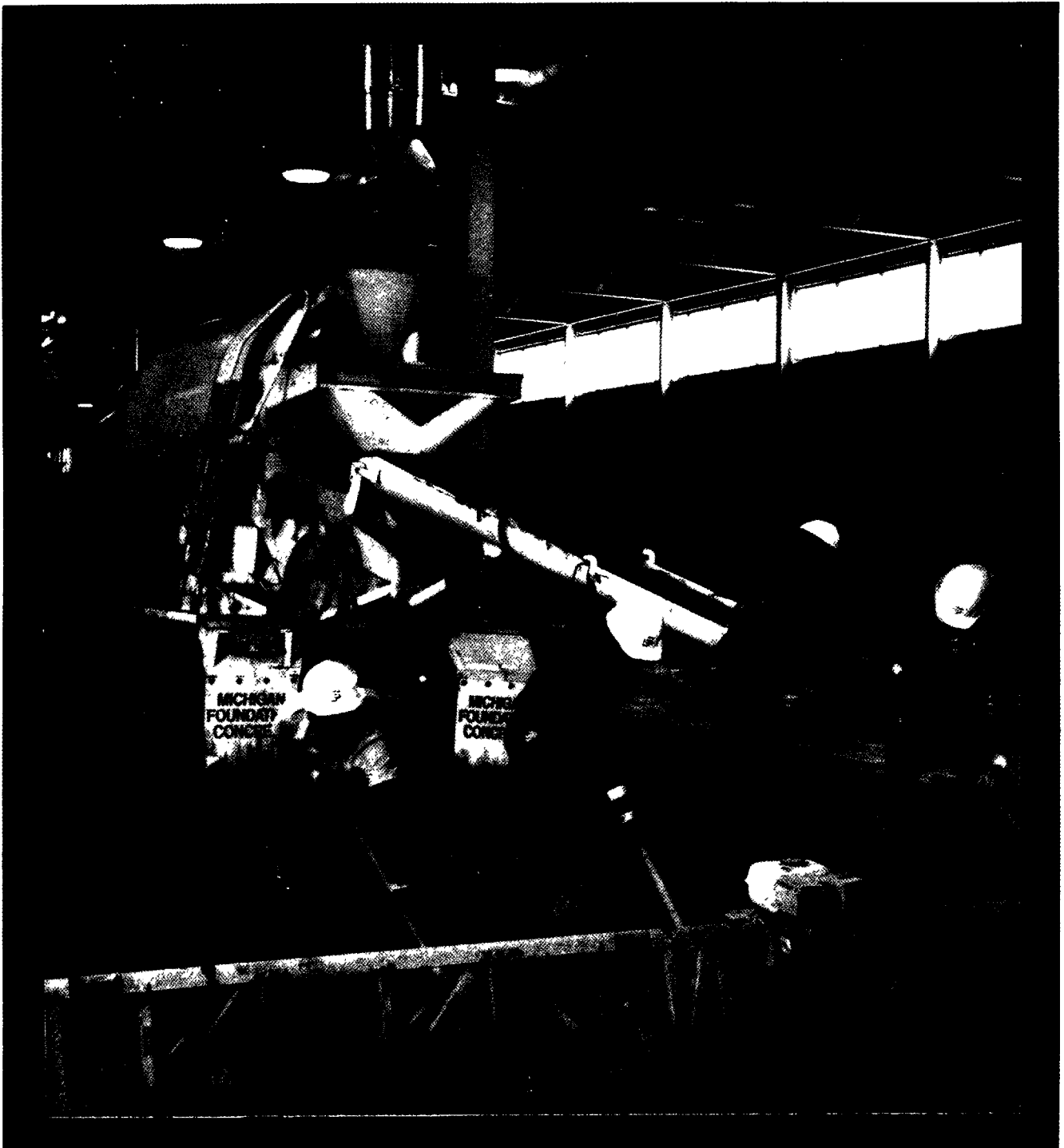


# STEEL FIBER REINFORCED CONCRETE



Compilation 27

American Concrete Institute

# Steel Fiber Reinforced Concrete

## ACI Compilation 27

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## Preface

ACI Compilations combine material previously published in Institute periodicals to provide compact and ready reference on specific topics. The Material in a compilation does not necessarily represent the opinion of an ACI technical committee — only the opinions of the individual authors. However, the information presented here is considered to be a valuable resource for readers interested in the subject.

James I. Daniel  
Chairman, ACI Committee 544  
Fiber Reinforced Concrete

**On The Cover:** The new Chrysler Jefferson North Assembly Plant in Detroit contains approximately 1.5 million square feet of steel fiber reinforced concrete slab-on-grade. Use of steel fibers in the concrete allowed control joint spacing to be increased, thereby eliminating 3 miles of jointing on the project, and made it possible to place most of the concrete using trucks. (See article starting on page 8.)



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## Observations about large scale tests

# Steel Fiber Reinforced Concrete in Industrial Floors

by P. C. Tamm and L. Kalkreuth

In the European industrial building industry, steel fibers have been used in place of conventional reinforcement in the form of reinforcing bars or welded wire fabric for many concrete floors on grade for 15 years. In that time, the use of these floors has grown steadily: in Belgium and the Netherlands, it is conservatively estimated that at least 40 percent, well over 32.5 million ft<sup>2</sup> (2.5 million m<sup>2</sup>) of the concrete floors constructed in 1991 contain steel fiber reinforcement. In Europe, over 320 million ft<sup>2</sup> (25 million m<sup>2</sup>) of steel fiber reinforced concrete (SFRC) floors are in use. The use of SFRC for industrial flooring is also growing in North America due to the economies it provides.<sup>1</sup>

Practical experience is available with SFRC floors that have been in service for many years. Knowledge and experience about the material's potential is becoming more widespread in the design world, and SFRC is being specified more systematically, demonstrating its increasing acceptance by designers, builders, and owners.

To date, very little is available in the way of instructions, specifications, or standards for designing SFRC floors. Only the Netherlands Commission for Active Research (Nederlandse Commissie voor Uitvoerende Research, or C.U.R.), under the umbrella of the Netherlands Concrete Society, has published a document about SFRC floors.<sup>2</sup>

In fact, standards covering traditional concrete floor design are also limited. France has its "Regles Professionnelles" (revised in 1990),<sup>3</sup> and in the United Kingdom there is "Technical Report 34," published by the Concrete Society in 1988.<sup>4</sup> The ACI Building Code does not mention slabs-on-grade, and the ACI Committee 302 and 360 documents are reports to be used only as guides for the design and

construction of floors. All of these are typical of what one finds worldwide; in some cases, documents mention the possible use of SFRC, but the responsibility is completely up to the design engineer.

Besides the practical experience, a great deal of research has been reported on SFRC. Much of this research was conducted on concrete with a steel fiber content of at least 1 volume percent (132 lb/yd<sup>3</sup>, or 78 kg/m<sup>3</sup>) and is not applicable to concrete floors where the usual proportion of steel fibers is between 0.25 and 0.5 volume percent. A few studies have been devoted specifically to SFRC floors, and these have been carried out on the initiative of the fiber manufacturers. As a result, it is possible to draw a first cautious connection between the material characteristics of the composite SFRC and its behavior on a large scale. In this way the picture of the behavior of SFRC with respect to load-bearing capacity, fatigue, impact resistance, shrinkage, and corrosion can be sketched. By extension, this may lead to the formulation of standards and specifications governing its practical use.

## Material characteristics of SFRC

Two countries, the United States and Japan, have established standards for characterizing the properties of SFRC — ASTM C 1018<sup>5</sup> and JSCE-SF4,<sup>6</sup> respectively. Both standard test methods, originally published in 1984, define the same two properties, namely, flexural strength and toughness. The standards prescribe a four-point bending test on a prismatic test specimen in which the load is recorded as a function of the deformation of the test specimen. The testing equipment must be able to maintain a constant rate of deflection of the test specimen. The

Netherlands C.U.R. Recommendation 10 is based on these principles.

## Flexural strength

In the ASTM Standard, flexural strength is defined at the occurrence of the first crack in the test specimen. This is the point at which the load-deflection curve deviates from a straight line — Point A in Fig. 1. Flexural strength is calculated from the load at first crack and the dimensions of the test specimen. In the Japanese Standard, flexural strength is defined in terms of the maximum load —  $P_u$  in Fig. 2 — and the dimensions of the test specimen, the so-called modulus of rupture.

## Toughness

In both standards, toughness is based on the energy required to deform the test specimen. This energy is represented by the area under the load-deflection curve.

The ASTM standard defines a toughness index that is the ratio of the absorbed energy up to a given deflection of the test specimen, as indicated in Fig. 1, to the absorbed energy up to first crack.

The Japanese Standard defines an equivalent flexural strength that is derived from the average load up to a deflection of the specimen of 1/150 of the specimen span length. This average load is found by dividing the absorbed energy up to the preset deflection by that deflection, as shown in Fig. 2.

## Testing

The Institute for Building Materials and Structures of the Netherlands Organization for Applied Scientific Research (TNO) performed a series of bending tests, each consisting of a minimum of six specimens, on concrete containing different types of steel

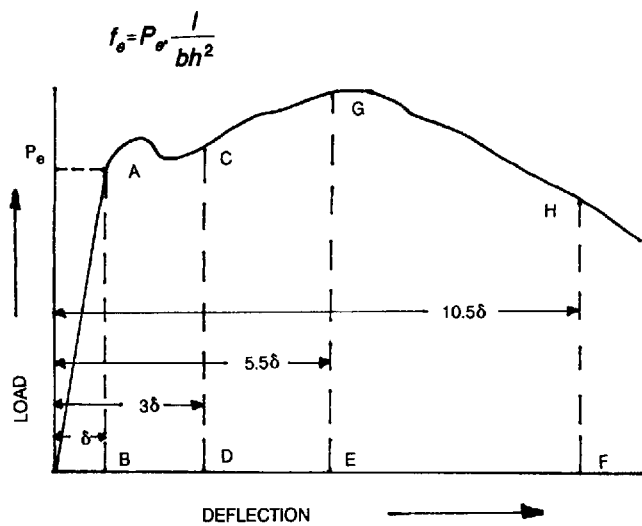


Fig. 1 — ASTM C 1080 test method.

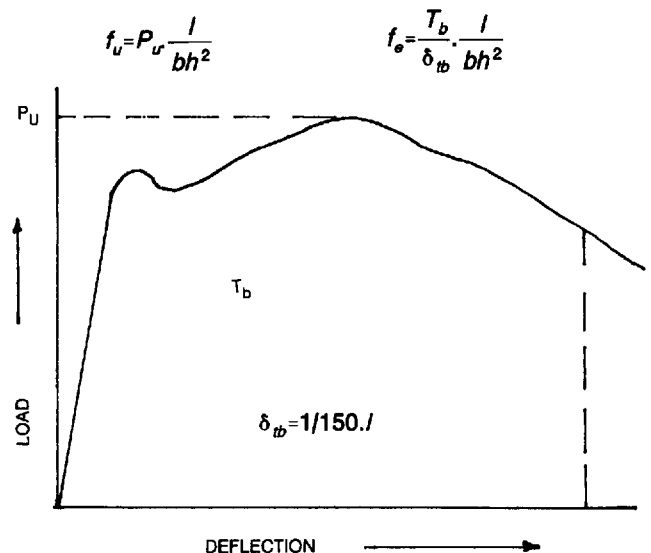


Fig. 2 — JSCE SF-4 test method.

fibers. However, each series contained 50 lb/yd<sup>3</sup> (30 kg/m<sup>3</sup>), with one additional series containing 34 lb/yd<sup>3</sup> (20 kg/m<sup>3</sup>).<sup>7</sup> The flexural strengths at first crack and the equivalent flexural strengths in accordance with JSCE-SF4 were reported. The results of three relevant test series are shown in Table 1. All fibers were made from cold drawn wire and had hooks on both ends.

Concrete composition, preparation, and curing of the test specimens was the same in all test series. The following conclusions apply to low fiber contents — 34 to 50 lb/yd<sup>3</sup> (20 to 30 kg/m<sup>3</sup>) — and to four-point bending tests on prismatic test specimens. The test results show that:

- The flexural strength at first crack  $f_o$  is not dependent on the fiber type or the quantity added. This is confirmed in the other test series with fibers of different origin.
- The post-crack behavior, characterized by the equivalent flexural strength  $f_e$ , is dependent on the fiber shape and the quantity added. In Table 1, the effect of the aspect ratio is apparent. This, too, is confirmed by the other test series.

## Large-scale tests

In the last decade, several research programs have been executed on slabs made with SFRC. The following summarizes three of these programs:

### Imperial College, London

In the Concrete Laboratory of Imperial College, London, 12 concrete slabs measuring 3.25 x 3.25 ft (1 x 1 m) and

2 in. (50 mm) thick were simply supported on the four edges and loaded in the center until fracture.<sup>8</sup>

The 12 slabs were divided into four groups of three slabs each. All slabs were cast from the same basic concrete mixture and reinforced with cold drawn wire fibers 2.4 in.

(60 mm) long, 0.04 in. (1.0 mm) in diameter, and with hooks at both ends (fibers No. 1 or 2 in Table 1). Fiber quantities varied as shown in Table 2.

In the test procedure, the load was applied to a base plate 8 x 8 in. (200 x 200 mm), and the loads and deflections at the center of the slabs were recorded. A typical load-deflection curve is shown in Fig. 3 for a SFRC slab specimen. The averages of the three test results for each group are shown in Table 2.

As the table shows, the first-peak load is only marginally influenced by the addition of fibers: with an addition of 50 lb/yd<sup>3</sup> (30 kg/m<sup>3</sup>), there is an increase in first-peak load of 18 percent relative to the non-fibrous slabs. For an addition of 34 lb/yd<sup>3</sup> (20 kg/m<sup>3</sup>), the increase is negligible. Before the first-peak load, the material exhibits elastic behavior with the modulus of elasticity being that of the non-fibrous concrete. This fact provides a simple means of verifying the accuracy of the test program.

Steel fibers have a pronounced effect on the maximum load: for the added quantities — 34, 42, and 50 lb/yd<sup>3</sup> (20, 25, and 30 kg/m<sup>3</sup>), the respective increase is 32, 40, and 47 percent. Calculating a corresponding stress in the material according to elastic theory is not worthwhile in view of

the fact that the behavior following first-peak load is not elastic. The plateau loads remain on a high level and equal the first-peak load for a fiber content of 50 lb/yd<sup>3</sup> (30 kg/m<sup>3</sup>) and is only slightly less for the lower fiber contents tested.

Although the load-deflection diagrams for SFRC four-point bending tests and these slab tests are similar, the effect of the steel fiber reinforcement in these slabs supported on four sides is different from the beam bending test. In the beam test, the load does not increase after first-crack; however, with the slab tests, there is a redistribution of the bending moments (stresses) after the first-peak load, which leads to higher ultimate load capacities and thus enhanced performance for the designer and owner.

### Thames Polytechnic, Dartford

The Civil Engineering Department of Thames Polytechnic in Dartford, United Kingdom, carried out a comparative study on a number of test slabs on ground.<sup>9</sup> Each of the slabs measured 9.8 x 9.8 ft (3 x 3 m) square and was 6 in. (150 mm) thick. The base consisted of a compacted sand bed, of which the Westergaard modulus of subgrade reaction  $k$  was recorded as 130 psi/in. (0.035 MPa/mm), or an equivalent CBR of 4. More than nine slabs were cast: non reinforced, conventionally reinforced, and with SFRC.

All the slabs were loaded until failure with a point load at the center of the slab on a 4 x 4 in. (100 x 100 mm) base plate. The load was applied in

**Table 1 — Netherlands beam bending tests**

|                                            | No. 1 | No. 2 | No. 3 |
|--------------------------------------------|-------|-------|-------|
| Fiber content, lb/yd <sup>3</sup>          | 34    | 50    | 50    |
| Length, in.                                | 2.4   | 2.4   | 2.4   |
| Diameter, in.                              | 0.039 | 0.039 | 0.031 |
| Aspect ratio, $l/d$                        | 60    | 60    | 75    |
| First-crack strength $f_o$ , psi           | 652   | 638   | 638   |
| Equivalent flexural strength $f_e$ , psi   | 348   | 464   | 508   |
| Equivalent/first-crack strength, $f_e/f_o$ | 53%   | 73%   | 80%   |

2.25 kip (10 kN) increments, and slab deflection was recorded at each increment. In particular, the load at first visible crack (at the slab edge) and the maximum load reached were recorded.

The test results relevant here are from nonfibrous slabs and slabs reinforced with drawn wire steel fibers with hooked ends, described as No. 2 and No. 3 in Table 1, and are shown in Table 3.

The results show that the load-bearing capacity of the slabs reinforced with steel fibers is considerably higher than that of the non-reinforced slab. The maximum load is increased by more than 50 percent when fiber No. 2 is used at an addition rate of 34 lb/yd<sup>3</sup> (20 kg/m<sup>3</sup>), and when fiber No. 3 is used at 34 lb/yd<sup>3</sup> (20 kg/m<sup>3</sup>) the maximum load virtually doubles. It can reasonably be expected that a test carried out to the maximum with 50 lb/yd<sup>3</sup> (30 kg/m<sup>3</sup>) of fiber No. 3 would lead to a maximum load of over 90 kips (400 kN).

The occurrence of the first visible crack also appears to be delayed; at 34 lb/yd<sup>3</sup> (20 kg/m<sup>3</sup>) of fiber No. 2, the load is 17 percent higher; at 50 lb/yd<sup>3</sup> (30 kg/m<sup>3</sup>) of fiber No. 3, the increase is 61 percent. The behavior is markedly different from that observed in four-point bending tests on beams, where the first-crack occurs at the same load as in a test specimen without steel fibers and where the load-bearing capacity after cracking does not increase significantly.

Two parameters varied in this test program: the fiber quantity added and the diameter of the fiber used. These tests confirm that:

- a higher quantity of fibers produces a higher load-bearing capacity
- a higher aspect ratio of the steel fiber produces a higher load-bearing capacity

Two observations are made concerning this study:

1. Because of the limited number of test specimens, there is no statistical data concerning the reliability of the results. However, the results are completely in line with expectations if the relation between the quantity of fibers added, the steel fiber characteristics, and the loads are considered. Where a higher first-crack load was achieved, the maximum load also increased.

2. This study leads to some conclusions concerning the behavior of steel fiber reinforced slabs on ground relative to unreinforced slabs on ground. Extension of these conclusions to slabs with different types and quantities of fibers, with different dimensions, on different bases, and loaded in a different way should be done with caution. For example, corner and edge loading were not investigated.

### Belgium Building Research Institute — in-situ testing

The Scientific and Technical Center for the Building Industry in Belgium has conducted various load tests in-situ on two monolithically cast and finished industrial floors.<sup>9</sup> Both floors were cast with SFRC with 50 lb/yd<sup>3</sup> (30 kg/m<sup>3</sup>) of the wire fibers described as No. 3 in Table 1.

Before placement of the ground slab the Westergaard modulus of subgrade reaction  $k$  was determined on the base.

**Table 2 — Imperial College supported slab tests**

| Quantity, lb/yd <sup>3</sup> | 0    | 34   | 42   | 50   |
|------------------------------|------|------|------|------|
| First-peak load, kips        | 2.09 | 2.14 | 2.47 | 2.47 |
| First-peak stress, psi       | 638  | 652  | 754  | 754  |
| Maximum load, kips           | 2.11 | 2.79 | 2.97 | 3.10 |
| Plateau load, kips*          | 0    | 1.96 | 2.36 | 2.47 |

\*See Fig. 3: plateau load on the curve corresponds to a state of increasing deflection under constant load and represents the collapse load of the slab.

During placement, concrete specimens were cast for compression and flexural testing at 28 days.

The floors themselves were loaded after 28 days with a concentrated load on a base plate of 4 x 4 in. (100 x 100 mm). Three tests were performed in each of the following loading cases:

1. In the center of a floor slab section formed by the sawn control joints
2. On a free (unsupported) edge
3. On a sawn joint
4. In the corner formed by a sawn joint and a free edge

The results of these tests were compared with the theoretical cracking load calculated according to the classical formulas for slabs on an elastic foundation (Westergaard). According to this theory, cracks occur when the calculated tensile stresses in the floor equal the flexural strength of the concrete as determined on prismatic beams in bending. The theoretical loads shown in Table 4 were calculated based on the measured  $k$ -value and the results of the bending tests on the beam specimens.

Because of limited loading capability, the cracking load for Case 1, central loading, was not reached for either Slab A or Slab B. Visual cracking was observed on the free edge condition, Case 2, in Slab A only. In all the other cases the crack formation could not be determined with certainty, and ultrasonic measurements were used to estimate cracking loads.

These test results show that crack formation occurs at much higher concentrated loads than indicated by the classical calculation models. The contribution made by the steel fiber rein-

**Table 4 — Summary of theoretical and experimental loads, Belgium in-situ slab tests, kips**

| Load condition | Slab A      |              | Slab B      |              |
|----------------|-------------|--------------|-------------|--------------|
|                | Theoretical | Experimental | Theoretical | Experimental |
| Center         | 6.5         | 31.1         | 13.8        | 39.3         |
| Free edge      | 3.8         | 23.6         | 8.1         | 38.2         |
| Sawn joint     | 3.8 - 6.5   | 29.0         | —           | —            |
| Corner         | —           | —            | 7.6         | 38.2         |

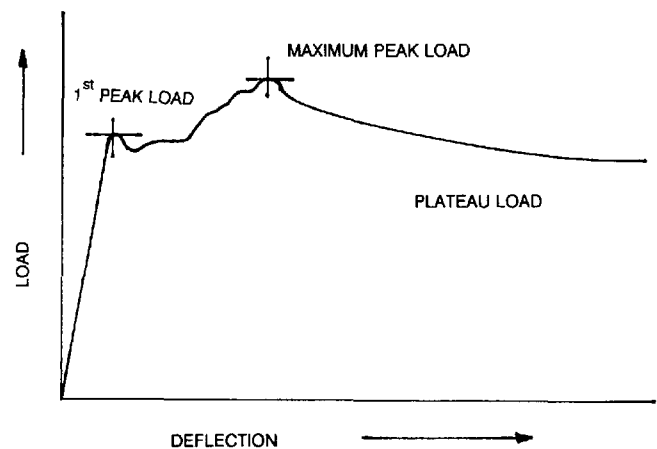


Fig. 3 — Typical load-deflection relationship for Imperial College steel fiber reinforced slabs.

**Table 3 — Thames Polytechnic slab on ground tests**

| Fiber type                        | None | No. 2-A | No. 2-B | No. 3-A | No. 3-B |
|-----------------------------------|------|---------|---------|---------|---------|
| Quantity, lb/yd <sup>3</sup>      | 0    | 34      | 50      | 34      | 50      |
| Load at first visible crack, kips | 40.5 | 47.2    | 53.9    | 58.4    | 65.2    |
| Maximum load, kips                | 45.0 | 73.1    | 76.4    | 87.7    | 77.6*   |

\*In this first test, the capacity of the testing apparatus was not sufficient; for subsequent tests, the apparatus was modified.

forcement cannot be derived accurately from this test program; however, comparison with the 9.8 x 9.8 ft (3 x 3 m) slabs described here does permit a rough estimate to be made. The behavior at the corners and edges also proves to be significantly better than the theoretical estimates.

## Discussion

The contribution limited additions (0.25 to 0.5 volume percent) of steel fibers make to concrete is toughness. Toughness, or post-crack strength, is also the factor that is determined according to the standards that exist for SFRC. This property is a new concept for concrete, and the way in which the building designer can apply this concept must be defined.

Four-point bending tests on SFRC beams show that toughness depends on the fiber type and quantity of fibers added. Therefore, toughness must be the criteria that is specified for SFRC. Then, the quantity of fibers to be added can be derived for a given fiber type.

In concrete slabs, toughness determines the load-bearing capacity. This is apparent from the tests on slabs supported on four sides and on slabs on ground. The increased toughness associated with higher quantities of fibers leads to higher loads before first crack

and to a pronounced increase in maximum load capacity.

The tests involving slabs on ground show the influence of the fiber type: a fiber that shows greater toughness behavior in beam tests also leads to higher load capacity of the slabs. Tests on slabs reinforced with fibers that do not provide toughness to the concrete, such as polypropylene and certain steel fibers, confirm this.<sup>9</sup>

The load-bearing capacity of SFRC slabs is also much greater than is indicated by the classical elastic theory of slabs on an elastic foundation. The in-situ load tests show this for all loading conditions. Part of this extra load-bearing capacity can be attributed to the conservatism of the classical theory. However, the comparative tests on the 9.8 x 9.8 ft (3 x 3 m) slabs on ground indicate that the steel fiber reinforcement is also responsible for some of the additional load-bearing capacity, and this increase is in direct proportion to the toughness the steel fibers impart to the concrete.

The calculation methods used to determine the thickness of industrial floors on grade are purely elastic and do not take into account the specific property of SFRC — toughness. This leads to a great deal of uncertainty concerning the way in which SFRC floors should actually be designed.

With its Recommendation 10, the Netherlands C.U.R. Commission has taken a first step toward a solution by suggesting the adoption of a lower elastic modulus for a tough SFRC to account for the redistribution of moments (stresses), and suggesting the use of the JSCE SF-4<sup>6</sup> equivalent flexural strength as a design value to further account for the property of toughness.

## Conclusion

Steel fiber reinforced concrete for industrial floors on grade has become more and more common in many countries. This results in a large data base of practical experience with this material for this application.

From the studies discussed here, it is apparent that the specific property of SFRC, namely toughness, determines the load-bearing capacity of slabs on grade. However, there remains uncertainty in the area of the design of these floors. There is only one relatively new specification that indicates how the toughness of SFRC should be taken into account.

Additionally, it is apparent from these studies that the classical elastic theory offers no appropriate solution for determining the thickness of steel fiber reinforced floors. Perhaps these studies and more like them will stimulate progress so that the design procedures used for SFRC floors will catch up with the building of these floors.

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Better crack control means fewer joints to maintain

# Steel Fibers Reinforce Auto Assembly Plant Floor

by Chuck Robinson, Angelo Colasanti, and Gary Boyd

**T**he new Chrysler Jefferson North Assembly Plant — a 1.5 million ft<sup>2</sup> (140,000 m<sup>2</sup>) facility — will be where the new 1992½ Jeep-type sport-utility vehicle will be assembled. The plant will be located on 283 acres (1.15 km<sup>2</sup>) in the City of Detroit, and will cost Chrysler approximately \$1 billion to construct. When developing this new industrial facility, one major objective of Chrysler and the construction team was to construct a plant with top-quality floor slabs.

Floor slabs are a very important element of all industrial facilities, particularly automotive assembly plants, since they support manufacturing equipment and absorb material-handling impact loads. The slabs must be uniformly flat and joints must be relatively level without excessive movement to allow manufacturing equipment and fork trucks to perform properly. The cost of maintaining a quality floor slab is also extremely important to an owner.

To construct the best possible floor within the constraints of Chrysler's construction schedule and budget, the architect/engineer (A/E) and construction manager (CM) were selected early in the project to allow time for research, evaluation of current and new technology, and estimation of the potential impact of new materials and construction techniques on the project schedule.

## Design process

A floor slab committee consisting initially of the owner, A/E, and CM developed project criteria and evaluated each aspect of the floor design against the criteria, as well as cost and schedule impacts. Joint details and spacings, floor finishes, aggregate shakes, slab thickness, and reinforcement were evaluated along with the many other variables that enter into the design of an automotive assembly plant.

The goal of the floor slab committee was to achieve the absolute best in quality and performance with the smallest initial investment and lowest operating and maintenance costs. Development and documentation of the design options was the responsibility of the A/E.

Cost estimates and schedule evaluation were performed by the CM. The combined evaluation was then reviewed with the Chrysler Project Design Team.

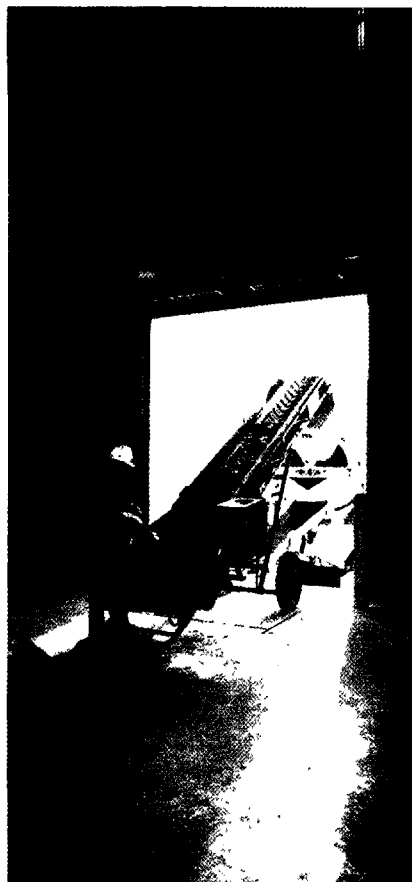
## Steel fiber reinforced concrete

One of the most interesting aspects of the research was the evaluation of steel fiber reinforced concrete (SFRC), primarily with the aim of reducing shrinkage cracking and increasing joint spacing.

Conventional industrial slab-on-grade designs depend on contraction joints and reinforcing steel to control shrinkage cracking. The purpose of contraction joints is to predetermine the location of cracks for aesthetic and performance purposes. When spaced at 2 to 3 times in feet the thickness of the slab in inches (ACI 302.1R-89), contraction joints will reduce the risk of objectionable shrinkage cracks, and may even eliminate them. If an adequate amount of reinforcement is used, crack width will be minimized, but there will be more cracks. Unfortunately, both approaches to crack control have undesirable effects.

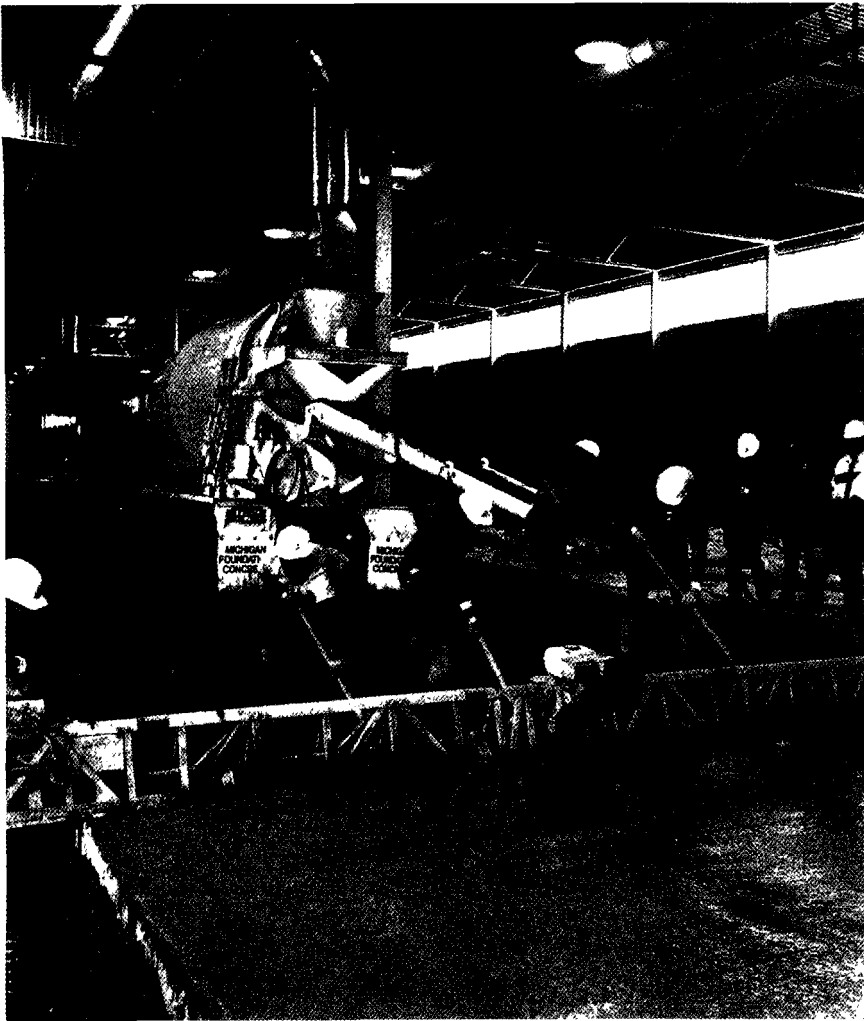
Closer joint spacings add to both construction and maintenance costs. The joints in assembly plants must be filled with epoxy to hold up under constant fork truck traffic and to facilitate floor cleaning. The saw cutting, cleaning, and filling of these joints, along with the future maintenance costs, make close joint spacing an undesirable way of reducing shrinkage cracking.

It is difficult to ensure that conventional reinforcement ends up in the upper third of the slab, where it is needed for effective shrinkage crack control.



Beth Singer, Photographer

Steel fibers were added to the truck mixer on-site.



Beth Singer, Photographer

The use of SFRC made it possible to place most of the concrete using trucks.

and initial finishing operations are very labor intensive. Welded wire fabric and reinforcing bars are invariably walked on, and even if supported on vertical spacers or chairs usually end up near the bottom of the slab, or worse yet lying on the subgrade.

Since most industrial floor slab concrete is placed in long narrow lanes, the reinforcement also restricts concrete truck access and decreases productivity due to the placement crew having to walk through the mesh. These difficulties, including the significant costs associated with the materials and labor for placement, must be evaluated before adding more steel for crack control.

With SFRC, most of the problems associated with placement of reinforcement are eliminated because the steel fibers are placed directly into the truck mixer at the jobsite or batch plant. Proper selection of fibers and mix proportions

will ensure the uniform and homogeneous distribution needed to maximize the ability of the fibers to control shrinkage cracking.

Use of SFRC for large industrial floor slabs is relatively new in the United States. SFRC has been used in Canada for more than eight years, and to date there are approximately 4.5 million ft<sup>2</sup> (0.42 million m<sup>2</sup>) of SFRC floors in the Toronto area. In Europe, where SFRC was originally developed and has been used for industrial floors for about 15 years, there are approximately 20 million ft<sup>2</sup> (1.86 million m<sup>2</sup>) of SFRC floors. When the Detroit Jefferson North Assembly plant is

completed, it will be the largest project in the United States to use SFRC for industrial floor slabs, incorporating more than 500 tons (227 Mg) of steel fibers.

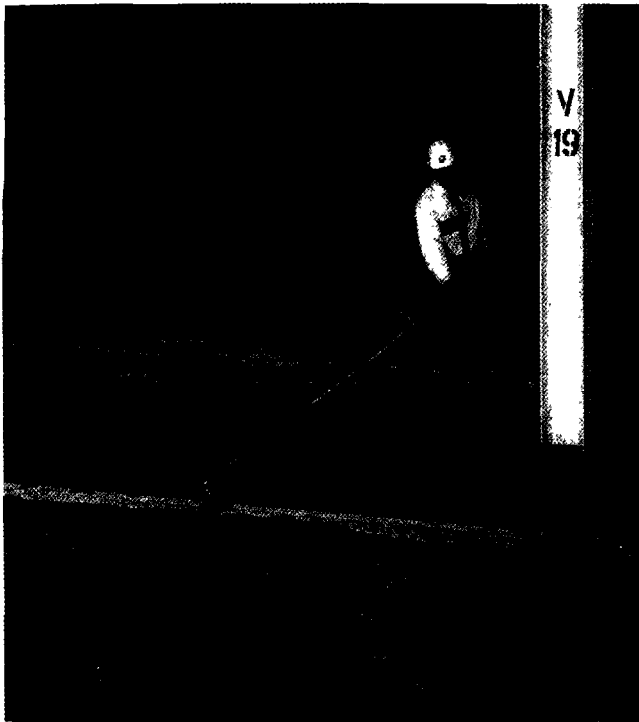
Since the use of steel fibers for large industrial floor slabs in the United States is still relatively new, the costs were difficult to estimate accurately. For this reason the SFRC was bid as an alternative to the conventional design. Contractors were encouraged to quote an SFRC alternative that included revised joint spacings and a warranty, based on a specified maximum crack width, that required the contractor to repair by epoxy injection any crack that exceeded the allowable limit within five years. This alternative was not accepted in the final bid analysis, but did serve to reduce unwarranted optimism about using large joint spacings for SFRC slabs.

The SFRC design was based on performance criteria to allow for variations in joint spacing, type (shape) of fiber, and weight of steel fiber to be added per cubic yard (0.76 m<sup>3</sup>) of concrete.

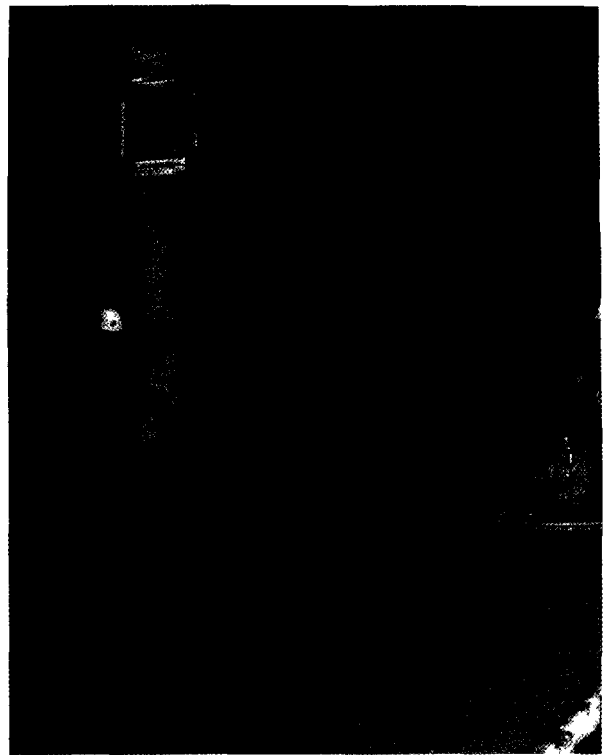
### Contractor input

The floor slab committee recognized early in their evaluation of options that contractor input was needed. To involve contractors in the design process, the floor slab bidders were pre-qualified. Four

|                                  |                                                         |
|----------------------------------|---------------------------------------------------------|
| <b>Owner:</b>                    | Chrysler Corporation, Highland Park, Michigan           |
| <b>Architect/Engineer:</b>       | Albert Kahn Associates, Inc., Detroit, Michigan         |
| <b>Construction Manager:</b>     | Barton Malow Company, Southfield, Michigan              |
| <b>Primary Floor Contractor:</b> | Colasanti Corporation, Roseville, Michigan              |
|                                  | (joint venture) Gough-Johnson & Sons, Detroit, Michigan |
| <b>Steel Fiber Supplier:</b>     | Bekaert Corporation, Marietta, Georgia                  |
| <b>Concrete Supplier:</b>        | Michigan Foundation Concrete, Detroit, Michigan         |



Beth Singer, Photographer



Beth Singer, Photographer

The finishing techniques normally used on industrial floors work well with steel fibers in the mix.

contractors who had demonstrated the ability to construct quality industrial concrete floor slabs on large projects with tight construction schedules were selected.

Unfortunately these contractors had little or no practical experience with SFRC. To remedy this deficiency, the contractor who eventually became the successful bidder began researching materials and talking to recognized experts in SFRC. Armand Silverstri, president

of Duron Floors of Canada, was especially helpful and invited Angelo Colasanti to visit him, discuss the project, and spend a day observing SFRC slabs being placed. Consequently an initial comfort level with SFRC and its performance was developed. The contractor also invited the slab committee on a field trip to Toronto to inspect floors that had been in place for several years and observe SFRC being placed and finished in new work. The committee found that crack control was excellent and the floors were acceptable in appearance.

The contractor constructed a mock-up of a 5 in. (127 mm) thick slab, 35 ft (10.7 m) wide by 40 ft (12.2 m) long with no intermediate joints, using the mix proportions and steel fibers proposed for the project. This mock-up, constructed in the contractor's storage yard, confirmed that the SFRC would perform as expected and that finishing techniques used for industrial floors would work well with steel fibers in the mix.

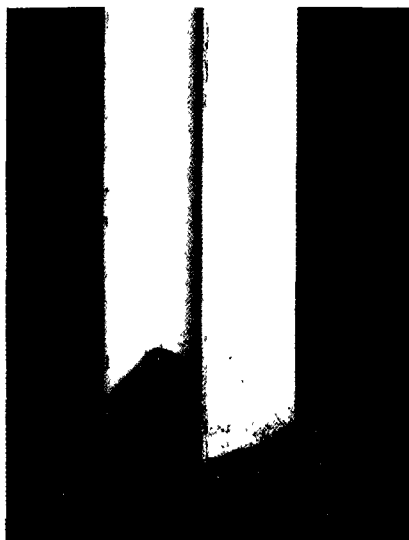
### Bidding

The bid documents were issued with a complete "base bid" design for 6 in. (152 mm) thick unreinforced concrete slabs in the paint building

and assembly area of the plant and 8 in. (203 mm) thick reinforced concrete slabs in the body shop. The joint spacing was included on the drawings. The base bid included floor flatness and levelness requirements, plus specifications for placing, finishing, curing, and joint filling, a liquid densifier, and a special aggregate gradation to help reduce shrinkage. Also included was a summary of loading requirements and the design subgrade modulus.

An alternative price was requested for SFRC. The proposal form requested the type of fiber and its rate of application, along with the contractor's proposed joint spacing. The special blended aggregate requirement was waived for the SFRC alternative. Steel fiber dosage and joint spacing varied with each bidder: steel fiber dosage from 50 lb/yd<sup>3</sup> (29.7 kg/m<sup>3</sup>) to 80 lb/yd<sup>3</sup> (47.5 kg/m<sup>3</sup>), and joint spacing from 20 ft (6.1 m) to more than 100 ft (30.5 m).

The SFRC design submitted by the successful contractor, prepared by the fiber manufacturer, was based on 50 lb/yd<sup>3</sup> (30 kg/m<sup>3</sup>) of ZC 60/.80 Dramix steel fibers. This design reduced the paint and assembly area slab thickness from 6 in. (152 mm) to 5 in. (127 mm) and added 1 in. (25 mm) of sand fill to



Beth Singer, Photographer

Pinwheel joint pattern produces a much cleaner detail at columns.

the subbase, and reduced the body shop slab thickness from 8 in. (203 mm) to 6½ in. (165 mm). The joint spacing in the 70 x 40 ft (21.3 x 12.2 m) bays was increased from 14 x 13½ ft (4.3 x 4.1 m) to 23½ x 20 ft (7.1 x 6.1 m). The spacing in the 50 x 50 ft (15.2 x 15.2 m) bays was increased from 16½ x 16½ ft (5.1 x 5.1 m) to 25 x 25 ft (7.6 x 7.6 m). The revised joint spacings eliminated 3 miles (4.8 km) of control joint on the project.

### Pre-construction meeting

As soon as the bids were evaluated and the contractor selected, a pre-construction meeting was organized to bring all the players together to discuss every aspect of the design, schedule, materials, working conditions, and responsibilities. The pre-construction meeting was attended by representatives of the four key members of the design team — owner, architect/engineer, construction manager, and floor slab contractor — as well as technical representatives for the concrete, admixture, and steel fiber suppliers, and the testing laboratory. This meeting allowed the details of the construction process to be discussed and final procedures to be established.

For example, the loading station for high range water reducer (HRWR) and steel fibers was on-site. Some of the mix water was held back at the concrete plant, and the remaining mix water, plus water adjustments needed to provide a consistent slump prior to adding HRWR, was added at the loading station. The supplier agreed to deliver the steel fibers to the site in special 50 lb (22.7 kg) bags rather than their standard 66 lb (30 kg) bags, so adding fibers became a simple matter of one bag for each cubic yard (0.76 m³) of concrete in the truck mixer.

The quality control measures were also worked out at this meeting, along with many other significant detailed procedures as follows:

- Critical requirement to complete roofing before floor placement
- Approval of subgrade relative to nature of fill, compaction, etc.
- Concrete mix proportions and field control procedures
- Staging of the HRWR and SFRC

- Monitoring the amount of steel fibers added
- Testing laboratory's role
- Column isolation details
- Timing and depth of sawing joints
- Possible use of an accelerating admixture (winter work)
- Agreement to have regular scheduling and coordination meetings on site
- Placement sequence and schedule
- Placing and finishing techniques
- Curing
- Initial protection of freshly placed slabs (construction traffic)
- Monitoring of flatness and levelness procedures and testing

**Table 1 — Mix proportions.**

|                            |             |
|----------------------------|-------------|
| Cement, ASTM C-150 Type II | 611 lb/yd³  |
| Fine aggregate (2NS sand)  | 1487 lb/yd³ |
| Coarse aggregate (1 ½ in.) | 1570 lb/yd³ |
| Water                      | 271 lb/yd³  |
| HRWR (Eucon 37)            | 73 oz/yd³   |

- Enclosure of buildings (allowing continuous pouring operations through varying ambient conditions)
- Lights (including temporary power and lighting for saw cutting operation at night)
- Underground piping, including process piping
- Mechanical and electrical contractors activity, in the truss space above, and below ground
- Coordination of process equipment delivery schedule with slab placement

### Curing

Seven days of water curing was specified for the project. The contractor used Visqueen to limit evaporation and to keep the slab wet for the required period. This method was selected by the slab committee as providing the best quality concrete floor curing.

### Concrete

The concrete mix proportions were finalized at the pre-construction meeting (Table 1). Following approval of the mix proportions, a test placement proved the mix to be workable and capable of providing the desired finish.

The design compressive strength of the floor slab concrete was 4000 psi (27.6 MPa) and the design flexural strength (modulus of rupture) for the plain concrete base bid was 550 psi (3.79 MPa). The design flexural strength (modulus of rupture) for the SFRC was 700 psi (4.83 MPa) in the paint shop and 750 psi (5.17 MPa) in the assembly and body shop. A slight increase in compressive strength with SFRC was obtained, but the increase in flexural strength was much more significant.

### Subgrade

Calculations for concrete stress under fork truck and process post loads were based on a subgrade modulus (k) of 100 lb/in.³ (27.15 MPa/m).

The subgrade at the site, which had been used for industrial purposes for many years, was less than ideal. Chemical contamination was found throughout the plant construction area, and this material could not be removed from the site. There were strong practical and economic reasons to leave the existing materials in place, which resulted in an inconsistent subgrade modulus and some concern that cracking could occur. The increased modulus of rupture and toughness made SFRC a desirable alternative to a conventional plain concrete floor.

### Flatness and finish

Floor flatness and levelness were specified by F-Numbers. The required  $F_F$  was 25 with a minimum local value (MLV) of 17, and the required  $F_L$  was 17 with a MLV of 11. These F-Numbers correspond to approximately ¼ inch in 10 feet using the gap-under-a-straightedge system. A cost penalty for failing to meet the criteria was specified, but the contractor had no difficulty in achieving the required results.

The slab committee did not assume that steel fibers would improve the wearability of the floor. Traprock aggregate hardener was used in heavily-trafficked locations such as the truck dock and rack storage areas, and a liquid densifier (Ashford Formula Concrete Treatment) was used elsewhere.

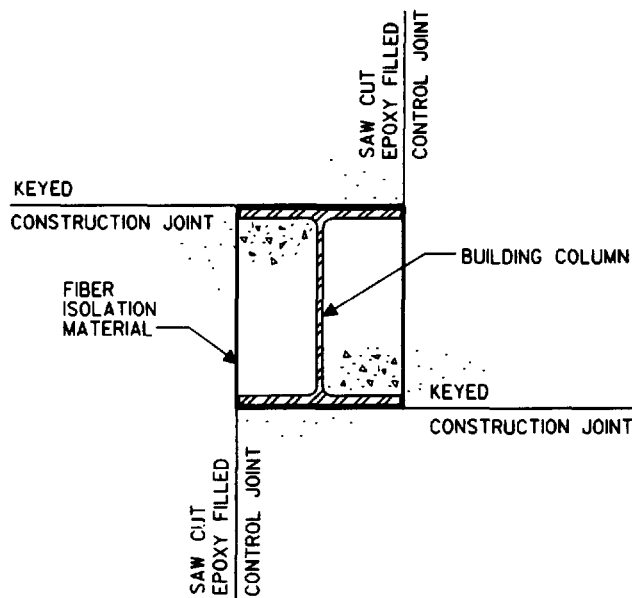


Fig. 1 — Pinwheel joint pattern at columns.

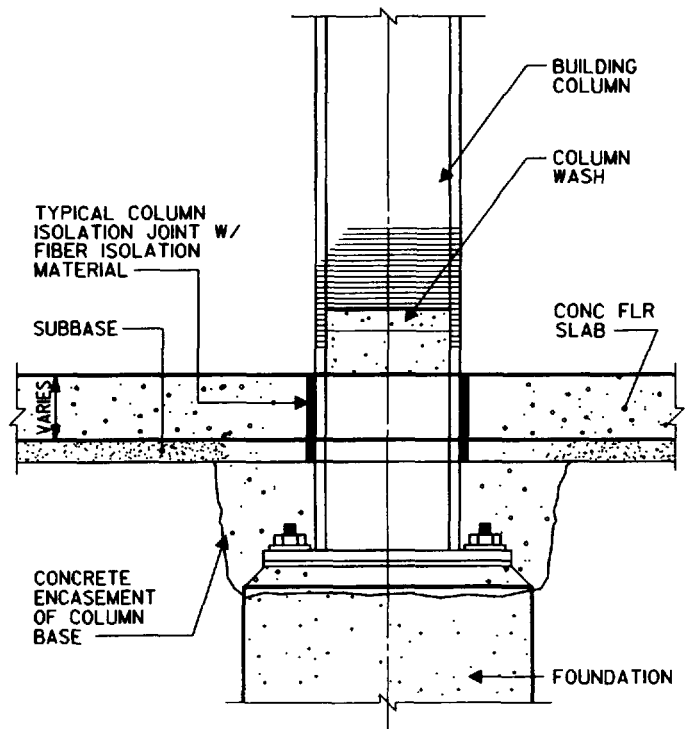


Fig. 2 — Column isolation joint.

## Joints

Pinwheel joint patterns (Fig. 1 and 2) were used at each column to eliminate the diamond or circular column isolation joint patterns generally used in industrial floors, which are an additional expense and can become a maintenance problem due to edge spalling from fork truck traffic. Using the pinwheel pattern also eliminated one step in construction and produced a much cleaner detail at the columns.

Saw-cut control joints divided the long-lanes into relatively square sections. Control joints in SFRC slabs need to be one-third the slab depth to ensure that shrinkage cracks will occur only along the joint. The width of cut was approximately  $\frac{1}{8}$  in (3.2 mm) to enable the joints to be correctly filled with a flexible epoxy (Fig. 3). To allow the saw blade to cut cleanly and joint cutting to be completed before random shrinkage cracks could occur, cutting was usually scheduled for between 8 and 12 hours after the concrete was placed.

Construction joints on the sides and ends of each lane were the A/E's special "inverted key" detail (Fig. 4), in which the male end of the keyway is formed first. On industrial floors, joint forms are nor-

mally stripped very early to prepare for the next placement. Damage to the top edge of the key due to stripping operations or accidental construction traffic loading is eliminated with the inverted key detail, which has been very successful on other projects for Chrysler Corporation and is less costly than steel dowels.

## Cost

Costs for the Jefferson North facility floor slabs have been averaging \$3.20/ft<sup>2</sup>, including final subgrade preparation and 4 in. (102 mm) of sand fill. Cost differences between the SFRC floor and a conventional concrete automotive industrial floor are summarized in Table 2. The construction cost savings for increased joint spacings are included.

The increase in cost for the paint shop floor was justified by the increased process and truck loading capacity provided by the SFRC design. An offsetting cost savings was realized in the process equipment installation contract. The increased flexural capacity of the SFRC floor allowed the process equipment to be delivered inside the plant on heavy roadway trucks, eliminating one handling operation. The conventional, non-reinforced, 6 in. (152

mm) thick slab design would not have allowed this.

Our investigation showed that the net cost of the steel fibers is typically less than the costs associated with the purchase and installation of steel mesh. Additional cost benefits can be derived from the reduced slab thickness and number of control joints. On the Jefferson North project, the use of SFRC made it possible to place most of the concrete using trucks, which contributed to the significant schedule gains achieved. Pumping was only needed for miscellaneous and inaccessible areas. If the slabs had been conventionally reinforced, truck discharge would have been precluded for at least half the floor area.

## Construction

A major emphasis was placed on curing procedure and timing, and the depth and timing of joint sawing. Use of Soff-Cut equipment, which allows early saw cutting, was discussed in order to address the timing issue, but was not used because the maximum depth of cut would not meet the D/3 requirement for SFRC.

To eliminate concern over amount of fibers being added to the concrete, it was mutually agreed

**Table 2 — Cost comparison between SFRC and conventional concrete floor.**

| Plant area        | Conventional design |                                     | SFRC alternative |                       | Cost difference for SFRC \$/ft <sup>2</sup> |
|-------------------|---------------------|-------------------------------------|------------------|-----------------------|---------------------------------------------|
|                   | Thickness           | Reinforcement                       | Thickness        | Reinforcement         |                                             |
| Paint building    | 6 in.               | —                                   | 5 in.            | 50 lb/yd <sup>3</sup> | +0.21                                       |
| Assembly building | 6 in.               | —                                   | 5 in.            | 50 lb/yd <sup>3</sup> | +0.19                                       |
| Body shop         | 8 in.               | #4 @ 12 in. O.C. or equivalent mesh | 6 1/2 in.        | 50 lb/yd <sup>3</sup> | -0.78                                       |

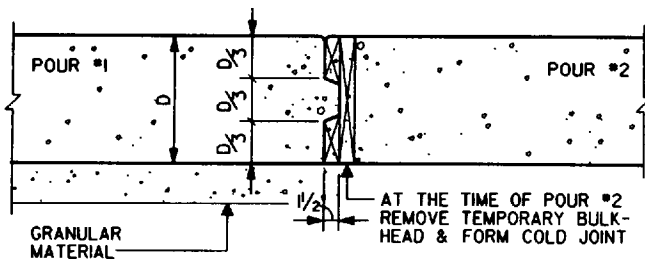


Fig. 3 — Floor slab construction joint.

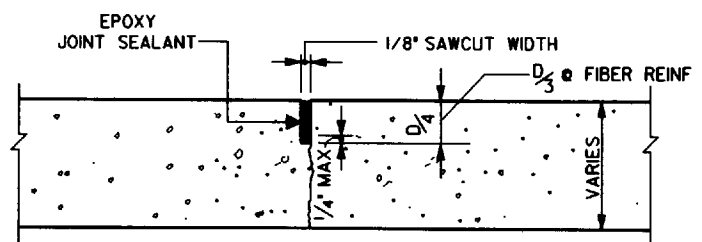


Fig. 4 — Floor slab control joint.

that all concrete trucks would have the same load — 10 yd<sup>3</sup> (0.76 m<sup>3</sup>) — so that the same number of 50 lb (22.7 kg) bags of steel fibers would be added to each load of concrete. This had a tremendous impact on the job: it ensured design conformance, improved concrete consistency at point of placement, eliminated confusion, accelerated the staging process, and guaranteed daily concrete production.

The first 1.1 million ft<sup>2</sup> (102,000 m<sup>2</sup>) of floor slab was constructed over 94 working days between July 30 and December 7, 1990. The contractor's original schedule was based on placing and finishing the floor slabs during 80 "pouring" days; the actual work schedule was 83 days. Floor slab production averaged approximately 13,500 ft<sup>2</sup> (1250 m<sup>2</sup>) per day. The largest placement was 28,000 ft<sup>2</sup> (2600 m<sup>2</sup>).

In keeping with the quality assurance program developed early in the project and finalized at the pre-construction meeting, the consistency of the concrete was closely monitored, along with the handling of beams for flexural tests and cylinders for daily field control. Appropriate concrete staging areas were established to ensure the expedient unloading of concrete once the truck was in place, avoiding any

unnecessary delays. All placing and finishing procedures and techniques followed practices recommended by ACI.

## Conclusion

The teamwork and cooperation between the committee members, contractor, suppliers, and field personnel resulted in a top-quality industrial floor. The slab preconstruction meeting was a major factor in achieving the desired results.

The net result of using SFRC has been very positive: excellent crack control was achieved at reduced cost. As the floor work on this project nears completion, all participants in the slab committee — owner, architect/engineer, construction manager, and contractor — agree that the use of steel fibers will be a consideration on future work. As competition increases between manufacturers of fibers and more concrete contractors gain practical experience with the use of steel fibers, costs are expected to decrease. This, combined with construction schedule improvements and reductions in the number of joints that owners must maintain, makes SFRC an attractive alternative to conventional industrial slab-on-grade designs.

Selected for reader interest by the editors.

ACI member **Chuck Robinson** is Vice President, Corporate Director, and Chief Structural Engineer with Albert Kahn Associates, Inc., Detroit, Mich. He has an MSc in Civil Engineering from Wayne State University, Detroit.



ACI member **Angelo Colasanti**, CEO of Colasanti Corporation, Roseville, Mich., is a member of ACI Committee 302, Concrete Floor Construction. The Colasanti Corporation, which began 38 years ago as a finishing contractor, is now a specialist in total concrete systems.



**Gary Boyd** is Project Engineer, Advance Manufacturing Operations, with the Chrysler Corporation, Highland Park, Mich. In addition to the Jefferson North Assembly Plant he has worked on four other Chrysler assembly plants.



Use of steel fiber reinforced concrete  
has advanced substantially in the last decade

# Applications of Steel Fiber Reinforced Concrete

by Gary L. Vondran

**S**teel reinforcement in the form of mesh and bars was first patented in France by Joseph Monier in 1867. Steel fibers, as we know them today, were first patented in the United States by James Romualdi and Battelle Development Corporation in 1962. Besides Romualdi's work, research in the early 1960s by Batson, Heneger, Lankard, Ramakrishnan, Shrader, Shah, Swamy, Zollo, and many others has led to industry acceptance of steel fiber reinforced concrete (SFRC) for many applications. Through their dedicated research, SFRC has matured into a proven concrete building material.

Throughout the ages, material engineering seems to parallel attempts at stopping and evading the consequences of structural cracks. Most of this engineering was, and is today, empirical. Concrete designers noted that cracks occurred at certain stress points, and in their next design used more reinforcing to stop it.

Concrete is the number one structural material in the world, with annual production of over six billion tons. For a variety of reasons, much of this concrete is cracked. The cause of concrete cracks can be structural or economic, but many cracks are due to the inherent tensile weakness of the material. As concrete shrinks, and if it is restrained, it will crack. Steel fiber reinforcement offers a solution to the problem of cracking by making concrete tougher and more ductile.

## Technical background

Engineers, testing laboratories, universities, concrete producers, and fiber manufacturers have tested SFRC for various physical properties. Concrete reinforced with steel fibers that meet ASTM A 820 standards for Type I cold drawn crimped wire segment with an average tensile strength of 180,000 psi (1200 MPa) can have up to twice the modulus of rupture, shear strength, torsional strength, and fatigue endurance; up to 1.4 times the abrasion and erosion resistance; and up to 5 times the impact energy absorption of plain concrete.

Most steel fibers on the market today have little effect on the modulus of elasticity, creep, poisson's ratio, compressive strength, and electrical conductivity. Adding steel fibers at the rate of 17 to 150 lb/yd<sup>3</sup> (10 to 89 kg/m<sup>3</sup>, or up to 1.1 percent volume) slightly increases the density of concrete. Curling of SFRC slabs on grade for a given cement factor, water content, and slab thickness is not much different than for equivalent plain concrete exposed to the same thermal and moisture gradients.<sup>1</sup>

## Durability

Fibers in general do not change the permeability that is due to concrete's porosity, but do decrease the permeability that is due to cracking. Steel fibers prevent microcracks from becoming working cracks, and thus protect the porous concrete from further aggressive environmental attack. Numerous

bridge decks exposed to deicing chemicals, sea walls, and precast concrete breakwaters attest to the superior durability of SFRC.<sup>2</sup>

Steel fibers rust only on the concrete surface. The amount of surface oxidation is very minimal, since the composite is about 99 percent concrete and insulates the individual discrete fibers with a passive skin of cement paste. The surface oxidation has no structural effect,<sup>3,4</sup> and the only cosmetic discoloration is an occasional surface freckle.

The corrosion behavior of SFRC is very different from concrete reinforced with steel bars. Galvanic corrosion in reinforced concrete depends on the development of electrochemical corrosion cells in which the steel forms a conduit along which electrons migrate from the anode (where the corrosion takes place) to the cathode.

A corrosion cell can develop whenever sufficiently dissimilar conditions exist to produce a cathode and an anode. It is much easier for one large corrosion cell to develop incorporating a section of rebar that is continuous over a relatively long distance than for many small corrosion cells to develop incorporating discrete steel fibers. Also, when fibers do corrode they do not exert a strong enough expansive force to disrupt the concrete.<sup>5,6</sup> Consequently, SFRC remains strong even at the surface where corrosive elements permeate.

With concrete containing both steel fiber and conventional reinforcement, called **Documents**



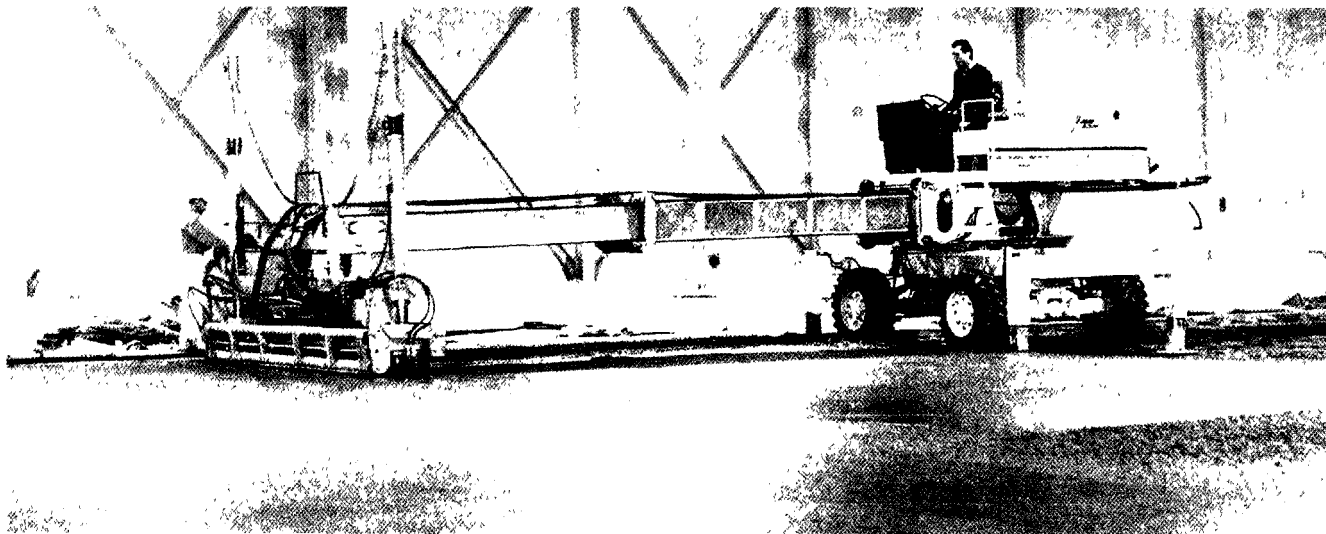


Fig. 1 — SFRC placed using laser screed.

reinforced concrete (FR-RC), cracking of the concrete cover over the structural steel rebars is controlled by the steel fibers.

### Mix proportions

The above-mentioned advantages of SFRC assume that good concrete mixes employing proven concrete materials are used. The use of 17 to 100 lb/yd<sup>3</sup> (10 to 59 kg/m<sup>3</sup>) of crimped cold drawn steel wire segment fibers normally does not require major mix adjustments. When higher fiber concentrations are used, a fiber factor mix proportion adjustment is sometimes necessary to accommodate the higher surface area of the fibers with additional cement paste. Normally it is necessary for quality control (QC) purposes to proportion a mix to meet compressive strength requirements. This is equally true for SFRC, even though the fibers contribute little to compressive strength. When adjustments are necessary it is always practical to rely on the local concrete producers quality control engineer. When a QC engineer is not available, follow ACI 211 to adjust for workability, placeability, appearance, and strength. Fiber factor adjustments are necessary when using 2 in. (51 mm) steel fibers in quantities exceeding 100 lb/yd<sup>3</sup> (59 kg/m<sup>3</sup>) that affect consistency or slump.

### Slump

Some researchers look at slump as an exact measure. Many also report that adding fibers to concrete re-

duces the slump. However, variations in weather conditions, air content, aggregate gradations, and moisture content play a much more important role in altering slump in a batch-to-batch comparison<sup>7</sup> than addition of 17 to 100 lb/yd<sup>3</sup> (10 to 59 kg/m<sup>3</sup>) of steel fibers. When designing a fibrous concrete mixture with a given set of materials in accordance with ACI 211, the slump can be very stiff at 0 to 2 in. (0 to 51 mm) or plasticized to 6 to 10 in. (150 to 250 mm).

Even though it is widely used in the field, the uniformity or repeatability of the slump test is not precise. ASTM C 143, "Test Method for Slump of Portland Cement Concrete," does not have a precision statement. In "Interpreting the Slump Test," Jim Shilstone writes, "It should be constantly recalled that the slump test is merely an indicator of batch consistency. Nothing more should be interpreted."<sup>8</sup> This is equally true of SFRC.

### Mixing, placing, finishing

Most SFRC uses ordinary mixing, placing and finishing methods and equipment.

Steel fibers can be added before, after, or during the batching sequence of charging the concrete materials. If balling occurs, it is usually eliminated by altering the batch sequence much in the same manner that concrete producers eliminate cement balling.

Placing SFRC may require a little more energy, but SFRC responds well to wet screeding and vibratory

screeds, commonly used for flat work. The laser screed is very efficient for placing and finishing very large volumes of SFRC (Fig. 1).

When the concrete is vibrated or floated, the steel fibers sink down in the slab, leaving a virtually fiber-free surface. When using internal vibrators, one may have to make changes in the vibrating methods to minimize fiber-free zones. When pumping SFRC, rubber elbows in the lines should be avoided and steel elbows used instead; flexible lines are fine for the end discharge lines.

SFRC can be finished using conventional techniques. Most surface textures attainable with regular concrete can be obtained with SFRC, including floated, broomed, jitter buggy, roller buggy, slip-formed, roller compacted, dry shake hardened, shot textured, formed, and stamp patterned, as well as any number of hand and machine trowelled or burnish finishes. Tyned and burlap-dragged finishes require some adjustments in finishing technique so as not to rake fibers across the surface (e.g., tilting a tyning rake at 30 degrees will usually produce a satisfactory finish). Vibrating screeds, magnesium bull floats, and magnesium hand floats are essential tools for achieving a variety of desired SFRC finishes. At higher fiber concentrations, dry shake hardeners are an effective means of providing a non-fiber finish. For steel fiber reinforced shotcrete (SFRC), a plain final flash coat is effective in producing a regular finish.

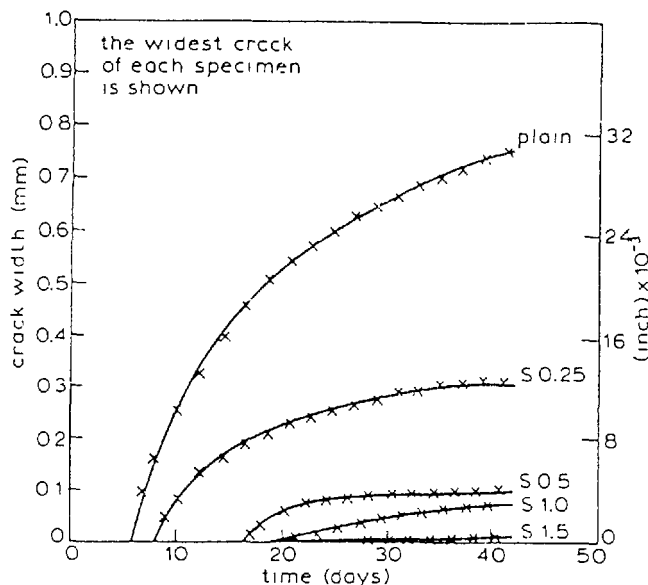


Fig. 2 — Crack width versus time for various fiber volumes.

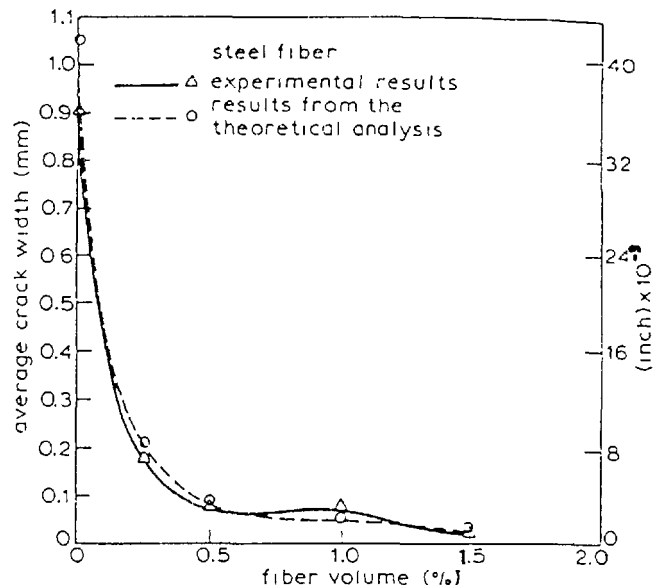


Fig. 3 — Average crack width versus steel fiber volume percentages.

## Toughness

“Toughness” is a good term for describing the post-crack behavior of SFRC and what steel fibers do to strengthen concrete. Different authorities define toughness in different ways: the Japanese Concrete Institute defines toughness in absolute terms as the energy required to deflect a FRC beam to a midpoint deflection of 1/150th of its span; ASTM C 1018 defines toughness as the energy equivalent to the area under the load deflection curve up to a specified deflection. Cold drawn steel crimped wire fiber, when tested according to ASTM C 1018, typically produces Toughness Index values of  $I_5 = 3$  to 5,  $I_{10} = 5$  to 9 and  $I_{30} = 11$  to 21, depending on the type, amount, and length of fibers.<sup>9</sup>

## Crack resistance

The efficiency of fibers in arresting concrete cracks was reported by Grzybowski in 1989.<sup>10</sup> He concluded that the replacement of conventional rebar with fiber reinforcement has many structural advantages, particularly where cracking is independent of loading. The reason is that with fibers the internal stresses are much more evenly distributed throughout the cross section of the structure and along the length of the in-place concrete. With conventionally reinforced concrete, large visible cracks occur. Even if a fiber reinforced concrete

structure cracks, the cracks are micro in size, or small enough to make them invisible and acceptable in width.

In research reported in 1990, Grzybowski and Shah confirmed that small amounts of steel fibers “... can substantially reduce crack widths due to restrained drying shrinkage.”<sup>11</sup> Fig. 2 shows reduction in crack widths as the fiber volume increases from 0.25 to 1.5 percent. It is interesting to note that the starting time of cracking is delayed as the fiber addition increases. Fig. 3 illustrates that the average crack widths versus plain concrete are reduced 80 percent with only 0.25 percent fibers. Even at these small percentages steel fibers increase the tensile strain capacity enough to substantially stifle crack propagation.

Grzybowski and Shah used straight steel wire fibers. Crimped or deformed steel fibers with better mechanical anchoring and bonding properties would likely show superior performance in crack resistance effectiveness.

Fiber orientation also plays an important role in minimizing cracking of concrete. Soroushian and Lee<sup>12</sup> concluded that steel fiber efficiency is due to a preferential alignment. In their study they discovered more fibers wherever a boundary exists. At the job site a boundary would be a finished or formed outermost concrete surface. When

SFRC is placed in a form, basically a box with four sides and a bottom, the fibers align along the thinnest section, which is where the reinforcing is needed the most to resist cracking.

Fig. 4 illustrates the difference between the distribution of fibers and rebar in slabs. In the middle of a section of mass concrete the fibers are oriented randomly, but in a slab the fibers tend to orient themselves horizontally, especially in the top and bottom surfaces. This is due to the placing and finishing operations in flatwork, which knock the fibers down into a horizontal position, and to the effect of gravity. This automatic horizontal alignment contributes to the ability of fibers to control cracking at the slab surface.

Replacing non-structural conventional steel rebar or wire mesh with SFRC eliminates the time consum-

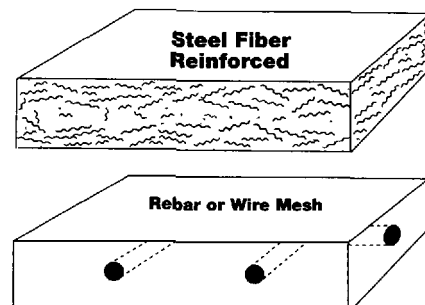


Fig. 4 — Comparison of fibers and rebar in slabs

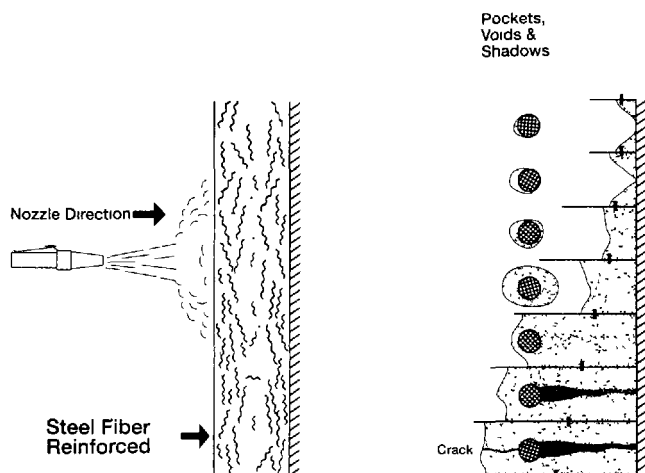


Fig. 5 — Comparison of fibers and rebar in shotcrete.

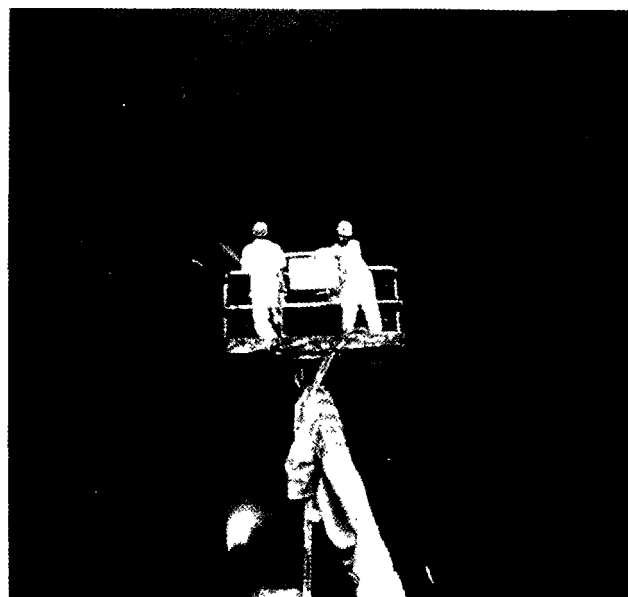


Fig. 6 — Replacing wooden tunnel lining with SFRC.

ing work of placing rebars and cuts down on construction time. This time savings along with the ability to produce concrete with smaller (and in many cases no visible) cracks is why SFRC is becoming more widely used.

## Practical applications

### Shotcrete

Shotcrete mixes are generally oversanded and therefore require high cement percentages, which leads to increased shrinkage cracking. Also, thin section shotcrete on irregular surfaces, much of which is placed vertically and is difficult to properly cure, has a high tendency to crack. Steel fibers are an economical and practical way of reinforcing both wet and dry mix shotcrete to control cracking.

In Fig. 5 the differences between two methods of reinforcing shotcrete are compared, one with steel fibers and the other with rebar. When shotcreting through rebar or wire mesh reinforcement, air voids, sand pockets or what are commonly called “shadows” occur. Shadows can lead to pattern surface cracks and corrosion problems. Time consuming attention by experienced nozzle men is needed to correctly place shotcrete around rebar. With SFRC, the reinforcing is shot with the concrete, thus eliminating the shadow problem<sup>6</sup> and speeding up production. SFRC provides more uniform reinforcement

throughout the entire shotcrete mass, thus allowing for thinner sections on very irregular surfaces as shown in Fig. 6.

A typical blasted rock tunnel is very irregular and it is difficult to bend bar or mesh reinforcement to the contours of the surfaces. With SFRC a uniform steel reinforced shotcrete can be quickly applied as support lining. SFRC has been successfully used to repair dams, spillways, spilling basins, caissons, bulkheads, culverts, piers, locks, inverts, piles, columns, water tanks, aqueducts, tunnels, and refractories. The successful repair work has led to SFRC specifications for new construction of the same group of structures.

### Precast concrete

Precast concrete producers are using SFRC to eliminate pattern cracking, reduce chipping and cracking in handling units, increase performance in corrosive environments, resist thermal shock and impact, and minimize cracking in casting beds.

The precast dolosse (twisted H units) in Fig. 7 show what can be done with SFRC. In the 1970s the U.S. Army Corps of Engineers used 80 to 120 lb/yd<sup>3</sup> (47 to 71 kg/m<sup>3</sup>) of steel fibers as the only reinforcement in these massive, 42-ton (38 Mg) units. When transported to the breakwater site, only two out of the 600 units fractured. The Corps also tried conventional rebar to rein-

force the dolosse, but the pounding surf caused the concrete cover over the rebar to crack, leading to salt water intrusion and accelerated corrosion of the rebar; within a few years 80 percent of the rebar units disintegrated. The Corps has monitored these SFRC units periodically and have found them to be structurally sound and durable in this harsh environment. After 14 years exposure in the Pacific Ocean, the Corps concluded that “... the fiber reinforced concrete is in good condition. No visual signs of fiber corrosion were evident.”<sup>14</sup> Other similar applications of SFRC precast units confirm this durability.

Many different sizes and shapes of precast units are utilizing SFRC to eliminate congested steel rebar and mesh. The mining crib block industry has used steel fibers since the 1960s for post-failure toughness. SFRC crib blocks do not crumble like ordinary concrete and offer greater safety and economy in mine roof support systems. Many other SFRC precasters are developing innovative applications that perform better at lower costs.

### Concrete slabs

The primary SFRC slab applications are for factory floors, industrial floors where damaging dynamic and concentrated loads require added reinforcing, commercial floors where crack and fatigue resistance is needed, and composite metal deck/SFRC floors. Precast

uses include highways, roads, parking areas, bridge decks, thin-bonded overlays, airport runways, taxiways, aprons, and truck weight stations.

### Industrial floors

Most industrial and commercial slabs-on-grade are subjected to severe conditions. One such slab, a manufacturing distribution center in Missouri, used 33 lb/yd<sup>3</sup> (20 kg/m<sup>3</sup>) of steel fibers in a 5 in. (127 mm) thick 4000 psi (28,000 kPa) 240,000 ft<sup>2</sup> (22,300 m<sup>2</sup>) SFRC slab with a monolithic traprock hardener. Discharge of the concrete together with the reinforcement directly from the truck produces savings in labor and equipment: to the ready mixed concrete producer it means better turn around time efficiencies of their \$100,000+ trucks; to the contractor it means time saved by eliminating the step of placing reinforcing steel and chairs. The workplace is also safer, with no reinforcing steel to trip over.

SFRC slabs on grade should be engineered floors with the proper attention devoted to subbase preparation, concrete mix design, and a thorough analysis of loading conditions. Industries recognize the toughness of SFRC floors for assuring minimal costly downtime repairs.

### Pavements

Steel fibers have been used successfully in millions of square feet of pavements for: roads, highways, bridges, and air fields. Early concerns with joint spacing, curling, and exposed fibers have been overcome and remedied by fine tuning design thickness, joint procedures, and finishing techniques.<sup>1</sup> One such test pavement that has been closely monitored is Interstate 610 Loop South in Houston, Texas, where 2 and 3 in. (50 and 75 mm) thick bonded overlays containing 85 lb/yd<sup>3</sup> (50 kg/m<sup>3</sup>) of steel fibers were placed over a severely cracked existing concrete in 1983-84. Periodic evaluation surveys indicates good performance of the fibrous concrete with virtually no micro-cracking along longitudinal saw-cut joints. Whereas the pavement reinforced with steel mat shows D-cracking that will eventually chip

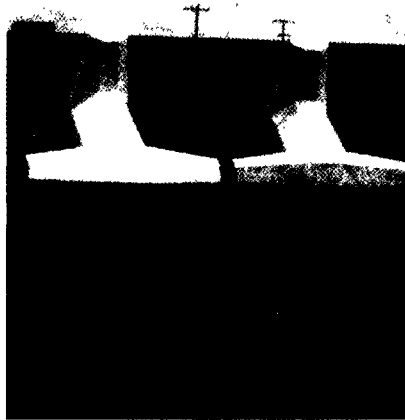


Fig. 7 — Precast SFRC breakwater units for jetty in California.

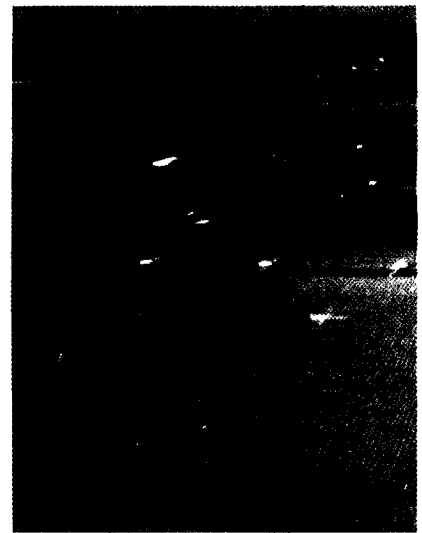


Fig. 8 — Thin bonded SFRC overlay on I-610 in Houston, Texas.

off and spall, conclusion number 16 of the report on the test overlay states "... the fiber sections proved to be far superior in their ability to control longitudinal and transverse cracking."<sup>13</sup> Notice in Fig. 8 that a tined finish is attainable and maintains a skid resistant surface with little or no cracking.

### Metal deck/SFRC floors

Steel framed buildings are using steel fibers for shrinkage/temperature control in concrete slabs on metal decks. Typically the steel fibers are replacing light gauge welded wire fabric as secondary reinforcement. SFRC is gaining acceptance among architects, structural engineers, owners, contractors and developers. Steel fibers offer the structural integrity of the steel mesh it replaces, plus the added benefit of being more efficient and ductile. Whenever floors are subjected to high frequency repetitive loadings, specifying steel fiber quantities that can handle the loads will increase their endurance limits and longevity. Metal deck/SFRC floors are not only more crack resistant but safer and more economical. Fig. 9 shows a typical metal-deck/SFRC project where the SFRC was pumped through 300 ft (91 m) of hose.

### Seismic structures

Living in earthquake zones makes one more conscious of the test a structure goes through during a severe ground shaking. The 1989

Loma Prieta Earthquake lasted 15 seconds and tested the Stanford Linear Accelerator, which used 80 lb/yd<sup>3</sup> (47 kg/m<sup>3</sup>) of steel fibers as the only reinforcing in the 4 in. (100 mm) thick [two 2 in. (50 mm) lifts] shotcrete tunnel lining. The 9000 ft (2700 m) long tunnel survived the 7.1 earthquake without any structural damage, even though the accelerator was knocked out of alignment and several million dollars worth of repairs to the equipment in the tunnel were required.

For earthquake resistant structures, SFRC produces a more damage tolerant concrete, particularly in areas where the steel rebar is highly congested at beam column joints in buildings. During an earthquake, conventional reinforced concrete first loses the concrete cover over the rebar. Pieces of concrete wedged in between the rebar crumble and fall out, causing a loss of stiffness and structural integrity. With SFRC there is very little spalling, and much more energy is needed to lose the concrete wedged in between the rebar. In SFRC the fibers add a toughness that maintains better structural stiffness. This added ductility of SFRC makes safer buildings in earthquake zones.

### Other common applications SIFCON

With slurry infiltrated fibrous concrete (SIFCON), preplaced fibers are grouted, usually in precast forms employing a vibrating table. Up to 25 percent of the volume





Fig.10 — SFRC was pumped up to 300 ft for this metal deck/SFRC floor.

bers can be incorporated using this technique; with these high steel fiber volumes the concrete acts more like steel with very high compressive, tensile, flexural, and shear strengths. It is an economical means of producing military blast resistant structures.

### Refractory

When concrete is exposed to high temperatures and fire it sometimes explodes due to expansive moisture pressure trapped in the pore structure of the concrete. SFRC performs better than mesh reinforcing as the fibers constrain the expansive and explosive pressures.

### FR-RC combinations

In those congested areas where higher tensile, shear, and flexural strengths are needed, steel fibers add a composite action in combination with less conventional rebar that is superior to reinforced concrete.

### Repair of concrete and masonry

SFRC and SFRS are being used regularly for repairing concrete and masonry structures. Steel fiber reinforcement adds the material integrity necessary to repair earthquake damage as well as deteriorated concrete and masonry that has failed due to long term environmental exposures.

### Roller compacted concrete

Roller compacted concrete (RCC) is advancing as an economical means

of placing concrete with typical grading and paving equipment. However, RCC is difficult to reinforce with conventional rebar. Steel fibers offers a simple, effective solution to reinforcing RCC.

### Conclusions

The concrete construction industry is one that produces clever approaches to practical ways of using concrete. The growth of the industry through the years is a testimonial of this ingenuity. Concrete is a very versatile building material; however, it would be used for many more applications today if it did not crack. Steel fiber technology will advance many new solutions for the cracking problem by making concrete tougher and more ductile.

Most of today's SFRC is well beyond the experimental stage of development. SFRC has been accepted by owners, government agencies, architects, engineers, specifiers, contractors, and developers for many practical applications. These proven applications of SFRC include:

- Shotcrete
- Precast concrete
- Slabs and floors
- Pavements
- Seismic structures
- Repairs

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# Steel Fiber Reinforced Shotcrete for Support of Underground Openings in Canada

by Dudley R. Morgan

The concept of support of underground openings with shotcrete is not new. As early as the 1930s Rabcewicz in Iran and Europe began using shotcrete for tunnel support, leading eventually to the development of the New Austrian Tunnelling Method (NATM). Rabcewicz and his colleagues used shotcrete in conjunction with rock bolts to produce a "rock arch" concept for tunnel support. The prime conceived purpose for the shotcrete was to prevent rock from ravelling between

rock bolts.<sup>1</sup> This simple rock support concept has since undergone considerable refinement. Sophisticated rock-mechanics approaches are now being applied to design and installation of shotcrete support systems in underground openings.

## History

Prior to the 1970s shotcrete used in underground openings was either applied plain, or it was reinforced with reinforcing steel, wire mesh, or chain link mesh. In the early 1970s the Battelle Memorial Institute's

Columbus laboratories made the first application of steel fiber reinforced shotcrete (SFRS) in North America. The first use of SFRS in a tunnel in North America was in 1972 when the U.S. Army Corps of Engineers placed SFRS in an adit at the Ririe Dam. The first experimental use of SFRS in Canada was carried out in 1977.<sup>2</sup> Further experimental evaluation was conducted by Morgan et al in 1979<sup>3</sup> to compare the performance of mesh and steel fiber reinforced shotcrete. This led to the first practical application of SFRS technology in Canada, for stabilization of a sloughing 100 m (109 yd) long railway embankment in Burnaby, B.C. in 1979. This was closely followed by the use of SFRS to rehabilitate deteriorating rock tunnels on the Canadian Pacific Railway Fraser Canyon line.<sup>4</sup>

SFRS has since enjoyed widespread usage in Canada. Hundreds of thousands of tons of the material have been used in dozens of different construction, infrastructure rehabilitation, tunnelling, mining, railway, and highway projects. Some 20 different projects in Canada that have used SFRS for underground support are listed in Reference 5. Rose<sup>1</sup> provides a review of the state-of-the-art of the use of SFRS for tunnel linings in North America. A more general overview of the state-of-the-art for SFRS world-wide, up to 1985, is provided in the US/Sweden joint seminar paper by Ramakrishnan.<sup>6</sup> Additional information is available in

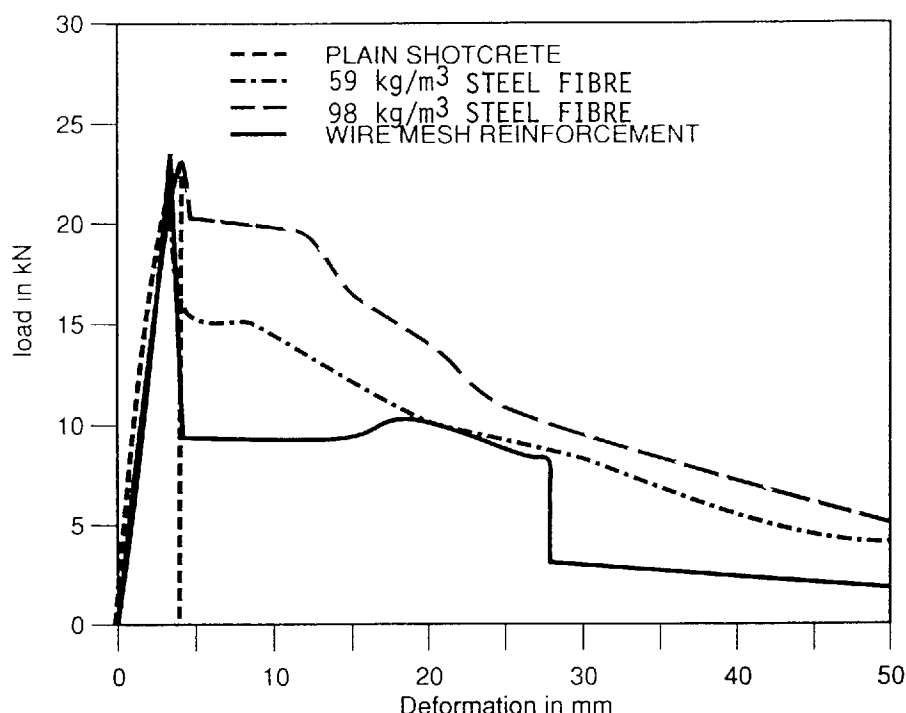


Fig. 1 — Comparison of load carrying capacity of plain, wire mesh reinforced, and steel fiber reinforced shotcretes.

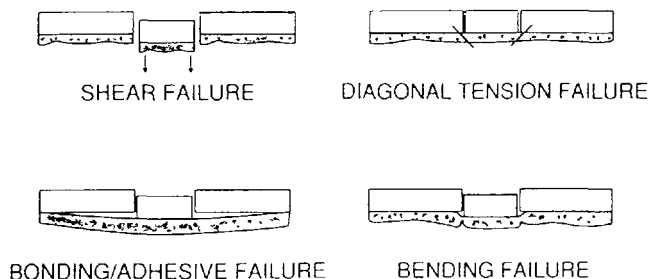


Fig. 2 — Shotcrete failure modes in simulated falling block test.

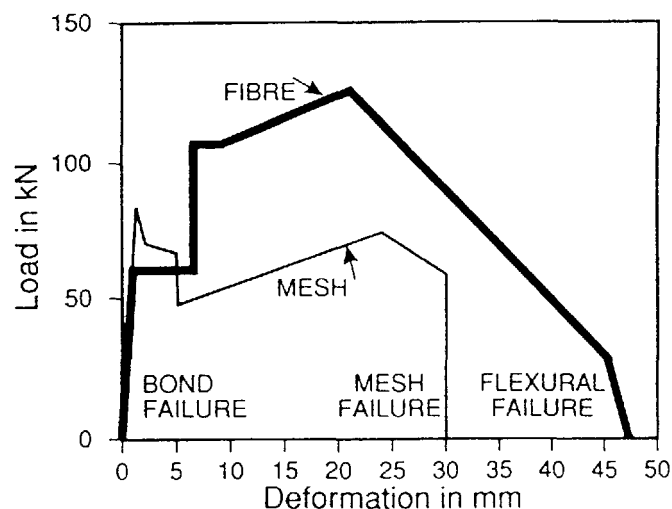


Fig. 3 — Load versus deformation behavior of wire mesh and steel fiber reinforced shotcrete in a falling block test.

506.1R-84, "State-of-the-Art Report on Fiber Reinforced Shotcrete."<sup>7</sup>

### Why use SFRS?

Plain, unreinforced shotcrete, like unreinforced concrete, is a relatively brittle material with little capacity to resist pronounced tensile stresses or strains without cracking and disruption. Steel fibers are incorporated in the shotcrete to improve its crack resistance, ductility, energy absorption, and impact resistance. Properly designed SFRS can reduce or even eliminate the cracking that is a common cause for concern in plain shotcrete.

### Mesh versus steel fibers

The question is often asked: "How does SFRS perform compared to mesh reinforced shotcrete in conditions of loading that might be experienced in applications such as support of rock slopes or underground openings?" Some limited studies at the University of Illinois and some early Scandinavian research indicated favourable performance by SFRS. In 1979 Morgan and Mowat<sup>3</sup> undertook a detailed comparative evaluation of plain, mesh and steel fiber reinforced shotcrete. The results of part of this study are illustrated in Fig. 1. They demonstrated in load/deformation tests on large panels, that SFRS can provide superior residual load carrying capacity to wire mesh reinforced shotcrete at small deformations after first crack and equivalent perform-

ance at large deformations. These conclusions were subsequently supported by the results of similar work carried out by Little<sup>8</sup> for the British Columbia Hydro and Power Authority.

Since these early studies, extensive research has been conducted in the Scandinavian countries<sup>10</sup> comparing the performance of SFRS and mesh reinforced shotcrete under simulated "falling block" tests. This test simulates the condition where a shotcrete lining is subjected to loading from loosening blocks of rock in the crown of a tunnel. Shotcrete failure occurs through one or more of the failure modes illustrated in Fig. 2, the particular mode depending on a variety of factors, including shotcrete strength and thickness, quality of bond to the substrate, and size of the displaced block. SFRS has generally shown superior performance to mesh reinforced shotcrete in such tests. Load versus deformation response in a typical falling block test is shown in Fig. 3 from Reference 9.

### Advantages of SFRS

One of the factors that makes SFRS particularly appealing to contractors is the ability to do away with the need to install wire mesh, which can be a time consuming and sometimes hazardous process. Another advantage is that SFRS can follow the exact contours of the rock, whereas mesh reinforcement often requires 50 mm (2 in.) of cover as well as filling of all the voids behind the mesh with shotcrete (Fig.

4). It is not uncommon with blocky or fractured rock surfaces to use up to 40 percent more shotcrete with mesh reinforcement than if SFRS were used.

SFRS is also free of the difficulties sometimes encountered in thoroughly encapsulating reinforcing mesh with shotcrete. Improper shooting technique can result in "shadowing" and voids behind reinforcing mesh. Such mesh reinforced shotcrete is vulnerable to the deteriorating influences of corrosion from aggressive atmospheric or groundwater exposure. "Ice-jacking" in cold weather exposure, such as is frequently encountered in tunnel and mine portal areas in Canada, is another cause of concern with improperly encapsulated mesh reinforced shotcrete. Properly applied SFRS should be free of these concerns.

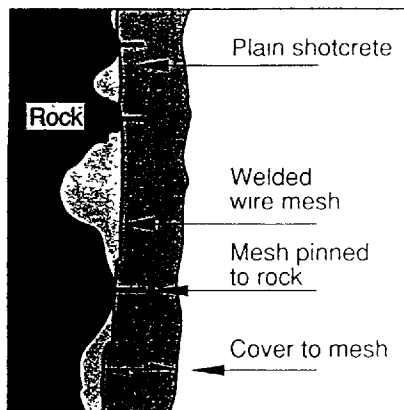
### Fiber types

There are a variety of proprietary types of steel fiber available in the North American market. A variety of processes are used for manufacturing steel fibers, including:

- cutting cold drawn wire
- slitting steel sheet
- the melt-extraction process
- milling steel blocks

The most useful parameter for describing fibers is the aspect ratio, which is defined as the length-equivalent diameter ratio. The most important aspects controlling the performance of steel fiber in shotcrete (and concrete) are the aspect

## MESH REINFORCED SHOTCRETE



## STEEL FIBRE REINFORCED SHOTCRETE

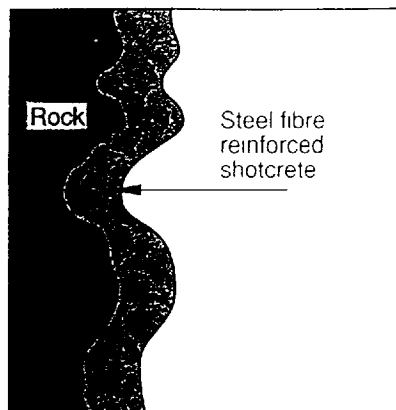


Fig. 4 — Difference in shotcrete consumption between wire mesh and steel fiber reinforced shotcrete applied to blasted rock.

ratio and volume concentration. Theoretically, the higher the aspect ratio and volume concentration of the fiber, the better the performance of the SFRS with respect to impact resistance, toughness, ductility, crack resistance, etc. Unfortunately, the higher the aspect ratio and volume concentration of the fiber, the more difficult the shotcrete becomes to mix, convey, and shoot. Thus there are practical limits to the amount of fiber that can be used in SFRS, with the amount varying with different proprietary fiber types.

In the 1970s, a wide variety of different fiber types were promoted, with fiber sizes varying from 12 x 0.25 mm ( $\frac{1}{2}$  x 0.010 in.) and an aspect ratio of 50, to 64 x 0.76 mm ( $2\frac{1}{2}$  x 0.030 in.) and an aspect ratio of 83. Most of these fibers were straight, and post-first-crack performance (as measured by the toughness test) was less than impressive. Manufacturers then devised a variety of means of improving the "effective aspect ratio" of steel fibers by techniques such as:

- crimping the fibers
- introducing bent or enlarged ends
- making special deformations on the fibers
- increasing roughness of the fiber surface texture

In the 1980s virtually no straight steel fibers were used in SFRS in Canada. The most commonly used fibers are deformed in one way or another and have typical fiber lengths of 30 to 38 mm ( $1\frac{1}{4}$  to  $1\frac{1}{2}$  in.) and aspect ratios varying from 40 to 60. Typical fiber addition

rates vary between 50 and 80 kg/m<sup>3</sup> (85 and 135 lb/yd<sup>3</sup>), with 60 kg/m<sup>3</sup> (100 lb/yd<sup>3</sup>) being commonly used in tunnelling and mining applications.<sup>10</sup>

### Shotcrete mix proportioning

Shotcrete mix proportioning is governed by the same principles that govern concrete mix proportioning (i.e., Abrams' law applies and the prime factors controlling strength and quality are the water-cement ratio, air content, and degree of consolidation achieved). There are, however, a number of considerations in mix proportioning in which shotcrete differs from conventional structural concrete, the major differences being in the aggregate gradation and cementitious content.

ACI 506R-90<sup>11</sup> provides guidance for selecting aggregate gradations for both wet and dry-mix shotcrete (Table 1). Gradation No. 1 is essentially a mortar mix, whereas shotcrete with aggregate conforming to Gradation No. 2 typically contains about 25 to 30 percent 10 mm ( $\frac{3}{8}$  in.) coarse aggregate. Gradation No. 3 contains 20 mm ( $\frac{3}{4}$  in.) maximum size aggregate and produces shotcrete that is more like conventional concrete. ACI Gradation No. 1 shotcrete (mortar mix) tends to be preferred in certain parts of North America, particularly in the Southern U.S.A. The use of mortar mixes tends to be historical, relating to the original use of mortar in the Guniting process. In Western Canada, and increasingly elsewhere in North America, for both dry and wet-mix shotcrete, the great major-

ity of engineered shotcrete construction is being performed with shotcrete conforming to ACI Gradation No. 2. ACI Gradation No. 3 shotcrete is rarely used except for mass shotcrete applications such as construction of underground bulkheads.

Fortunately, no special changes need to be made to conventional shotcrete mix proportions to utilize steel fiber. The same characteristics that are inherent in shotcrete mix proportioning (low coarse aggregate content and high cementitious materials content) are also conducive to good mixing and dispersion of fibers and indeed application and performance of the hardened SFRS. The only areas in which the shotcrete mix proportioner can really get into difficulty are: where attempts are made to cut back excessively on the cementitious content of the mix; this can lead to high total rebound, as well as excessive fiber rebound, particularly in the dry-mix process; and where fibers are used that are vulnerable to the formation of "birds nests" or balling in shotcrete mixing, transporting, and application procedures (e.g., fibers with too high an aspect ratio; too high a volume concentration of fibers; first generation straight fibers without a proper means of dispensing the fiber).

A summary of mix proportioning concepts is presented in Table 2.<sup>5</sup> Typical examples of both wet and dry-mix SFRS mix proportions, such as commonly used in tunnelling and mining projects in Canada in the 1980s, are shown in Table 3.

Water reducing admixtures and superplasticizers are not normally used in dry-mix shotcrete because they cannot be effectively activated in the short wetting time from mixing at the nozzle to impact on the wall. In fact, the addition of dry powdered superplasticizer can have disastrous consequences for dry-mix shotcrete — it can create a delayed

**Table 1 — Gradation limits for combined aggregates.<sup>11</sup>**

| Sieve Size<br>U.S. standard<br>square mesh | Percent by weight passing individual sieves |                 |                 |
|--------------------------------------------|---------------------------------------------|-----------------|-----------------|
|                                            | Gradation No. 1                             | Gradation No. 2 | Gradation No. 3 |
| ¾ in. (19 mm)                              | —                                           | —               | 100             |
| ½ in. (12 mm)                              | —                                           | 100             | 80 - 95         |
| ⅜ in. (10 mm)                              | 100                                         | 90 - 100        | 70 - 90         |
| No. 4 (4.75 mm)                            | 95 - 100                                    | 70 - 85         | 50 - 70         |
| No. 8 (2.4 mm)                             | 80 - 100                                    | 50 - 70         | 35 - 55         |
| No. 16 (1.2 mm)                            | 50 - 85                                     | 35 - 55         | 20 - 40         |
| No. 30 (600 µm)                            | 25 - 60                                     | 20 - 35         | 10 - 30         |
| No. 50 (300 µm)                            | 10 - 30                                     | 8 - 20          | 5 - 17          |
| No. 100 (150 µm)                           | 2 - 10                                      | 2 - 10          | 2 - 10          |

fluidity, causing the plastic in-place shotcrete to sag and slough. However, water reducers and superplasticizers are commonly used in high quality wet-mix SFRS. Air-entraining agents should be used in wet-mix shotcrete that will be subjected to freeze-thaw exposure, and there is some evidence (based on recent work at Laval University in Quebec) that the addition of an air-entraining agent to the mix water added at the nozzle is beneficial for the freeze-thaw durability of dry-mix shotcrete (particularly where de-icing chemicals are used).

### SFRS batching, mixing, and supply

**Dry-mix SFRS** can be batched, mixed, and supplied by any of the following processes:

- Central mixing in a rotary drum or pan mixer prior to discharge into a transit mixer, Moran car, conveyor belt, or other means of feeding the shotcrete gun.
- Transit mixing, with the fibers added directly into the ready mix truck together with the materials feed, or separately with special fiber feeders.
- Volumetric site batching with steel fibers added at the mixing auger with special fiber dispensers.
- Dry bagged premix with the steel fibers and any other special materials (dust suppressants, silica fume, dry powdered accelerators, etc.) in the bag.

Care has to be taken in dispensing the fibers to ensure that clusters or balls of fiber are not added to the mix, as these can be difficult to disperse and give rise to blockages in the gun and the formation of birds nests in the in-place shotcrete.

In Western Canada there has been some limited dry-mix transit mix SFRS batching, mixing, and supply, but most dry-mix SFRS has been supplied as dry bag premix. SFRS has typically been supplied in

**Table 2 — Summary of mix proportioning concepts.**

| Material/Property         | Comments                                                                                                                                                                                                                                                                                                                                                                                                |
|---------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Cement content            | 18 to 21% by mass of dry component.                                                                                                                                                                                                                                                                                                                                                                     |
| Silica fume               | 8 to 13% by mass of cement.                                                                                                                                                                                                                                                                                                                                                                             |
| Aggregate gradation       | ACI 506R-90, Table 2.1, Gradation No. 1, or (more commonly) No. 2.                                                                                                                                                                                                                                                                                                                                      |
| Steel fiber type          | High strength, deformed, drawn, or slit sheet steel fibre.                                                                                                                                                                                                                                                                                                                                              |
| Aspect ratio              | Length: Equivalent diameter ratio of 50-70.                                                                                                                                                                                                                                                                                                                                                             |
| Steel fiber addition rate | 50-80 kg/m <sup>3</sup> (85-135 lb/yd <sup>3</sup> ) depending on required toughness.                                                                                                                                                                                                                                                                                                                   |
| Admixtures                | 1. Water reducers used in wet-mix shotcretes at about 0.5 l/100 kg cement (8 fl.oz/100 lb cement).<br><br>2. Superplasticizers required in wet-mix silica fume shotcrete at 1 to 1.5 l/100 kg cement (16 to 24 fl.oz/100 lb cement).<br><br>3. Air entraining admixtures used in wet-mix shotcrete where freeze-thaw durability important (10 to 12% air content at pump, 4 to 6% air content as-shot). |
| Accelerator               | Dosage depends on accelerator type and required setting time (2 to 5% by mass of cement typical).                                                                                                                                                                                                                                                                                                       |
| Water-cement ratio        | 0.3 to 0.4 for dry-mix shotcrete.<br>0.4 to 0.5 for wet-mix shotcrete.                                                                                                                                                                                                                                                                                                                                  |
| Slump                     | 40 to 100 mm (1½ to 4 in.) for wet-mix shotcrete.                                                                                                                                                                                                                                                                                                                                                       |

30 kg (66 lb) paper bags on pallets, or in 1600 kg (3520 lb) bulk bin bags.

**Wet-mix SFRS** can be batched, mixed, and supplied by essentially the same processes suitable for supply of conventional concrete (i.e. it can be central-mixed or transit-mixed, or volume-batched on site using mobile mixer units or other suitable equipment). The bulk of wet-mix SFRS used in Canada has been either central or transit-mixed, with the steel fibers being added either at the batch plant during charging of the other ingredients or separately to the transit mixer at the job site.

Unlike some of the earlier generation straight fiber types (particu-

larly those with higher aspect ratios) that could be quite difficult to disperse, most current generation deformed fibers are designed so that they can be added directly to the back of a transit mixer at the job site and thoroughly dispersed without balling.

Particular care has to be taken when adding steel fibers to avoid the temptation to excessively retemper the shotcrete with water. SFRS will appear much stiffer than conventional plain shotcrete and will show much lower slump after fiber addition when tested using the standard slump test. But visual appearance and the slump test are not good indicators of the true workability of SFRS — mixes that appear stiff and have low slump can be