2.2 Fibre reinforced concrete

Plain concrete has two major deficiencies; a low tensile strength and a low strain at fracture. The tensile strength of concrete is very low because plain concrete normally contains numerous microcracks. It is the rapid propagation of these microcracks under applied stress that is responsible for the low tensile strength of the material. These deficiencies have lead to considerable research aimed at developing new approaches to modifying the brittle properties of concrete. Current research has developed a new concept to increase the concrete ductility and its energy absorption capacity, as well as to improve overall durability. This new generation technology utilizes discrete steel or synthetic fibres from 19 to 64mm in length. The fibres are randomly dispersed throughout the concrete matrix providing for better distribution of both internal and external stresses by using a three dimensional reinforcing network. General requirements for the fibres used as temperature/moisture, shrinkage reinforcement include: high tensile strength, high bond strength (typically mechanical) and ease to incorporation into the matrix to ensure optimum distribution. The primary role of the fibres in hardened concrete at low volume is to modify the cracking mechanism. By modifying the cracking mechanism, the macro-cracking becomes microcracking. The cracks are smaller in width; thus reducing the permeability of concrete and the ultimate cracking strain of the concrete is enhanced. Unreinforced concrete will separate at a crack, reducing the load carrying ability to zero across the crack. The fibres are capable of carrying a load across the crack, if all of the characteristics listed above are met by the fibres. Fibres reinforced concrete (FRC) specimens, unlike plain concrete specimens which fail at the point of ultimate flexural strength or the first crack, do not fail immediately after the initiation of the first crack. After first crack, the load is transferred from the concrete matrix to the fibres.

Because of the flexibility in method of fabrication, fibres reinforced concrete is an economic and useful construction material. A major advantage of using fibre reinforced concrete besides reducing permeability and increasing fatigue strength is that Fibre addition improves the toughness or residual load carrying ability after the first crack. Additionally, a number of studies have shown that the impact resistance of concrete can also improve dramatically with the addition of fibres. Low modulus of fibres, like polypropylene, seems to be particularly effective in this regard. Although every type of fibre has been tried out in cement and concrete, not all of them can be effectively and economically used. Each type of fibre has its own characteristic
properties and limitations. Currently steel, glass, polymeric and carbon fibres are commonly used and natural fibres, such as bamboo, jute, asbestos cotton etc are of limited use. These various available fibres are classified into metallic fibres and non-metallic fibres. (2)(85)

2.2.1 Metallic fibres

Some of the metallic fibres used in concrete are steel fibre, low carbon steel fibre, galvanized iron fibre and aluminum fibre. Among these fibres, steel fibre is one of the most commonly used fibres. Other fibre, such as low carbon fibre is having some disadvantages such as low strength, high cost and more corrosive nature as compared to steel fibre. Aluminum fibre is also having some disadvantages such as light weight, high cost and low strength. Due to above said limitations these fibres are rarely used in construction with concrete.

2.2.1.1 Steel fibres

Research and design of steel fibre reinforced concrete began to increase its importance in the 1970s, and since those days various types of steel fibres have been developed. They differ in material as well as in size, shape and surface structure, as shown in fig. 2.5. Due to different manufacturing processes and different materials, there are differences in the mechanical properties such as tensile strength, grade of mechanical anchorage and capability of stress distribution and absorption. They range in ultimate strength from 345 to 2070 MPa. Fibre size ranges from 13 X 0.25 mm to 64 x 0.76 mm. Fibres with hooked or deformed ends could be used in smaller quantities because they develop higher pullout resistance. Fibres with large surface area, square or rectangular as compared to round, have more concrete bonding area, and fibres with pitted surface have a greater surface area. For high temperature application up to 1650° C, stainless steel fibres are used.

![Fig. 2.5 Different types of steel fibres](image)

Corrosion of steel fibres in concrete with a high water/cement ratio may cause deterioration. The free moisture in wet concrete provides an aqueous medium, which facilitates transport of chlorides towards the metal. It also increases the electrical
conductivity of material, thus aiding any tendency for electrochemical corrosion. However, in actual field cases, corrosion of carbon steel fibres has been found minimal.

When fibres were exposed on a surface, they showed evidence of corrosion; however, internal fibres showed no corrosion. Fibre loadings in construction projects have typically ranged from 0.5 to 2.0% by volume and 47 to 157 kg/m$^3$ of fibres.

The crack-arrest and crack control mechanism of SFRC results in the improvement of all properties associated with cracking, such as strength, stiffness, ductility, energy absorption, and the resistance to impact, fatigue and thermal loading. The crack controlling property of fibres has three major effects on the behavior of concrete composite.

Fibres delay the onset of flexural cracking, the increase in tensile strain at first crack being as much as 100 percent. The ultimate strain may be as large as 20 to 50 times that of plain concrete.

The fibres impart a well-defined post-cracking behavior to the composite. The crack arrest property and consequent increase in ductility imparts greater energy absorbing property to the composite prior to failure. With a 2.5 percent fibre content the energy absorbing capacity is increased by more than ten times as compared to unreinforced concrete.

2.2.2 Non metallic fibres

In this classification we come across many fibres such as asbestos, glass, carbon, polypropylene, recron, nylon, acrylic, coconut coir, sisal, sugar cane bagasse, bamboo, jute, wood and vegetables. In these fibres some are available naturally, such as coconut coir, sisal, bamboo jute and some fibres are manufactured such as recron, polypropylene, nylon, glass fibre etc. among these fibres glass, carbon and propylene fibre are most commonly in use.

2.2.2.1 Glass fibres

Glass fibre is a recent introduction in making fibre concrete. Commonly used glass fibres are round and straight and have diameters of 0.0005 to 0.015 mm, but these fibres may be bonded together to produce glass fibre elements with diameters of 0.13 to 1.3 mm. It has very high tensile strength of 1020 to 4080 N/mm$^2$. Glass fibre, which is originally used in conjunction with cement, was found to be effected by alkaline condition of cement. Therefore, alkali resistant glass fibre by trade name 'CEM-FIL' has been developed and used. The alkali resistant fibre reinforced concrete shows
considerable improvement in durability when compared to the conventional E-glass fibre.

2.2.2.2 **Carbon fibres**

Carbon fibres are very small in diameter and are generally used in shorter lengths. They are also manufactured as continuous mats and continuous straight fibres. They can be manufactured in strength as high as steel with a density only one-fifth that of steel. Carbon fibre is inert in aggressive environments, abrasion-resistant and stable at high temperatures, with relatively high stiffness. Carbon fibres perhaps possess very high tensile strength in the range of 2110 to 2815 N/mm². It has been reported that cement composite made with carbon fibre, as reinforcement will have very high modulus of elasticity and flexural strength. The uniform dispersion of carbon fibre in concrete is more difficult than the other fibre types.

2.2.2.3 **Polypropylene fibres**

Polypropylene fibres are specially engineered for use in concrete and mortar as a micro reinforcement system. They possess very high tensile strength, but their low modulus of elasticity and higher elongation do not contribute to the flexural strength. These fibres get uniformly dispersed in the concrete or mortar as millions of fibres in every cubic meter to reduce plastic shrinkage and settlement cracks. They reduce permeability, increase impact and abrasion resistance to freeze/thaw, reduce honeycombing, segregation, unequal bleeding, prevent corrosion of reinforcement, prevent explosive scaling of concrete due to tire and there by vastly improve overall quality and durability.

2.2.2.4 **Asbestos fibres**

The naturally available inexpensive mineral fibre, asbestos, has been successfully combined with Portland cement paste to form a widely used product called asbestos cement. Asbestos fibres have a thermal, mechanical and chemical resistance making it suitable for sheets, pipes, tiles and corrugated roofing elements. Asbestos cement products contain about 8 to 16 percent by volume of asbestos fibres. The flexural strength of asbestos cement board is approximately 2 to 4 times that of unreinforced matrix. However due to their relative short length (10mm), they have low impact strength. There is some health hazards associated with the use of asbestos cement. In the near future, it is likely that glass fibre reinforced concrete will replace asbestos completely.

2.2.3. **Advantages of fibre reinforced concrete**

1. Reinforcement can be positioned where it is needed. Extra amount of fibres can be
added to any part of the member, when excess load would be coming on that particular part.

2. As the fibres are uniformly dispersed all over the member the surface wear characteristics of concrete are considerably improved.

3. The joint edges of a FRC member do not spall and chip away easily under heavy service loads.

4. FRC products give more resistance to impact.

5. FRC can be pumped and sprayed like ordinary concrete.

6. It is very light, so requires less craneages for lifting, and being thinner they give greater use able floor area.

7. It cracks less extensively in severe fires than ordinary concrete.

8. Wide range of surface finishes is possible.

2.2.4 Disadvantages of fibre reinforced concrete

1. Steel fibres are being costlier at present, FRC becomes very expensive compared to R.C.C. in terms of materials only.

2. The balking effect of fibres in FRC is very undesirable.

2.2.5 Properties of steel fibre reinforced concrete

A numerical parameter called the aspect ratio is commonly used to describe the geometry of a steel fibre. This is the ratio of fibre length to fibre diameter or equivalent diameter for nonround fibres. Typical aspect ratios range from about 20 to 100, while length dimensions range from 6.4 to 76 mm.

Generally, higher the fibre aspect ratio, the greater is the individual fibre efficiency in the concrete. At first glance, it would appear that the designer should specify a fibre with a high aspect ratio; however this generally is not realistic. As the aspect ratio of fibre increases, the mixing, placing and finishing operations may be additionally complicated. Therefore, the industry has adjusted production techniques and material compositions to manufacture rigid, lower aspect ratio fibres with mechanical deformations that perform similarly to higher aspect ratio fibres without inherent mixing problems. (80), (85)

2.2.5.1 Compressive strength

Compressive strength is little influenced by steel fibre addition. Increase in compressive strength ranging from 0 to 15 percent for up to 1.5% volume of fibres is observed. It is mainly controlled by the concrete matrix design. If higher compressive strengths are required, then the addition of silica fume or an appropriate combination of
silica fume and other admixtures can be useful.

2.2.5.2 Tensile strength

Fibres aligned in the direction of the tensile stress may bring about very large increases in direct tensile strength, as high as 133% for 5% of smooth, straight steel fibres. However, for more or less randomly distributed fibres, the increase in strength is much smaller, ranging from as little as no increase in some instances to perhaps 60%, with many investigations indicating intermediate values.

2.2.5.3 Flexural strength

Elements incorporating steel fibres have higher flexural stiffness (reduced deflections) and smaller crack widths when subjected to service loads. The improvements in flexural strength resulting from steel fibre reinforcement are not large enough to give steel fibres the potential to fully substitute continuous bars in flexural reinforced elements. Increase in flexural strength is ranging from 0 to 20 percent up to 1.5 percent by volume of fibres. Optimum conditions in flexural elements may be achieved through the use of steel fibres together with conventional steel bars.

2.2.5.4 Toughness

Toughness was recognized very early in the development of fibre reinforced concrete as the characteristic property that above all others most clearly distinguishes it from concrete without fibres. Under impact conditions, toughness can be qualitatively demonstrated simply by trying to break through a thin section with a manually operated hammer. For example, a thin fibre reinforced mortar flower pot withstands multiple hammer blows over a period of time before a hole is punched at the point of impact. Even then, the rest of the pot retains its structural integrity. In contrast, a similar pot made of mortar without fibres fractures into several pieces after a single hammer blow, totally losing its structural integrity as a pot.

Under slow flexure conditions, toughness can be qualitatively demonstrated by observing the behavior of simply supported beams loaded in bending. A concrete beam containing fibres suffers damage by gradual development of single or multiple cracks with increase in deflection, but retains some degree of structural integrity and post crack strength even when deformed to a considerable deflection. In contrast a similar beam without fibres fails suddenly at a small deflection by separation into two pieces, totally losing its structural integrity as a beam.

The toughness index for plain concrete is equal to 1 because all plain concrete beams fail
immediately after the first crack. The toughness indices for FRC vary greatly depending on the position of the crack, the type of fibre, aspect ratio, the volume fraction of the fibre and the distribution of the fibres.

2.2.5.5 Corrosion

When using steel fibres in concrete, attention has to be given to the question of corrosion of the fibres. As the steel volume locally is very small when fibres are used, only limited expansion forces develop due to the corrosion and normally no spalling occurs. Steel fibres in the immediate surface layer rapidly corrode to the depth of surface carbonation, which might however give aesthetical defects in the form of rust coloured surfaces. The loss of contribution to the strength of a corroded fibre has also to be considered. In most applications low carbon, plain steel fibres are used. Steel fibres are less susceptible to corrosion than conventional reinforcing as they are electrically discontinuous.

2.2.5.6 Creep and shrinkage

Concrete shrinks when it is subjected to a drying environment. The extent of the shrinkage depends on many factors including the properties of the materials, temperature and relative humidity of the environment, the age when concrete is subjected to drying environment and the size of the concrete mass. If concrete is restrained from shrinkage, then tensile stresses develop and the concrete may crack. Shrinkage cracking is one of the more common causes of cracking for walls, slabs and pavements. One of the methods to reduce the adverse effects of shrinkage cracking is reinforcing the concrete with short randomly distributed steel fibres. Since concrete is almost always restrained, the tendency for cracking is common. Steel fibres have three roles in such situations. They allow multiple cracking to occur, they allow tensile stresses to be transferred across cracks and stress transfer can occur for a long time permitting healing of the cracks.

2.2.5.7 Fatigue

In composites, crack initiation and propagation produce simultaneous growth of cracks that may (a) extend through the matrix (b) be stopped at a fibre or (c) propagate along a fibre matrix interface. Cracks are initiated by factors such as debonding, voids or fibre discontinuity. The cracks propagation results in cracks joining each other to the extent that matrix is unable to perform its basic function of transferring the load from one fibre to the next in fibre composites. The fracture surface of a matrix usually shows evidence of a complex assortment of fibre failure and fibre pullout.
2.2.6 Requirements of good fibre

The basic requirement of fibre for improving strength properties are high tensile strength and elastic modulus, adequate extensibility, a good bond at the interface and good stability. The fibre should be capable of withstanding stress for a long period of time. The tensile strength of the fibres may not be critical if composite falls by significant role in determining the strength capability of the composite.

2.2.7 Applications of fibre reinforced concrete

Most current applications of fibres are non-structural. Fibres are often used in controlling (plastic and drying) shrinkage cracks, a role classically played by steel reinforcing bars or steel wire mesh. Examples include floors and slabs, large concrete containers, and concrete pavements. In general, these structures and products have extensive exposed surface areas and movement constraints, resulting in high cracking potential. For such applications, fibres have a number of advantages over conventional steel reinforcements. These include

a. Uniform reinforcement distribution with respect to location and orientation,
b. Corrosion resistance especially for synthetic, carbon, or amorphous metal fibres, and
c. Labour saving by avoiding the need of deforming the reinforcing bars and tying them in the form-work, which often leads to reduction of construction time.

Elimination of reinforcing bars also relaxes constraints on concrete element shape. This functional value of fibres has been exploited in the curtain walls of tall buildings. The Kajima Corporation (Japan) has taken advantage of fibres in the manufacture of curvilinear-shaped wall panels valued for their aesthetics.

In some applications, the use of fibres enables the elimination or the reduction in the number of cut-joints in large continuous structures such as containers and pavements. Especially in pavements, joints are locations of weaknesses at which failure frequently occurs. Thus, fibres have been exploited to enhance the durability of concrete elements.

Repair of concrete structures appears to be a sizable application of FRCs. This includes restoration of pavements, airfields, bridge decks, and floor slabs. With the decaying infrastructure coupled with increasing demand in their performance in most industrialized countries, it is expected that the need for durable repairs will increase over time. Fundamental understanding of durable repairs is lacking at present. However, it is generally agreed that repair failures are often related to mechanical property incompatibility between the repair material and substrate concrete. Dimensional stability
of the repair material and delaminating resistance is often cited as some of the controlling factors. Fibres can be and have been used to advantage in this area.

The adoption of new materials in the highly cost-sensitive construction, building, and precast products industries generally requires justification of cost advantage. The dollar value of durability is difficult to quantify, but durability demand clearly represents one of the driving forces in the use of fibres, especially when shrinkage crack resistance is considered. As mentioned above, labour saving via elimination of joints or re-bars provides extra financial incentives.

2.2.7.1 Highway pavements

High first crack flexural strength and fatigue endurance limit of FRC make it suitable for use in highway pavements and for overlays. Normal loading condition requires the FRC pavements to have a thickness of about half that of conventional concrete pavements.

A 333m long and 80mm thick FRC overlays was slip formed on a major high traffic volume street in Detroit, Michigan, USA in Oct 1972. Two fibre contents of 0.8% to 1.5% by volume were used. Traffic was allowed on the overlays after 48 hours paving.

2.2.7.2. Airport runways

The US army Construction Engineering Research Laboratory (CERL) Champaign, Illinois performed controlled testing of FRC slabs at the US Army Waterways Experiment Station, Vicksburg, Mississippi, USA was constructed in 'Wired' concrete in Feb. 1972 using a slip form pavers. The mix contains 1.5% of fibres by volume, Portland cement, Fly ash and 20mm size aggregate. Two overlays, 100mm and 150mm thick were placed and subjected mainly to Boeing-272 traffic. Reflection cracks developed in the 150 mm slab, which were hairline and nonworking.

In collaboration with IAAI, the Cement Research Institute of India has laid three pavement slabs in a jet at Palam airport, New Delhi. This provided an opportunity to study the effect on mixing, handling, placing and compaction of SFRC under Indian conditions where the concrete operations are essentially in extensive.

Out of the three slabs, the slab was of concrete with a design thickness of 400mm, laid over 150mm water-bound macadam base. The section was laid with a full depth of SFRC of 300mm thickness. The third was laid with SFRC at the top and bottom edge of the slab. Although the theoretical calculation indicated that the pavement thickness could be reduced up to 40% the actual reduction provided was only to the extent of 25% mainly to
ensure common sub grade pressure conditions. The performance of the three slabs, which are subjected to full parking load of Jumbo aircraft, has been quite good.

### 2.2.7.3 Deck slab construction

The decking slab of two-storied car park at Heathrow airport, London was constructed by using SFRC. The size of each demountable panel was 1.1m x 1.1m x 63.5mm and had to support live load of 2500N/m². The mix used was 1:1.5:3 with W/C ratio of 0.65 and 3% fibres by weight were dispersed uniformly.

### 2.2.7.4 Wall and roof units

Isotropic strength properties obtained by the uniform dispersion of fibres throughout the volume of concrete will permit thinner flat and curved plate elements, resulting in significant weight reduction for small structures. A residential building with a total area of 11.7 sq.m was erected within a day using about 39 cu. m. of fibrous concrete. Fenrith in Australia, small steel fibres of about 150mm length were used and entire concrete was poured in one stretch. The process is cheap, less lime consuming and do not require close site supervision. The system is recommended mainly for schools, houses and other building in developing countries.

### 2.2.7.5 Marine structures

Water front marine structures must have resistance to deterioration at the air water interface and resist impact loading. Control of cracking by fibrous concrete could reduce the corrosion that develops at the air water interface. The energy absorption capacity of fibrous concrete also imparts strength to it. This is a significant requirement of the marine structure.

### 2.2.7.6 Breakwater armor units

SFRC can be used as identical material for break water armor units as it possesses good physical properties such as density, strength, toughness, resistance to impact, abrasion and resistance to deterioration in marine environment. Other potential applications are underwater storage structures, waterfront warehouse floors and decking. According to ACI 544, steel fibre reinforced concrete has been investigated to be durable to surface erosion and cavitations. Tests by the Corps of Engineers suggest that erosion resistance against scour from debris in flowing water is not improved. These tests show that when erosion is due to the gradual wearing of concrete due to relatively small particles of debris rolling over the surface at low velocity, the quantity of aggregate and hardness of the surface determine the rate of erosion. The largest project of this kind yet
undertaken was the repair of the stilling basin of Tarbella Dam in Pakistan in 1977.

2.2.7.7 **Blast resistance structure**

The design of blast resistance structures made from concrete require that they should be capable of resisting the blast wave which cause complex stressing of the structure in compression, tension and shear. Fibre reinforced concrete in conjunction with conventional reinforcement could provide the necessary strength. Fibre reinforcement can advantageously be used in foundation for machinery where shocks and vibratory loads are encountered.

2.2.7.8 **Reactor pressure vessels**

Fibre reinforcement in concrete reactor pressure vessels could reduce the congestion of the reinforcing rods and allow higher tensile stress and provide better crack control.

2.2.7.9 **Shear reinforcement**

Fibres can be partly used in place of stirrups for shear reinforcement in beams. The other applications can be in multi-story frames. The ductility of fibre reinforced concrete would permit the development of plastic hinges from overload conditions.