Current Research and Applications of Fiber Reinforced Concrete Composites in India

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Cement and concrete matrices reinforced with randomly oriented short fibers are finding increasing applications in both precast and in situ concrete construction. Fibers made of steel, polypropylene, and glass are already being used in load-bearing structural members; attention is turning now to using organic and natural fibers as macroreinforcement in cement and concrete matrices. Research and developmental work in fiber reinforced concrete composites began in India in the early 1970s. Fiber concrete technology is no longer confined to laboratory experiments—it is used in the production of precast concrete components and for in situ strengthening and repairs of concrete structures. Current applications are for flooring and roofing components, pipes, manhole covers and frames, precast thin-wall elements, construction of blast-resistant structures, and currency vaults.

The behavior of fiber reinforced concrete (FRC) composites subjected to combined static loads and to impact, dynamic, and blast loads has been studied by researchers in India for quite some time. Work is under way too on the development of polymer-impregnated fiber reinforced concrete and fibrous ferroconcrete, with which precast concrete components can be produced to meet specific functional and strength requirements. A great deal of work has also been carried out in developing precast roofing units, particularly for housing, using natural fibers. This paper describes some of these current research efforts and applications for FRC composites in India.

BACKGROUND

Combining two or more materials to obtain a composite is not new to the civil engineer. Natural fibers such as straw have long been used in brickmaking to modify and improve the properties of the brittle matrix. The concept behind FRC is that the deformation of the matrix under stress will transfer the load to the fibers. (Asbestos cement roofing sheets, used for more than six decades, are one example of a cement composite in which fibers play an important role in improving the strength and deformation properties of the cement matrix.) But to realize substantial improvements in the composites' static, dynamic, and impact strength properties, the added fibers must be strong and possess good bonding properties.

Fibers have been produced in various shapes and sizes from steel, carbon, glass, polypropylene, nylon, rayon, polyethylene, and asbestos, as well as from cotton, coir, sisal, and other natural fibers. Low-modulus fibers such as nylon and polypropylene may not lead to significant improvement in composite strength, but they do help absorb huge amounts of energy and resist impact and shock loading. For structural applications using concrete, however, steel and glass fibers are usually used since they possess a high modulus of elasticity and lead to strong, stiff composites.

How much high-modulus steel and other fibers can strengthen composites depends on the strength characteristics of the fibers themselves, the bond in the matrix-fiber interface, the ductility of fibers, the volume of fiber reinforcement and its spacing, the dispersion of orientation of fibers, and their shapes and aspect ratios. High-strength fibers, a large volume of fibers, longer fibers, and small-diameter fibers each improve the strength of the composites.

Research and developmental work on FRC composites started in India in the early 1970s. The analytical and experimental investigations carried out during that time were confined mostly to the use of steel fibers (*1–5*). Interest in fibers such as polypropylene and polymer-impregnated glass fibers and natural fibers such as coir or cotton arose later; investigations covering their use for specific applications have been detailed in several publications.

Steel fibers are not yet produced on a commercial scale in India, although plans for their manufacture, in collaboration with U.S. fiber manufacturers, are under way. Fibers must therefore be obtained from wire coils. The usual procedure is to straighten the coil and chop it into small lengths, producing plain, smooth, round fibers with diameters from 0.4 to 1.5 mm. (Some investigators, however, have used black annealed steel binding wires to produce fibers with diameters ranging from 0.5 to 2.0 mm.) Most investigations of steel fiber reinforced concrete (SFRC) in India therefore address only such plain steel fibers or wires.

Natural fibers, such as coir and bamboo, and synthetic fibers, such as nylon and polypropylene, have also been used in India for the production of roofing sheets and other housing structural components. Alkali-resistant glass fibers are not now being produced in India, so the use of glass fibers in concrete is precluded. Nevertheless, the properties of glass fiber reinforced resin composites, both with and without polymer impregnation, have been investigated; the experimental test results are promising (*6,7*).

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STUDIES ON STEEL FIBER REINFORCED CONCRETE STRUCTURAL ELEMENTS

Several studies have addressed the flexural behavior of steel fiber reinforced concrete (SRFC) beams, focusing particularly on improvements in cracking resistance, stiffness, and ductility. Other improvements attributable to the addition of steel fibers, for instance, in shear capacity, impact resistance, resistance to abrasion, and energy absorption, have also been noted by investigators. Early investigations carried out at the Structural Engineering Research Centre, Madras (hereafter SERC), studied improvements in the properties of concrete when plain steel wires were randomly distributed with an aspect ratio of about 100 (*1*,*2*). More recently investigations were conducted on the behavior of SFRC beams provided with equal tension and compression reinforcement (*8*).

The SERC investigation employed test beams 200 by 100 mm, with an effective span of 2060 mm, which were designed to avoid shear failure. Steel fibers 40-mm long and 0.4 mm in diameter were used, with the percentage of fiber in the composite varying from 0.5 to 1.0, by volume. The concrete used was M-20 grade (cube compressive strength of 20 N/mm^2). Details of the test beams are presented in Table 1.

SERC experiments on the beams revealed that SFRC beams have much better load distribution characteristics than do normal reinforced concrete beams. Experimental data led to empirical expressions for determining the static rigidity of beams subjected to differing levels of bending moments. The SFRC beams were found to fail by the rupture of tensile steel preceded by large rotation and deflection similar to laced reinforced concrete beams, thereby establishing their potential for use in the design of blast-resistant structural elements.

SERC also examined the dynamic behavior of SFRC beams by varying the percentages of steel fibers and the main reinforcing steel (*9*). Test beams with cross sections measuring 100 by 200 mm were cast with equal tension and compression reinforcement. They were subjected successively to steady-state forced vibration tests after they were loaded to particular static loads that simulated different levels of cracking. A schematic diagram of the dynamic test set-up is shown in Figure 1. Dynamic flexural rigidity (EI_d) and damping (ξ) were determined from the data collected from the tests.

Tests showed that the dynamic stiffness of SFRC beams in the uncracked state was only marginally higher (about 15 percent for a fiber-volume content of 1 percent) than for reinforced concrete beams. However, the increase in stiffness in the post-cracking stage was larger; it was nearly the same for all the fiber volumes studied (0.5 to 1.0 percent). In addition, the damping values exhibited by SFRC beams showed significant scatter.

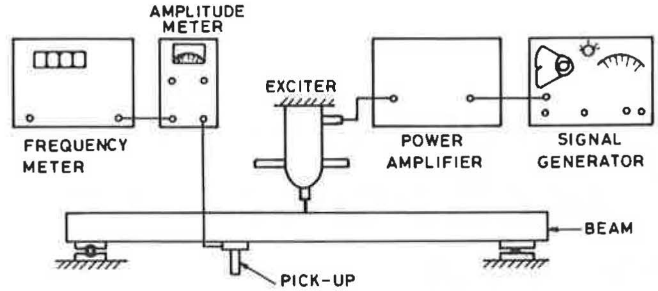

FIGURE 1 Schematic diagram of dynamic test set-up.

Researchers concluded that the average value, in the uncracked state, applicable to the design of machine foundations is 1-percent critical. Equations were formulated from the tests results to estimate the dynamic stiffness of SFRC beams in the post-cracking stage for use in designs involving SFRC elements in blast- and earthquake-resistant structures. Further tests to quantify the variation of stiffness with fiber content and to evaluate the impact resistance of SFRC beams are in progress.

Rao et al. (*10*) studied the influence of fiber reinforcement on the ultimate strength of reinforced concrete columns subjected to axial compression and uniaxial bending. The main variable in their study was applied compression, which varied from 0 to 150 mm for test columns that were 100 by 150 by 1200 mm. The tests indicated that adding fibers to columns reinforced with main continuous steel bars produced only minor improvement in ultimate carrying capacity. However, for plain concrete columns, the addition of fibers significantly improved the columns' ultimate strength. Substantial improvement was also reported in reduction of tranverse tensile stress and deformations.

Dwarakanath and Nagaraj (*11*) investigated whether beams incorporating steel fibers over the entire beam depth performed better than beams with fibers over only half the depth, on the tension side. They found that, for under-reinforced beams, including the fibers over half the depth proved as beneficial as full-depth inclusion in controlling cracking and deflection and in increasing the stiffness of the beams. For over-reinforced beams, however, the fiber addition was not found to be effective in bringing about any appreciable modification in the deformational behavior of the beams.

Studies on the influence of concrete strength, aspect ratio, volume of steel fiber, and quantity of tensile reinforcement on the cracking characteristics of SFRC beams have been reported by the Indian Institute of Technology, Madras. Smooth, round, galvanized iron binding wires of 0.56-mm diameter were cut into small lengths to produce the fibers for

TABLE 1 DETAILS OF TEST BEAMS

Serial Number	Designation	Main Reinforcement (at top and bottom)		Volume (%) of Fibers	Transverse Steel
1	B1	2 nos.	10#	0.50	2 legged 8# at 150 mm centers
2	B2	2 nos.	10#	0.75	2 legged 8# at 150 mm centers
3	B3	2 nos.	10#	1.00	2 legged 8# at 150 mm centers
4	B4	2 nos.	12#	1.00	2 legged 8# at 150 mm centers
5	B5	2 nos.	16#	1.00	2 legged 8# at 150 mm centers
6	B6	2 nos.	10#	0.00	2 legged 8# at 150 mm centers

the experiments. The concrete mix proportion was 1:1.25:1.25, with a water/cement ratio of 0.48. Findings were that inclusion of the steel fibers over the whole section of the SFRC beam produced an increase of 50 to 128 percent in the load at first visible crack. The increase dropped to about 30 percent when fibers were provided only around the tension steel. Inclusion of fibers also substantially reduced both crack width and crack height. Similar observations were reported by several other investigators in India who used fiber contents varying from 0.5 to 1 percent by volume and aspect ratios from 80 to 100. Besides finding significant improvement in crack control and crack propagation, the investigators reported attainment of concrete compressive strain at ultimate load ranging from 330 to 700×10^{-5}.

Moment distribution characteristics of two-span SFRC continuous beams have been studied at the College of Engineering, Madras (*12*). The test beams, 100 by 200 mm in cross section, were supported at three points with two equal spans of 2900 mm. Beam reinforcement was sufficient to prevent premature shear failure. Fibers (1 percent by volume) were added only to the midspan and support portions of the continuous beams. The inclusion of steel fibers in the hinging zones resulted in a 25-percent increase in stiffness at service load, a 15-percent increase in ultimate load, a 20-percent reduction in crack widths, a 10-percent increase in ductility, and 25 percent less stiffness degradation, compared to conventional reinforced concrete beams. Monotonic and reverse cycle loading carried out on prestressed FRC and on conventional prestressed concrete beams showed FRC to be superior with respect to load carrying capacity, stiffness, ductility, and energy absorption characteristics. (In the reverse cycle loading tests, however, the improvement was noted only before the yield level.)

Corrosion of fibers in SFRC is one important factor affecting the durability of the composite matrix under prolonged exposure to adverse environmental conditions. Some investigators in India have reported, however, that the damage due to corrosion in SFRC beams is generally not very extensive (*13*). Experiments conducted by these investigators employed a fiber content of 1.5 percent by volume, with an aspect ratio of 60 to 80. The fiber was obtained from 0.46-mm diameter mild steel annealed wires. The mix proportion was 1:2.07:2.4, with a water/cement ratio of 0.62.

Using steel fibers as web reinforcement in reinforced concrete beams is being studied by many researchers in the country. Findings suggest that conventional vertical stirrups could effectively be replaced by steel fibers and that the shear strength could be predicted using the equation proposed by Muhudin (*14*). The studies concluded so far have shown that inclusion of fibers up to 1.5 percent by volume (with an aspect ratio of 100) increases the ultimate nominal shear stress by about 67 percent. In addition, the ultimate concrete compressive strain has proved to be around 0.007, compared to 0.0035 for reinforced concrete beams.

The use of fibers in ferrocement structural components has been investigated at SERC. Preliminary experiments indicate that the fibers contribute to the flexural stiffness and fracture toughness of the composite. Further investigations are in progress. SERC is also looking into the effects of using a very large percentage volume of fibers (as much as 8 to 12 percent) to improve the impact and abrasion resistance properties of cement mortar. The role of "fiber casements" in confining concrete in compression members is being studied as well.

Other research and academic institutions in India are studying several other aspects of the behavior of SFRC elements subjected to combined static loading, including torsion, and to dynamic, impact, and reversal of loads. The drift of all the investigations, at SERC and elsewhere, is that SFRC structural components present advantages over conventional components, particularly in crack control, improvement in ductility and resistance to impact, abrasion, blast, and other kinds of impulse loads.

INVESTIGATIONS USING NATURAL FIBERS

Most of the natural fibers used for investigations in India are of vegetable origin. Of these, sisal, coir, jute, and bamboo fibers have commonly been used in experiments and in field applications. Besides the work carried out by many universities in the country, research laboratories such as the Regional Research Laboratories at Jorhat, Bhopal, and Trivandrum have carried out a number of experiments using vegetable fibers in the production of precast structural elements. Tests conducted on concrete cubes and flexural beams containing bamboo and coir fibers have shown that the addition of fibers effectively arrests the growth and propagation of cracks, although it does not improve compressive strength. Coconut fibers (coir) have been used in the production of roofing sheets and tiles; reportedly, the durability of these products is good (*15*).

Some research has been carried out on the use of asbestos fibers in its macrofine form in lightweight, reinforced, aerated precast concrete components. Because asbestos fibers may pose some health hazard, however, further investigations are required before their use in aerated and other types of concrete can be advocated.

INVESTIGATIONS USING GLASS AND SYNTHETIC MANMADE FIBERS

Not much work has been done in India yet on the use of glass fibers in FRC because the available fibers are not alkali-resistant. Experiments were conducted at SERC on polymer-impregnated glass fiber reinforced concrete and cement composites in an effort to find a way to protect the glass fibers from the alkalinity in concrete. Polymer impregnation, besides making the glass fibers durable, makes the composites resistant to chemicals. The abrasion resistance of polymer-impregnated glass fiber reinforced mortar composites was found to be more than those without fibers (*6*). E-glass fibers 6- and 12-mm long were used to reinforce the mortar. Methyl methacrylate monomer with benzoyl peroxide as a catalyst was used for impregnation of the glass reinforced mortar specimens. A cement mortar ratio of 1:2, with a 0.5 water/cement ratio, was used to prepare the test specimens, which essentially consisted of cylinder, direct tension specimens, and flexural prisms. Investigations are now under way on the behavior of polyester resin composites reinforced with E-glass fibers.

Investigators have studied nylon and polypropylene fibers, too, with the aim of developing precast concrete components.

DEVELOPMENT OF ULTRAHIGH-STRENGTH STEEL FIBERS

Recent research by a steel manufacturing concern in the country has suggested the possible application of ultrahigh-strength steel fibers, which reportedly possess a superior combination of strength and durability. The ultimate tensile strength typically varies from 165 kg/mm^2 to 200 kg/mm^2, compared to 120 kg/mm^2 for the low carbon steel fibers presently available in India. These high-strength, high-ductility steel fibers are produced with a ferritic-martensitic steel formula in diameters ranging from 0.4 to 1 mm. The fibers have a corrugated profile which improves their bonding characteristics with concrete. Preliminary investigations carried out by the firm on fibers with an 80 aspect ratio have shown considerable improvement in both flexural strength and toughness, compared to conventional plain fibers. These new fibers will likely be commercially available in the country soon.

NEW SHAPES OF FIBERS

At present, only straight steel fibers are used in SFRC. However, some experimental work carried out at SERC on helical and twisted fibers indicates their superiority over plain fibers in pull-out strength and also in the elimination of balling when they are mixed with concrete (*3*). The shapes of the fibers are shown in Figure 2.

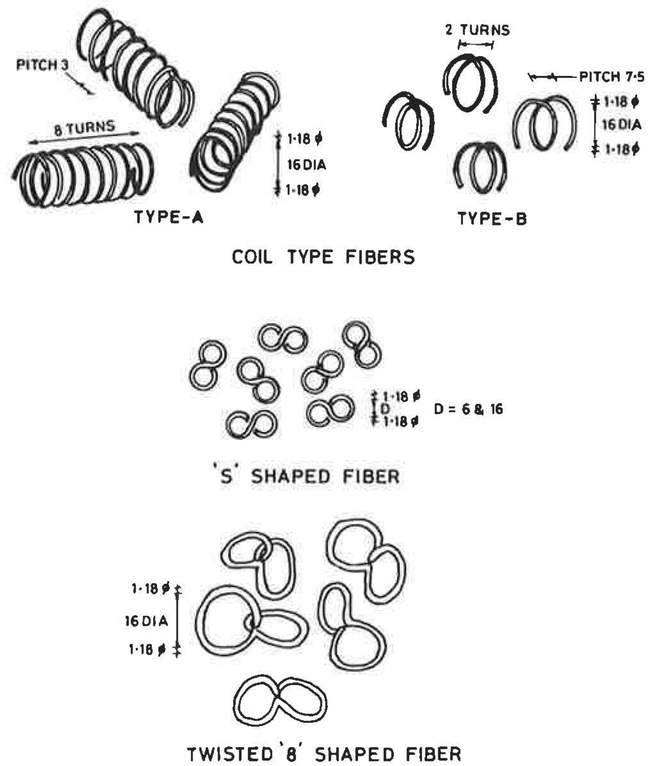

FIGURE 2 Different shapes of steel fibers (in mm) developed at SERC, Madras.

PRODUCTION OF FRC IN INDIA

Conventional techniques are now used only in mixing, placing, and compaction of fiber reinforced concrete. Both pan and tilt-up drum mixers are used for mixing concrete with fibers. Normally, the fibers are dispersed by sieves or by hand after all other ingredients have been placed inside the mixer drum, although special fiber-dispensing devices sometimes are used. The fiber volume content generally ranges from 0.5 to 2 percent, depending on the application. Sand content is usually more in concrete mix proportions, and coarse aggregates sized greater than 10 mm are not usually used. Superplasticizers, which are now available in India, are used only in certain applications. In most of the investigations carried out in the laboratories and in many applications in the field, the FRC mix is so designed that it is workable without the addition of superplasticizers. The compaction of the wet mix inside the molds or over the forms is achieved by means of a table or shutter vibrator. The slump cone test is used to measure workability, even though this test is not unfailingly reliable. The cement content in a typical fiber concrete mix used in laboratory and field applications varies from 350 kg/m^3 to 400 kg/m^3.

When the percentage of fibers added is more than 1.5 percent, superplasticizers are generally used, and sometimes fly ash is also added to improve workability and to reduce cement consumption. For very high-volume FRC mortars containing 6 to 12 percent of fibers, the fibers are first spread on the molds/forms and compacted thoroughly by rolling or other means before the cement slurry is added. Superplasticizers are invariably used in such situations to make the slurry flow freely.

While straight fibers are generally chopped from coils with a shear cutting machine, the Cement Research Institute at New Delhi (now the National Council for Cement and Building Materials) has developed a fiber-forming machine that can produce fibers in various shapes at the rate of about 600 gm/hr. The machine can handle steel wires 0.32 to 0.50 mm in diameter and produce fibers from 25-mm to 45-mm long. The Institute also developed a steel fiber dispenser which ensures that the fibers are de-nested and fed uniformly into the concrete mixing drum, thereby avoiding the balling effect. The dispenser's capacity to feed fibers is 20 kg/min and can be increased by suitable scaling up.

APPLICATIONS OF FRC COMPOSITES IN INDIA

One of the largest applications of FRC has been in the production of precast manhole covers and frames, which make use of both steel and polypropylene fibers. SERC developed the design and production technology for light-, medium-, and heavy-duty manhole covers and frames using SFRC (see Figure 3), and this technology has already been transferred to 17 parties in the country for commercial exploitation. Covers and frames are also being produced using polypropylene fibers, the technology for which was developed by an entrepreneur in New Delhi. The FRC manhole covers and frames possess high ductility and impact resistance and cost less than companion cast iron manhole covers and frames.

FIGURE 3 Fiber reinforced concrete manhole cover and frame developed at SERC, Madras.

FIGURE 4 FRC corrugated roofing sheets used in Orissa, India.

Applications of SFRC in the construction of blast-resistant structures and currency safe vaults is also being investigated by SERC. Preliminary tests carried out on prototype wall elements indicate that the addition of fibers improves the rotation at failure of the structural element, thereby enabling it to absorb the high energy released due to blast, impact, and other types of high velocity impulse loads. Use of steel fibers in machine foundations is being investigated, as it is in ferrocement construction to improve impact resistance. Permanent stay-in-place forms made out of SFRC are being developed at SERC for use in the construction of floor slabs, beams, columns, etc. Moreover, polymer-impregnated precast FRC components and in-situ overlays are expected to find field application soon, based on SERC research and development.

Both steel and vegetable fibers have been used in the development and production of several FRC building components by the Central Building Research Institute, Roorkee. Some of the components developed by the Institute are as follows:

Precast doubly curved roofing tile:
 1000-mm long, 1000-mm wide, and 20-mm thick
Precast doubly curved roofing tile:
 700-mm long, 700-mm wide, and 20-mm thick
Precast lintel:
 1200-mm long, 230-mm wide, and 75-mm thick
Precast plank:
 1200-mm long, 400-mm wide, and 25- or 50-mm thick

Corrugated roofing sheets made out of coconut-fiber reinforced concrete or enriched mortar were used at a leprosy settlement in a village near Titilagarh in Orissa, under the technical guidance of the Swiss Centre for Appropriate Technology (SKAT), Switzerland (see Figure 4). Production of the sheets began in 1982, and the roofs have already withstood five monsoon seasons. Such roofing is also being used in several villages in Andhra Pradesh.

Producing coir-reinforced FRC sheets is simple and does not call for special skills; only a metal frame, a working bench, molds, plastic sheets, and traditional masonry tools are needed for their production. First, the plastic sheet is laid on the table top. The metal frame, with a 10-mm thickness, is then placed on the sheet. The mortar is mixed manually with coir fibers, and then the mixture is cast on the table. It is spread by trowels and leveled according to the thickness of the metal frame. After lifting off the metal frame, the wet mortar laid on the plastic sheet is slid, with the support of the plastic sheet, over a corrugated asbestos cement sheet which forms the mold. The sheet is demolded 24 hours after production, and the normal curing procedure begins. The production cost of these FRC sheets is around $2–3 (U.S.) per square meter. FRC tiles with coir fibers have also been produced using molds. The 6-mm-thick tiles are made using 1:2 or 1:3 cement mortar. By vibrating the wet mix in the mold, the consumption of cement content in the mix can be reduced. A hand-operated or electric power vibrating table is used for this purpose. The economic benefits of the coir FRC sheets are obvious: the simplicity of the production procedure leads to an affordable product, yet the producers still get income.

SFRC made with straight fibers has also been used by the International Airport Authority of India in the construction of airfield pavement at New Delhi (*15*). The thickness of the pavement was 300 mm, compared to the 400-mm thickness of its companion plain concrete slab. The reduction in thickness was made possible by the flexural strength of SFRC, which was found to be 80 to 100 kg/cm^2 for the pertinent FRC mix. Conventional methods of handling and laying were adopted, with a slight modification to the conventional concrete mixer. Salient features of the SFRC mix are presented in Table 2.

A simulated dynamic aircraft loading was carried out on the slabs when they were vibrated with a dynamic force of ± 3.6 tons, coupled with the static load of equipment weighing 8.2 tons. The SFRC slab showed more resistance to fatigue and failure during the tests than the companion plain concrete slab of greater thickness. The frequency of the load in the test was kept equal to the natural frequency of the slabs (which was measured earlier with the same dynamic equipment). The pavement has now been in service for nearly 6 years and is used for parking B-747s, DC-10s, and similar classes of aircraft. No cracking, spalling, pitting, or damage of any other kind has appeared in the SFRC slabs.

SFRC in the form of precast interlocking blocks is proposed

TABLE 2 SALIENT FEATURES OF MIX DESIGN FOR SFRC

Cement Content	410 kg./m^3
Water/Cement Ratio	0.6
Sand	730 kg./m^3
Coarse Aggregate:	
10 to 20 mm	399 kg./m^3
4.75 to 10 mm	339 kg./m^3
2.36 to 4.75 mm	151 kg./m^3
Steel Fibres	106 kg./m^3
Shape	Trough type
Length	36 mm
Diameter	0.45 mm

for haul roads used by heavy-duty dumpers in an iron ore project site in Central India. The blocks are now undergoing trials at SERC. The possibility of using SFRC overlays on roads traversed by army tanks is also being explored. The percentage of added fibers will have to be very high to resist the high impact and abrasion loads caused by sudden braking and maneuvering of the tanks on the roads.

CONCLUSIONS

FRC's potential is now well known in the country, but its application has not yet caught up with its repute. Fiber reinforced concrete has many potential areas of applications, such as mass concrete structures, pavements, bridge decks, airport runways, tunnel linings, defense installations, and precast products. The technology of FRC is well understood in India, but the problem remains that metal fibers are not being manufactured in India on a commercial scale. Commercial production of steel fibers is expected to begin within the next couple of years, which may boost the use of FRC composites for a variety of structures. Natural fibers have also proved effective and useful in making low-cost roofing sheets and tiles; their use in housing construction projects is increasing.

Several applications of FRC using either steel or natural fibers have been reported, and the performance of structures and products built with FRC has been laudable. Several institutions and research laboratories in the country are now conducting research and development work aimed at utilizing the full potential of FRC either alone or in combination with ferrocement and polymer impregnation.

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