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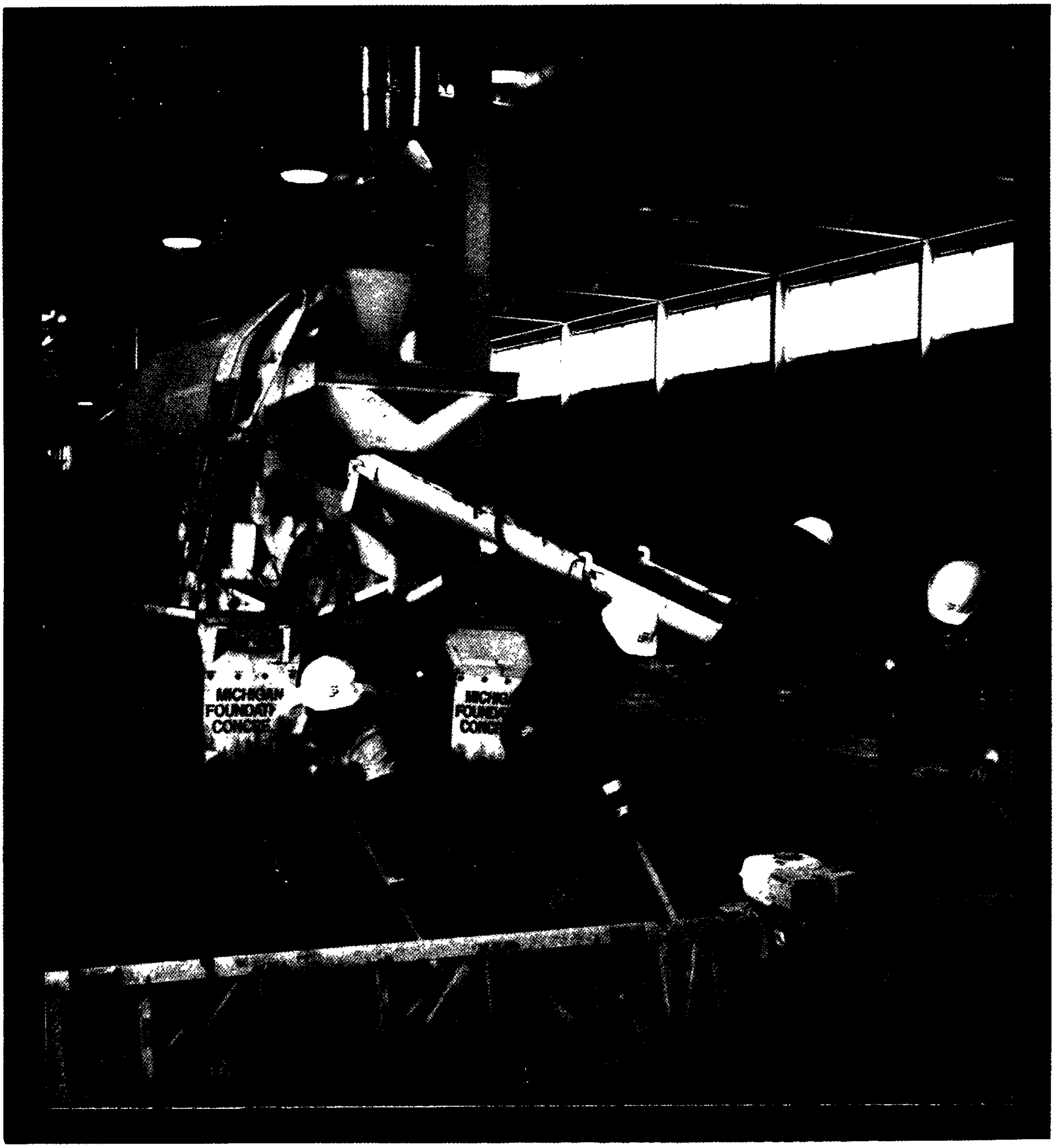
STEEL FIBER REINFORCED CONCRETE



Compilation 27

American Concrete Institute

Steel Fiber Reinforced Concrete

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Contents

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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Steel Fiber Reinforced Concrete in Industrial Floors

By P. C. Tatnall and L. Kuitenbrouwer

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^2 (2.5 million m^2) of the concrete floors constructed in 1991 contain steel fiber reinforcement. In Europe, over 320 million ft^2 (25 million m^2) 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.[1]

Practical experience is available with SFRC floors that have been in service for many years. Kowledge 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.[2]

In fact, standards covering traditional concrete floor design are also limited. France has its "Regles Professionnelles" (revised in 1990),[3] and in the United Kingdom there is "Technical Report 34," published by the Concrete Society in 1988.[4] 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^3, or 78 kg/m^3) 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[5] and JSCE-SF4,[6] 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 occurence 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

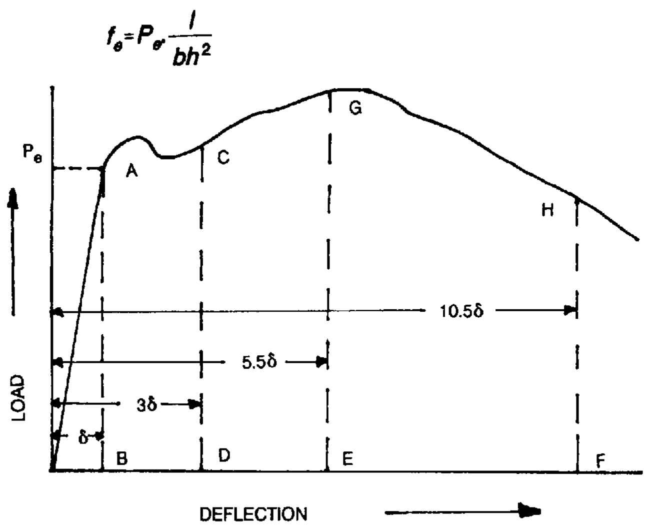

Fig. 1 — ASTM C 1080 test method.

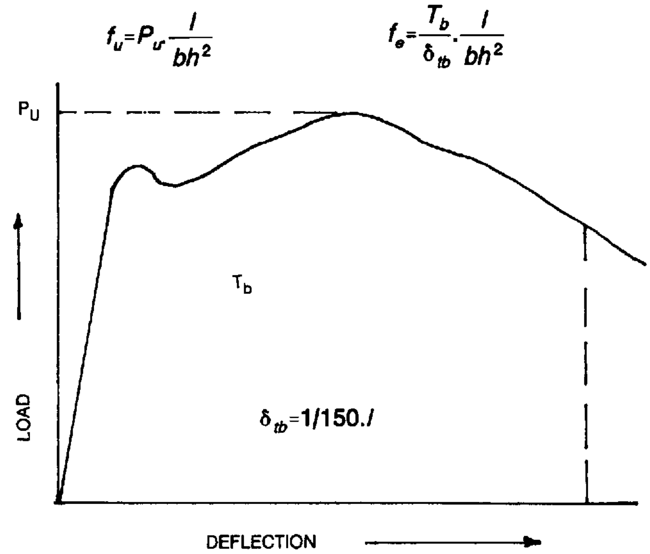

Fig. 2 — JSCE SF-4 test method.

fibers. However, each series contained 50 lb/yd^3 (30 kg/m^3), with one additional series containing 34 lb/yd^3 (20 kg/m^3).[7] 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^3 (20 to 30 kg/m^3) — and to four-point bending tests on prismatic test specimens. The test results show that:

- The flexural strength at first crack *fo* is not dependent on the fiber type or the quantity added. This is confirmed in the other test series with fibers of different origin.[7]
- The post-crack behavior, characterized by the equivalent flexural strength *fe*, 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.[8]

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^3 (30 kg/m^3), there is an increase in first-peak load of 18 percent relative to the non-fibrous slabs. For an addition of 34 lb/yd^3 (20 kg/m^3), 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^3 (20, 25, and 30 kg/m^3), 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^3 (30 kg/m^3) 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.[9] 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^3	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%

Table 2 — Imperial College supported slab tests

Quantity, lb/yd^3	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.

2.25 kip (10 kN) increments, and slab deflelction 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^3 (20 kg/m^3), and when fiber No. 3 is used at 34 lb/yd^3 (20 kg/m^3) the maximum load virtually doubles. It can reasonably be expected that a test carried out to the maximum with 50 lb/yd^3 (30 kg/m^3) 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^3 (20 kg/m^3) of fiber No. 2, the load is 17 percent higher; at 50 lb/yd^3 (30 kg/m^3) 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.[9] Both floors were cast with SFRC with 50 lb/yd^3 (30 kg/m^3) 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. 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

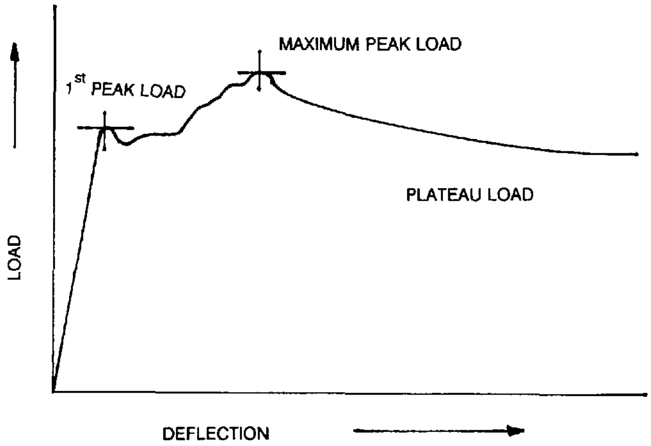

Fig. 3 — Typical load-deflection relationship for Imperial College steel fiber reinforced slabs.

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^3	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 critera 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.[9]

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[6] 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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