Chapter 1

FIBRE REINFORCED CONCRETE

1.1 Concrete in Brief

Concrete is most widely used man made construction material today. We take concrete for granted in our everyday activities and tend to be impressed by the more dramatic impacts of technology.

The versatility and mouldability of this material, its high compressive strength and ability to redistribute the stresses, and the discovery of reinforcing and prestressing techniques which helped to make up for its low tensile strength have contributed largely to its widespread use. We can rightly say that we are in the age of concrete.

With the passage of time and due to the fast improving technology, we have seen many improvements and even discoveries of new concrete. Polymer concrete, air-entrained concrete, lightweight concrete, vacuum concrete, etc., are few to mention among them.

Concrete is the most widely used construction material. Because of its specialty of being cast in any desirable shape, it has replaced stone and brick masonry. In spite of all this, it has some serious deficiencies which but for its remarkable qualities of resilience, flexibility, and ability to redistribute stress, would have prevented its use as a building material (Rafat Siddique, 2002).

Cement concrete is the area in which the civil engineer has applied the idea of composite materials by combining cement paste and aggregates. When two different kinds of materials with contrasting properties of strength and elasticity are combined together, they realize a great portion of the theoretical strength of the 'stronger' component, and these combined materials are called 'two phase composites'. In an idea two-phase composite, the strength of the weak phase is thus improved by the strong phase.

Usually, a two-phase composite material is obtained by combining one material of greater tensile strength and modulus of elasticity with another material of relatively low modulus of elasticity. The high strength material is more or less finely 'divided' and evenly 'distributed' or 'dispersed' in a matrix and then mixed with the low-modulus material. So the whole material withstands the loading which would have otherwise ruptured the weaker material easily (Parameswaran, 1988).
1. 2 Limitations of Concrete

Plain concrete possesses two major drawbacks as a structural material. They behave in a brittle or semi-brittle fashion and possess a very low tensile strength. Compared to other construction materials, it possesses a low specific modulus, limited ductility and little resistance to cracking. Microcracks develop in the material during its manufacture due to inherent volumetric and microstructural changes, and an essential discontinuous, heterogeneous system thus exists even before any external load is applied. In addition to the low tensile strength, the material possesses little resistance to tensile crack propagation in turn results in a low fracture toughness and limited resistance to impact and explosive loading. The successful use of the material in construction, therefore, depends in restricting the stresses in the material under working load condition, and cracking and deformation further limit the exploitation of the material.

It is necessary, therefore, to impart tensile resistance properties to a concrete structural member in order to use it as a load bearing material. This has been achieved since a hundred years or more, by the use of reinforcing bars. Reinforcement with iron bars enables concrete to carry tensile stresses quite successfully but the cracking strain of concrete is still so low that it cracks long before the wire is seriously loaded, and if a larger tensile load is put upon the combined system an elaborate pattern of cracks appears in the concrete. In conventional concrete reinforcement, the cracks are a great disadvantage since if small, they let water in and the iron is attacked, if large, the concrete falls out in pieces. To avoid these difficulties, one thing to do is to put the concrete permanently into compression, by putting the steel reinforcement permanently in tension. This is nothing but the method of prestressing. But then, there are two very large disadvantages (Prakash K. B. 1998).

Although both these methods provide tensile strength to the concrete members, they do not increase the inherent tensile strength of concrete itself. Thus, the overall performance of the traditional reinforced concrete composite material is still effectively dictated by the individual performance of the concrete phase and the steel phase. This has led to the search for new materials—particularly two phase composites—in which the weak matrix is reinforced with strong stiff fibers to produce a composite of superior properties and performance.

It has been found that the addition of small closely spaced and uniformly dispersed fibers to concrete would act as crack arrestors and would substantially improve the tensile strength and other properties of concrete. This type of concrete is called as Fiber Reinforced Concrete.
"Fiber Reinforced Concrete (FRC) can be defined as a composite material consisting of a mixture of cement mortar or concrete and discontinuous, discrete, uniformly dispersed suitable fibers".

Fiber Reinforced Concrete is thus a relatively new material in which steel or other fibers are introduced as micro reinforcements. By the introduction of steel or other fibers, not only is the occurrence of the first crack delayed but flexural strength, modulus of rupture, fatigue, impact strength, shock resistance, shear and torsional strength, ductility, and failure toughness are also greatly improved (Prakash K. B, 1998).

1.3 Historical Background

Cement concrete is an area in which the civil engineer has applied the idea of composite materials by combining cement paste and aggregates. When two different kinds of materials with contrasting strength and elasticity are combined together, they realize great portions of the theoretical materials and are called as two phase composite.

In an ideal two-phase composite the strength of the weak phase is improved by the strong phase. Usually, the two-phase composite material is obtained by combining one material of greater tensile strength and modulus of elasticity with another material of relatively low modulus of elasticity. The high strength material is more or less finally divided and evenly distributed or dispersed in a matrix and then mixed with the low modulus material. So, the whole material withstands the loading, which would have otherwise reputed the weaker material easily.

Conventional reinforced concrete is a two phase composite only after cracking i.e. when the reinforcing bars hold the cracked concrete matrix. On the other hand, when short, closely spaced fibres reinforced the concrete, an ideal two phase composite is produced in the sense that even the cracking strength is increased by the closely spaced fibres acting as crack arresters.

The idea of combining two or more materials to obtain a composite is not new to the Civil Engineer. Fibres have been used to reinforce brittle materials since ancient times. The concept of using fibres in a brittle matrix was first recorded with the ancient Egyptians who used hair (Horse hair) from animals. The use of straw to strengthen sun-baked bricks (mud bricks) as reinforcement and walls in housing and stabilize their dimensional instability has been practiced for centuries. This dates back in 1500 B.C. as given by Balaguru et al. (1992). At the similar time period, about 3500 years ago, straws were used to reinforce sun-baked bricks for a
57m high hill of 'Aqar Quf', which is located near Baghdad. It is until the 1900's that asbestos fibres were developed, manufactured and widely used to augment mechanical properties of cement matrix as described by Bentur and Mindess (1990). Horsehair was used to reinforce plaster and more recently asbestos fibres are being used to reinforce Portland cement. From straw in bricks and horsehair in plaster to asbestos in Portland cement, history is constantly undergoing a process of rebirth through new applications of different basic materials.

The idea that concrete can be strengthened by the inclusion of fibres was first put forward by Porter in 1910, but little progress was made in the development of this material until 1963, when Romualdi and Batson (1963) published their classical paper on the subject. Based on the principles of fracture mechanics, they showed that closely spaced fibres acting as crack arresters and established that the increase in strength is inversely proportional to the square root of fibres spacing. Since then, there has been a wave of interest in fibre reinforced concrete and several interesting experiments have been carried out all over the world using different kinds of fibres.

Balaguru and Shah (1992) reported that the modern developments of using only straight steel fibres began in the early 1960’s. Till now, wide ranges of other type of fibres are used in cement matrices. Construction industries have led the development different of type of fibres such as steel, stainless steel and glass; where new types of fibres such as Kevlar and carbon; and several low modulus fibres, such as man made fibres (polypropylene, nylon) or natural fibres (jute, sisal, bamboo and wood pulp), as they vary in their properties, cost and effectiveness. As they may produce as bundled filaments or fibrillated films, or may be used as mats or woven fabrics as given by Bentur et al. (1990). Primarily, the usages of fibres in modern industries are discontinuous fibres. Development of concrete with modified polymer fibres systems increases the explicit effects and mechanical properties of concrete.

In the early stage of fibre development, steel and glass fibres with geometry of straight and smooth were used, as these fibres improve in ductility, flexural strength and fracture toughness of concrete matrix. The primary factors that controlled for this composition were fibre volume fraction and length-diameter. However, the problems faced were difficulty in mixing and workability. Balaguru and Shah (1992) reported that fibres that are long and at higher volume fractions were found to ball up during the mixing process. The process called 'balling' affects the workability and strength characteristics of concrete.
This has a tendency to influence the quality of concrete and strength. In the last 40 years, discovery and acceptance of reinforcement and fibres for enhancement of concrete properties has rapidly increased for use in concrete industries. Numerous types of fibres have successfully been adapted in the different applications of concrete. Technological advances bought forward the development of fibres with different geometric shapes and properties to expand the benefits in concrete structures. New manufacturing techniques and applications on fibres for concrete have been developed.

All these fibres with more complicated geometric, shape and sizes have developed, mainly to modify each of their mechanical bonding with cement matrix. When fibre is added to a concrete mix, each and every individual fibre receives a coating of cement paste. Modification of fibre geometry includes hooked end fibres, deformed fibres, deformed wires, fibre mesh, wave cut fibres, large end fibres. This increases bonding without increasing in length and minimise chemical interaction between fibres and the cement matrices. This also modifies and enhances the mechanical properties and behaviour of concrete in its applications.

Fibre can be used with admixtures such as superplasticizer, air entraining, set retarding, set-accelerating admixtures and all types of cement and concrete mixtures. These produce special types of concrete with desired characteristics in fresh and hardened concrete. They increase workability, accelerated and retarded rate of hydration of cements, and resistance to freeze and thaw conditions. They provided a significant improvement to the fibre-reinforced concrete used in the fields.

1.4 Components (Constituent materials) of FRC

Fibre reinforced concrete is a composite material consisting of cement, aggregate, water, discrete discontinuous fibres and various additives. As the ingredients are responsible for producing good as well as bad concrete their contribution should be clearly understood.

The two major components of fibre-reinforced cement composite are the matrix and the fibre. The matrix generally consists of Portland cement, aggregates, water and admixtures.

1.4.1 Cement

It is the main component of concrete, which has good adhesive and cohesive properties so as to render it to form a good bond with other materials. It solidifies when mixed with water. The most commonly used cement is called ordinary Portland cement. Other types of cements that are available include high early strength cement.
low heat cement, and sulfate-resistant cement. All these cement types can be used to produce fibre-reinforced concrete (Rafat Siddique, 2002).

1.4.2 Aggregates

Aggregates are inert materials, which give body to the concrete. Sand, crushed rock and gravel are some examples. The aggregates suitable for plain concrete can be suitably used in FRC. The aggregates are normally divided into two categories i.e. fine and coarse aggregates.

Fine aggregate normally consists of natural crushed or manufactured sand. Natural sand is the usual component for normal light concrete. In some cases, manufactured lightweight particles are used for lightweight concrete and mortar. Heavy weight particles made of metallic components are sometimes used to produce heavy weight concrete for nuclear shielding purposes.

Fine aggregate is needed for both fibre-reinforced concrete and mortar. Fibre-reinforced mortar is normally used for making thin-sheet items such as glass fibre-reinforced cement products and for fibre reinforced boards using either polymeric or natural fibres. The maximum size and size distribution of fine aggregates depends on the type product being made. For example, fine sand is generally used for manufacturing thin sheets and relatively small diameter pipes, whereas sand containing coarse particles is used for shotcreting applications and for large diameter pipes with wall thickness exceeding 25 mm.

Coarse aggregates can be normal-weight, lightweight or heavy weight in nature. Normal-weight coarse aggregates can be made of natural gravel or crushed stone. Lightweight coarse aggregates are generally made of expanded clay such as shale pumice or blast furnace slag. Concrete made with normal weight coarse aggregate weighs about 22.4 KN/m³, whereas the structural lightweight aggregate weighs in the range of 14.6-17.8 KN/m³. Nonstructural weight components such as boards or noise barriers can weigh as little as 3.2 KN/m³ (Rafat Siddique, 2002).

1.4.3 Water-Reducing Admixtures

Water-reducing admixtures have become an integral part of fibre reinforced concrete. The addition of the fibres to a cement matrix normally reduces the workability. But the advent of water-reducing admixtures made it possible to maintain the workability of a fibre reinforced matrix without adding extra water. Since the addition of extra water reduces the strength, increases the shrinkage and enhances the tendency to crack.
resulting in the durability problems, it is always recommended to use minimum amount of water (Rafat Siddique, 2002).

There are two types of water reducing admixtures available. The first type can reduce the water demand by 12% to 23%. The second type of admixtures, known as high-range water-reducing admixtures or superplasticizers, can be used to obtain flowable mixtures even at a water-cement ratio of 0.28. The high range water reducing admixtures have been successfully used for both cast-in-place concrete and shotcrete applications (Rafat Siddique, 2002).

1.4.4 Mineral Admixtures

The most commonly used mineral admixtures are fly ash and silica fume. Fly ash is used to improve the workability of fresh concrete to reduce heat of hydration, and to enhance permeability characteristic. Silica fume is added mainly to obtain high strength. Use of mineral admixtures, especially silica fume, became more popularly after the usage of high-range water-reducing admixtures. In the case of fibre reinforced concrete, these admixtures produce a denser matrix, resulting in better mechanical properties of the concrete. For shotcrete applications, such as tunnel linings, the addition of silica fume has been found to reduce rebound. The addition of silica fume has been found to improve the bond between fibres and the matrix, durability of fibres added to the concrete (Rafat Siddique, 2002).

1.4.5 Other Chemical Admixtures

Air entraining and retarding admixtures have also been used in FRC. Air entrainment admixture is the most commonly used admixtures for exposed structures. Studies have shown that air entrainment is needed for exposed FRC structures such as pavements and linings, since FRC is as susceptible as plain concrete to freeze-thaw cycling as described by Balguru and Ramakrishnan (1986). Accelerating admixtures are normally used for shotcrete applications to hasten the setting process. Retarding admixtures are used when a reduction in the heat of hydration is needed.

1.4.6 Special Cements

Cementing materials other than Portland cement can also be used for fibre composites. There are primarily two classes of cementing materials in this category. The first consists of cementing materials developed for repairs. These are either blended Portland cements, such as rapid-set cement, or they are chemicals
that can act as cementing agents themselves, such as magnesium phosphate, which can develop compressive strengths up to 40MPa within an hour. Addition of fibres to these cementing materials was found to improve the shrinkage characteristics and ductility of the matrix as described by Balaguru (1992).

The second category of cementing material consists of low-cost materials such as lime or clay. These matrices are normally used with naturally occurring fibres in developing countries. One exception is the use of gypsum in industrialized nations for manufacturing a variety of building products.

1.4.7 Fibres

These are strong thread like filaments which when used in the concrete acts crack arrester. Continuous meshes woven fabrics and long rods do not fall within the category of discrete fibre type reinforcing elements. The main aim of introducing the fibres is to arrest cracks developed due to loading by applying the pinching force on the crack face. It doesn’t allow the cracks to widen further and thus creates a low crack propagation state. The fibre is often described by convenient numerical parameters called “Aspect Ratio”. It is the ratio of the length of the fibre to the least lateral dimension of the same. It normally ranges from 30 to 150 for fibre lengths of 6mm to 75mm (Sidney Mindess, 1981).

The further development of fibre reinforced concrete entirely depends upon the utility of appropriate type of fibre. Thus several investigations that had been carried out in the countries all over the world have made different types of fibres come in the field (Sidney Mindess, 1981).

1.4.7.1 Role of Fibres

When the loads imposed on concrete approach that for failure cracks will propagate, sometimes rapidly; fibres in concrete provide a means of arresting this crack growth. Reinforcing steel bars in concrete have the same beneficial effect because they act as long continuous fibres. Short discontinuous fibres have the advantage, however, of being uniformly mixed and dispersed throughout the concrete. Fibres are added to a concrete mix which normally contains cement, water and fine and coarse aggregate. Among the more common fibres used are steel, glass, asbestos and polypropylene (Parameswaran, 1988).

If the modulus of elasticity of the fibre is high with respect to the modulus of elasticity of the concrete or mortar binder, the fibres help to carry the load, thereby increasing the tensile strength of the material. Increase in the length: diameter ratios of the fibres usually augment the flexural strength and toughness of the concrete.
The values of this aspect ratio are usually restricted to between 100 and 200 since fibres which are too long tend to 'ball' in the mix and create workability problems (Parameswaran, 1988).

Unlike the fibre composites in resin and metal matrices, in which the fibres are aligned and amount to 60 to 80% of the composite volume, fibre cement/concrete composites contain much less fibres which are arranged in planar or random orientation. Since the tensile cracking strain of the cement matrix is very much lower than the yield or ultimate strain of the fibres, matrix cracking will occur at some level of loading before the maximum strength of the composite is reached. In the post cracking stage, the failure of the composite is generally by fibre pullout rather than by fibre yielding or fracture. In fibre reinforced concrete, therefore, fracture is a continuous process and not confined to the final stage only. The process of cracking occurs over a wide range of loading, and debonding of fibres occurs over several stages as shown in fig 1.1. In the post-cracking stage the resistance to full separation of the composite is provided by the fibres bridging across the cracked surfaces (Parameswaran, 1988).

![Diagram](attachment://fig1.1.png)

**Fig 1.1:** Multiple cracking process and stress/strain curve, related to the multiple cracking process (Source: Bentur and Mindeness, 1990).
The increase in strength by the use of fibres, the degree of ductility and the extent of post-cracking behaviour and whether simple or multiple cracking occurs depend on the strength characteristics of the fibres themselves, bond in the matrix-fibre interface, the ductility of the fibres, the volume of the fibre reinforcement and its spacing, the dispersion and orientation of the fibres and their shape and aspect ratio. High strength fibres, large volume of fibres, larger fibre lengths, and smaller fibre diameters have been found independently to improve the strength (Parameswaran, 1988).

The fibres may be non-uniformly dispersed and randomly oriented shown in fig 1.2. The orientation and dispersion effects may depend, among other things on the loading conditions. As a rule, fibres are generally randomly distributed in the concrete. Unidirectional fibres uniformly distributed throughout the volume are the most efficient in uni-axial tension. While flexural strength may depend on the unidirectional alignment of the fibres dispersed far away from the neutral plane, flexural shear strength may call for a random orientation. A proper shape and higher aspect ratio are also needed to develop adequate bond between the concrete and the fibres so that the fracture strength of the fibres may be fully utilized (Parameswaran, 1988).

![Diagram of fibre arrangement](image1)

Fig 1.2: Classification of fibre arrangement in 1, 2 and 3 dimensional (Source: Bentur and Mindess, 1990)

Descriptions:
(a) 1-dimensional arrangement
(b), (c) 2-dimensional arrangement
(d) 3-dimensional arrangement (a), (c) Continuous fibres (b). (d) Short discrete fibres
1.5 Definitions of some Parameters

1.5.1 Aspect Ratio

It is the ratio of the fibre length/equivalent fibre diameter where the equivalent diameter is the diameter of a circle having the same cross sectional area as the fiber (in the case of a plain circular fibre, it is the actual diameter of the fibre itself).

1.5.2 Minimum Effective Length: ($l_m$)

It is the minimum length at which the fibres have any effect on the first-crack strength of the concrete matrix.

1.5.3 Critical Length: ($l_c$)

It is the length above, which the fibres will fracture, rather than pull out when the crack intersects the fibre at its midpoint. It has been shown that the critical length is approximated by

$$l_c = \frac{d}{2\tau \times \sigma_f}$$

Where $d$ is the fibre diameter, $\tau$ is the interfacial bond stress, and $\sigma_f$ the fibre strength.

1.5.4 Orientation Factor or Fibre Efficiency Factor

This factor denotes the efficiency with which randomly oriented fibres can carry a tensile force in any one direction. Assuming perfect (three-dimensional) randomness, this can be shown to be 0.41 $l$, where $l$ is the fibre length, but with different assumptions (e.g. orientation effects near the surface), values from about 0.33 to 0.651 have been obtained. The effectiveness of fibre orientation is illustrated in table 1.1

<table>
<thead>
<tr>
<th>Orientation</th>
<th>% Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unidirectional</td>
<td>100</td>
</tr>
<tr>
<td>Orthogonal</td>
<td>40-50</td>
</tr>
<tr>
<td>Random planar (2D)</td>
<td>30 to 40</td>
</tr>
<tr>
<td>Random Spatial (3D)</td>
<td>41 (15-20)</td>
</tr>
</tbody>
</table>

1.5.5 Spacing Factor

If the fibres are close enough together, the first cracking strength is higher than that of the matrix alone because the fibres effectively reduce the stress intensity factor, which controls fracture. Using the concepts of fracture mechanics, Romualdi and Batson (1963) observed that, for the same volume of continuous reinforcing
of steel, if the spacing between the reinforcing bars or wires is reduced to less than 10.2mm, then the tensile strength of concrete itself is significantly increased. As a result, the load to initiate cracking is increased. However, there is no effect of spacing of wires on the ultimate strength, as concluded by Broms and Shah (1992). Realising the practical difficulties of achieving very small spacing with continuous wires, Romualdi and Mandel (1964) tested mortar reinforced with randomly distributed short steel wires and came to the same conclusion as with continuous wires, namely, that for spacing less than 10.2mm, tensile strength is proportional to the inverse square root of fibre spacing. This is because, at appropriate small spacing, cracks originating as incipient flaws are prevented from enlarging and propagating throughout the tension zone. Expressions for finding the average spacing and the percentage of reinforcement effective in crack control were also given by them. They also suggested that the existence of the ‘crack arrest mechanism’ in steel fibre reinforced concrete might result in high fatigue and impact resistance.

A typical expression for spacing factor, \( s \) is given by

\[
S = 13.8 \, \frac{d}{\sqrt{1/p}}
\]

Where \( d \) is the diameter and \( p \) the present fibre (by volume). Other similar expressions have also been developed. Swamy, Mangat and Rao (1974) have proposed strength equation based on effective spacing concept which takes into account the interfacial bond stress due to stress transfer at the onset of cracking of the matrix.

1.6 Load-Deflection Relationship

A typical load-deflection curve for fibre-reinforced concrete in flexure is shown in fig 1.3 as described by Paramewaran (1988). Point A represents the load at which the matrix begins to crack, referred to as the ‘first crack strength’. Usually, this is at about the same stress at which cracking occurs in non-reinforced concrete, and thus the segment OA is about the same for plain and fibre-reinforced concrete. Once the matrix is cracked, the fibres bridging the crack must carry the entire load. The segment AB represents the region where there is continued cracking of the matrix and some debonding and pulling out of the fibres. The maximum load (point B) depends on the fibre content and geometry. It should be noted that during this part of the debonding and pulling-out process, the fibre stress is generally substantially less than the yield stress of the fibres, so yielding of the fibres does not occur. In the declining portion of the curve, BC, matrix cracking and fibre pull-out continue: if the fibres are long enough to maintain their bond, they may eventually fail by yielding or fracture in this region.
of the curve. A reasonably good empirical equation has been developed by ACI Committee 544 (dealing with fibre reinforced concrete) for the ultimate strength $S_c$ as under:

$$S_c = AS(1-V_f) + BV_f(l/d)$$

Where $S$ is the ultimate stress of the matrix, $l/d$ aspect ratio, $V_f$ the volume fraction of fibres adjusted for the effect of randomness, and $A$ and $B$ are constants which can be obtained by a plot of $V_f(l/d)$ against composite strength.

![Load-Deflection curve](image)

Fig 1.3: Typical Load-Deflection curve for Fibre-Reinforced concrete in flexure

1.7 Mechanism of Fibre Reinforcement:

The idea behind fibre reinforced concrete as described by Rafat Siddique (2002) is shown in fig 1.4. Without the fibres the crack runs through the materials very easily indeed. It does not matter whether the crack is present initially or not. Brittle materials including concrete, possesses minimum resistance to any dangerous flaw.

When concrete is reinforced with small discrete fibres the fibres effectively help in delaying the occurrence of the first crack. However if cracks are present and the breaking strain is much greater—say 10 times greater than the cracking strain of concrete, then the fibres remain in place bridging the crack. Of course, the fibres, besides having larger failure strain that the matrix must be able to withstand the load placed upon them when the matrix breaks. This means that they must also be sufficiently strong. If both conditions are fulfilled then even if the crack in the concrete runs straight across the piece, the piece will remain unbroken because the
fibres hold it together. If at this stage straining is continued, the weak concrete will break again at another place and again will be held together by fibres bridging the cracks.

If FRC material is loaded in flexure, two distinct stages are generally observed in the load deflection curve as shown in Fig 1.5. The curve can be considered almost linear up to point X and beyond point X, the curve is significantly non-linear and attains a maximum at point Y. The load of the stress corresponding to point X has been called “first crack strength”, “elastic limit”, “proportionality limit”, while the stress corresponding to point Y has been called as “ultimate strength”.

Properties of FRC depend in general on the length, diameter and quantity of fibres, other factors include the degree of consolidation, which in turn depends on w/c ratio consolidation techniques and amount of fibre etc and also on the uniformity of fibre distribution and the surface condition of fibre.

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(a) No Fibres (Plain Concrete)

(b) Plain concrete with short discrete fibres

(c) Reinforcing bars or Pre-stressing wire, fibres or conventional continuous reinforced with short fibres

Fig 1.4: Flexural failure in an unreinforced beam and in beams with fibres
1.8 Fibre-Matrix Bond

For a composite system such as fibre-reinforced concrete, the mechanical behaviour depends not only on the properties of the fibre and the concrete, but also on the bonding between them. The nature of the interface in the cement-based systems is particularly complicated, since there may be chemical reaction between the cement and some types of fibre. Also, the nature of the interface may change with time as the cement matures or undergoes time-dependent volume changes. However, the general form of the bond is fairly well known for the different classes of fibres Parameswaran (1988).

- **Steel**: A combination of adhesion, friction, and mechanical interlocking, although some chemical reactions may also occur.
- **Glass:** There is some reaction between the cement and the glass; in particular, alkali attack tends to weaken the fibre reinforcement, although to a much lesser extent with the alkali-resistant glasses.

- **Organics:** The bond is primarily mechanical interlocking.

As mentioned above, most fibre-reinforced concrete failures occur due to bond failure (fibre pull-out). It is possible to increase the bond strength substantially by deforming the fibres in various ways so as to increase the end anchorage. Large changes in the bond strength are not reflected by similar changes in the concrete strength, but will improve the post-cracking behaviour. A very good bond may increase the tensile strength, while a poor bond may increase the energy absorption. A combination of critical length ($l_c$) and high modulus (and bond), high elongation fibres is suggested by Swamy for optimizing strength and energy absorption properties. Table 1.2 shows the pullout strengths for a number of different fibres in various matrices (Parameswaran, 1988).

**Table 1.2: Typical Fibre-Matrix Pull-out Strengths**

<table>
<thead>
<tr>
<th>Matrix</th>
<th>Fibre</th>
<th>Pull-out Strength (MPa)</th>
<th>Pull-out Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement paste</td>
<td>Asbestos</td>
<td>0.8-3.2</td>
<td>0.8-3.2</td>
</tr>
<tr>
<td></td>
<td>Glass</td>
<td>6.4-10.0</td>
<td>6.4-10.0</td>
</tr>
<tr>
<td></td>
<td>Polycrystalline Alumina</td>
<td>5.6-13.6</td>
<td>5.6-13.6</td>
</tr>
<tr>
<td></td>
<td>Steel</td>
<td>6.8 to 8.3</td>
<td>6.8 to 8.3</td>
</tr>
<tr>
<td>Mortar</td>
<td>Steel</td>
<td>5.4</td>
<td>5.4</td>
</tr>
<tr>
<td>Concrete</td>
<td>Steel</td>
<td>3.6 (First crack)</td>
<td>3.6 (First crack)</td>
</tr>
<tr>
<td></td>
<td>Nylon</td>
<td>0.14</td>
<td>0.14</td>
</tr>
<tr>
<td></td>
<td>Polypropylene</td>
<td>1.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>

1.9 **Shape, Geometry and Distribution of the Fibres in Cement Matrix**

The largest influences on the fibre reinforced concrete however were the shape, geometry and mechanical properties of fibres and the dispersion of fibres in the cementitious matrix. The knowledge on the fibre properties is important for design purpose. James (1990) stated that the high ratio of fibre modulus of elasticity would have direct influences to the matrix modulus of elasticity where this facilitates the stress transfer from the matrix to the fibre. Fibre which has a higher tensile strength is essential to reinforcing action. Furthermore, fibres that have large values of failure strain will tend to have high extend or prolongation in the composites. The most common types of fibres were steel fibres and polymers fibres, due to low cost and their
availability. However, other types of fibres may be used in the concrete composites depending on the needs. The properties and their respective types of fibres were shown in Table 1.3. Properties of cement matrix were also included in the Table.

Table 1.3: Fibre types and their properties (Source: James, 1990)

<table>
<thead>
<tr>
<th>Fibre type</th>
<th>Specific Gravity</th>
<th>Modulus of Elasticity (GPa)</th>
<th>Tensile Strength (GPa)</th>
<th>Failure Strain (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td>7.8</td>
<td>200.0</td>
<td>1.0-3.0</td>
<td>3.0-4.0</td>
</tr>
<tr>
<td>Glass</td>
<td>2.6</td>
<td>80.0</td>
<td>2.0-4.0</td>
<td>2.0-3.5</td>
</tr>
<tr>
<td>Asbestos</td>
<td>3.4</td>
<td>196.0</td>
<td>3.5</td>
<td>2.0-3.0</td>
</tr>
<tr>
<td>Nylon</td>
<td>1.1</td>
<td>4.0</td>
<td>0.9</td>
<td>13.0-15.0</td>
</tr>
<tr>
<td>Carbon</td>
<td>1.9</td>
<td>380.0</td>
<td>1.8</td>
<td>0.5</td>
</tr>
<tr>
<td>Polypropylene</td>
<td>0.9</td>
<td>5.0</td>
<td>0.5</td>
<td>20.0</td>
</tr>
<tr>
<td>Polyester</td>
<td>1.4</td>
<td>8.2</td>
<td>0.7-0.9</td>
<td>11.0-13.0</td>
</tr>
<tr>
<td>Polyethylene</td>
<td>0.9</td>
<td>0.1-0.4</td>
<td>0.7</td>
<td>10.0</td>
</tr>
<tr>
<td>Sisal</td>
<td>1.5</td>
<td>26.5</td>
<td>0.8</td>
<td>3.0</td>
</tr>
<tr>
<td>Kevlar</td>
<td>1.5</td>
<td>133.0</td>
<td>2.9</td>
<td>2.6</td>
</tr>
<tr>
<td>Wood fibre</td>
<td>1.5</td>
<td>71.0</td>
<td>0.9</td>
<td>-</td>
</tr>
<tr>
<td>Cotton</td>
<td>1.5</td>
<td>4.8</td>
<td>0.4-0.7</td>
<td>3.0-10.0</td>
</tr>
<tr>
<td>Acrylic</td>
<td>1.1</td>
<td>2.0</td>
<td>0.2-0.4</td>
<td>25.0-45.0</td>
</tr>
<tr>
<td>Rayon</td>
<td>1.5</td>
<td>6.8</td>
<td>0.4-0.6</td>
<td>10.0-25.0</td>
</tr>
<tr>
<td>Cement matrix</td>
<td>3.15</td>
<td>10.0-45.0</td>
<td>0.003</td>
<td>-</td>
</tr>
</tbody>
</table>

James (1990) stated that having a lower Poisson's ratio prevented these problems on fibre-matrix interface associated with the fibre debonding. Furthermore, Riley (1968) stated that most fibres have surface flaws, due to handling, processing and manufacturing, as these surface defects can affect the strength properties of the composite. Such presence of flaws varies by fibre length and diameter, which acts to strength reduction of fibre-reinforced concrete. Additionally, the tensile strength of the fibres decreases when the fibre length increases (James, 1990).

Each type of fibre can be categorised into two groups:

- Discrete monofilaments, which each fibres were separated one from another (e.g. steel)
- Bundles of filaments, which all the fibres assemble together as each with a diameter of 10μm or less.

Majority of man-made fibres, such as inorganic fibres (e.g. glass), organic fibres (e.g. carbon, Kevlar) and natural fibres (e.g. asbestos).

The monofilaments fibres due to their uniform improvement were commonly used in structural concrete to enhance the fibre-matrix interaction through mechanical anchoring such as ductility, toughness and strength of
The monofilaments fibres are rarely in an ideal cylindrical shape, but usually deformed into different configuration they desired. This configuration of fibres is shown in fig 1.6.

Bundled fibres usually do not break up into separate filaments, as they maintain their bundled nature in the cement matrix. This is shown in fig 1.6.

The reinforcing arrays of fibres were in two different ways: Continuous reinforcement and Discrete short fibres. The continuous reinforcement was usually in the form of long fibres, which incorporated to the matrix in the methods of filament winding or layers of fibre mats. However, discrete short fibres with a length approximately 50mm or less, incorporated to the matrix in the methods of spraying and mixing. The reinforcing arrays are classified as the distribution of fibres in the matrix as 1-, 2- or 3-dimensional. The fibres may be non-uniformly dispersed and randomly oriented. The classification of fibre arrangement was shown in figure 1.2. The orientation and dispersion effects may depend, among other things on the loading conditions. As a rule, fibers are generally randomly distributed in the concrete. Unidirectional fibres uniformly distributed throughout the volume are the most efficient in uniaxial tension. Whole flexural strength may depend on the unidirectional alignment of the fibres dispersed far away from the neutral plane; flexural shear strength may call for a random orientation. A proper shape and higher aspect ratio are also needed to develop adequate bond between the concrete and the fibres so that the fracture strength of the fibres may be fully utilized.

Plate 1.1: Monofilaments fibres and Bundled fibres. (Source: Bentur and Mindness, 1990)
1.10 Types of Fibres

Depending upon the parent material used for manufacturing fibres can be broadly classified as:

1. Metallic fibres (e.g. Low carbon steel, Stainless steel, Galvanized iron, Aluminum)
2. Mineral fibres (e.g. Asbestos, Glass, Carbon)
3. Organic fibres or Polymeric or Plastic or Synthetic (e.g. Cotton, Resin, Polyester, Nylon, Polypropylene and Polyethylene)
4. Inorganic or Natural fibres (e.g. Akwara, Bamboo, Coconut, Flax, Jute, Sisal, Sugarcane bagasse, Wood, Coir and others)

1.10.1 Metallic Fibers

Metallic fibers are made of either carbon steel or stainless steel. The tensile strength ranges from 345 to 1380MPa. The minimum strength specified in ASTM is 345MPa. The modulus of elasticity for metallic fibers is about 200GPa. The fiber cross section may be circular, square, crescent-shaped, or irregular. The length of the fibers is normally less than 75 mm even though longer fibers have been used. The length-diameter ratio typically ranges from 30 to 100 or more. Among metallic fibers the steel fibers are most widely used. As these fibers fulfill all the requirements and add to the properties of concrete. Application of these types of fibers is gaining importance. It has been observed that the steel gives good results (Balaguru and Surendra, P. Shah, 1992).

1.10.2 Fibre Shape and Geometry

Since last few decades, extensive studies carried out on this subject, have resulted in bringing up different shapes.

It is interesting to know that even the shape of fibre affects the strength of the member. The fibre can have any shape such as (a) Straight slit sheet or wire (b) Deformed slit sheet or wire (c) Crimped-end wire (d) Flattened-end slit sheet or wire (e) Machined chip (f) Melt extract etc. Some of the fibre shapes commonly used are shown in fig.1.7

The fibres may be categorized as straight, deformed, rippled, with special ends (e.g. enlarged or hooked ends) and with irregular cross sections.

Round, straight steel fibres are produced by cutting into pieces thin wires having a diameter in the range of 0.25 to 1 mm. Flat straight steel fibres are produced either by shearing thin sheets that are 0.16 to 0.41 mm thick or by flattening wires. These fibres have a width in the range of 0.25 to 1 mm. Crimped or
crimping the full length produces deformed fibres. Deformations are also made by flattening of wires to increase bonding. Fibres with crimped (hooked) ends are also available in collated form. Collation is done by gluing the fibres together along their sides with water-soluble glue. The glue dissolves during the mixing process, facilitating the distribution of individual fibres. Therefore, large fibre volume fractions of fibres with higher length-diameter (aspect) ratio can be incorporated into the concrete without balling of the fibres (Balaguru and Surendra. P.Shah, 1992).

Fibres are also produced from wires that have been shaved down in the steel wool making process. These wires, which have a crescent shaped cross section, are chopped and crimped to produce deformed fibres (Balaguru and Surendra. P. Shah, 1992).

Fibres produced by melt extraction processes have an irregular surface and are of crescent-shaped in cross section. Elongated chips produced by chatter machining, are also being used as fibres. These fibres have a rough and irregular surface (Balaguru and Surendra. P.Shah. 1992).

Fig 1.7: Various shapes of steel fibers used in fiber-reinforced concrete

1.10.3 Steel Fibers

Steel fibers for use in concrete are available in a number of shapes, sizes and metal types. Currently three different processes produce them
a. Wire drawing process
b. Melt extract process
c. Slit sheet process

1.10.3.1 Wire Drawing Process

In this process, cold-drawn wire is chopped to specific length. Sometimes these are collated with water-soluble glue into bundles of 10 to 30 fibers to facilitate handling and to increase their bond and anchorage parameters. The main disadvantage of this process is that the fibers produced are very costly. The other two processes which were developed in USA overcame this drawback. The use of scrap steels in slit sheet and melt extract processes ultimately results in fibers of low cost as compared to the fibers produced by this process.

1.10.3.2 Melt Extracts Process

This process, as shown in fig.1.8, one of the 100 top most industrial developments in USA was developed in 1971. It is capable of producing from scrap steel in many forms.

In this process, the periphery of a rotating multi edged heat-extracting disc is brought in contact with the surface of molten metal. As the periphery of the disc passes through the molten metal, the metal adheres to the disc, solidifies and continues to cool. As a result of thermal contraction and centrifugal force, the metal in the form of fibers is spontaneously thrown free of the disc after a short resident time.

The diameter of such fibers varies from 0.25mm to 0.76mm. Some time's also flat steel fibers, rectangular in cross section are used. Their cross section is 0.15 to 0.4 mm in thickness and 0.25 to 0.90 mm in width. Fibers square and rectangular in cross-section are produced by shearing sheets or flattening wires.

1.10.3.3 Slit Sheet Process

In this process, sheet of metal is cut or slit, producing a square or rectangular fiber, the process is as shown in fig.1.9. The steel strip guided by feed rollers comes in contact with the rotating cutter i.e. roller with blades at the circumference and thus gets chopped into thin fibers. Thus, these fibers are produced by cutting or chopping thin strips of steel and are called slit sheet process. As not much heavy machinery and labour is required, the cost of installation of this plant is very low and so is the cost of fibers (Prakash,K.B. 1998).
Many different fibers, with round, rectangular and crescent shaped cross sections, are commercially available. Plate 1.2 shows types of fibres available on market. They range in ultimate strength from 345 to 2070 MPa.

Fig. 1.8: Melt Extract Process

Fig 1.9: Slit Sheet process

Fiber sizes range from 13 x 0.25 mm to 64 x 0.76 mm. However, most successful shotcrete applications have utilized fibers with length of 13 to 30 mm. Brass plated cut steel wire tire cord with strength of 2758 MPa.
has been successfully used in investigation (Ramakrishnan, 1991). Fibers with hooked or deformed ends could be used in smaller quantities because they develop higher pullout resistance. Fibers with large surface area, square or rectangular as compared to round, have more concrete bonding area. Fibers with pitted surface have a greater surface area (Technical Manual, ICFRC-TM4, 1997).

Most of the early applications of FRC consisted of using relatively high fiber loadings of straight steel fiber, of relatively small diameter and high aspect ratios. These large quantities were needed to obtain higher flexural strengths. This caused serious problems namely "balling" of fibers during the mixing operation and "pull-out" of the straight fiber during loading due to lack of adequate anchorage. Balling of fibers in the mixer prevents uniform distribution and also causes problems when concrete is placed. Because of the pullout of the fibers, the SFRC did not achieve the required ductility and post-crack load carrying capacity. The addition of straight fibers had to be done by special vibrating sieves or manual sprinkling. The introduction of a new type of fiber (with hooked ends and bundled together with a water soluble glue) has eliminated these problems (Ramakrishnan, 1980). Collation of the fibers has eliminated balling and the fibers could be added to the mixer along with the aggregates all at one time eliminating the need for special devices and additional labor for addition of fibers. The improved anchorage (hooked ends) has made it possible for considerably smaller quantities (40% less) of fibers to produce the desired properties (Ramakrishnan, 1980). The later development of other deformed fibers (corrugated, crimped, paddled, etc.) had similar results of eliminating balling and they have improved anchorage (Ramakrishnan, 1989).

Fibre that has found extensive engineering application is steel. Most of the steel fibres available for use in concrete are obtained by cutting drawn wires, and fibres with different types of crimps, indentations, and shapes to increase mechanical bond are also being produced (e.g., Duoform). Steel fibres with lower tensile strength are also produced from low carbon flat rolled steel coils (e.g. Fibrecon). It has been found that steel tensile strength has little influence on the first crack flexural strength; although it may have a significant effect on the ultimate flexural strength if the composite failure occurs by fibre failure rather than by fibre pull out. The efficiency of the fibre distribution depends on the geometry of the fibre, the fibre content, the mixing and compaction techniques, the size and shape of the aggregates and the mix proportions (Rafat Siddique, 2002).
Plate a: Enlarged end, Deformed sheet steel fibres, and Steel fibres
(Source: www.scirus.com)

Plate b: Typical example of Steel fibres, Tores twisted triangular and square steel bars and Dramix Steel fibres
(Source: Japan Concrete Institute, Indian concrete Journal, and Grace Construction Products)

Plate c: Typical example of Glass fibres and Drums of Glass fibre strands
(Source: www.scirus.com and J & J Trading Corp. 2002)

Plate d: Synthetic "Structural" fibres and Polypropylene "Micro" fibres
(Courtesy: Grace Construction Products)

Plate e: Twisted wave geometry of Synthetic fibres (Film type) and Mesh geometry of Synthetic bundled or Polypropylene fibres (Monofilament type)
(Source: Bennur and Mindess, 1990)

Plate 1.2 Types of fibres available on market
Steel fibre reinforced concrete materials have been used for overlays and over slabbing for roads, pavements, airfields, bridge decks, and industrial and other flooring, particularly those subjected to wear and tear, and chemical attack. Guniting has been successfully applied with steel fibres (Rafat Siddique, 2002).

Different geometries and shapes of steel fibres are widely used in industry to fulfil the desirable behaviour and properties requirement of concrete. Fig. 2.0 below shows some deformed fibres that available in the market.

<table>
<thead>
<tr>
<th>Schematic cross section Profile</th>
<th>Equivalent diameter</th>
<th>Inventory lengths</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.5-0.8</td>
<td>30, 50, 60</td>
</tr>
<tr>
<td></td>
<td>0.4</td>
<td>19, 25</td>
</tr>
<tr>
<td></td>
<td>0.8, 1.0</td>
<td>25 to 76</td>
</tr>
<tr>
<td></td>
<td>0.3 to 0.5</td>
<td>19 to 36</td>
</tr>
<tr>
<td></td>
<td>0.4, 0.6</td>
<td>30</td>
</tr>
</tbody>
</table>

Fig 1.10: Different types and geometry of steel fibres. (Source: Bentur and Mindess, 1990)

1.10.4 New Development in Steel Fibres

Using Melt Overflow as a production process in the late 1980's, Ribbon Technology Corporation has recently introduced two new types of steel fibers for concrete. It is claimed (RIBTEC, 1993) that because of mass production these fibers are more cost effective than fibers made from drawn wire and other wrought metal processes. Corrosion resistant 16 mm fine fibers are used for crack controlling reinforcement for concrete. So far steel had not been used as such fine fiber. It is claimed (RIBTEC, 1993) that these fibers will perform as well or better than the polypropylene fiber with the cost equivalent or slightly less than the polypropylene. The high modulus of elasticity of the steel fiber has the advantage over the polypropylene fiber in having less deformation.

The second application of these fibers is in shotcreting and particularly as a stainless steel alloy for shotcreting of thin architectural panels. Thus these fibers could replace the unstable glass fibers currently used for these applications. Higher modulus and unlimited life of the reinforcement are the added advantages compared to glass fibers. These fibers could also be used as supplemental reinforcement of normal steel fiber reinforced concrete and increase the first crack strength significantly (Technical Manual, ICFRC-TM4, 1997).
Another significant development is the production of steel fiber mats in continuous lengths and widths up to 1.22m wide and 50 mm thick. The mats are made of long steel fiber spun directly from the molten metal and air laid on a conveyor system to form an entangled mat of uniform density, thickness and width. These mats are then coiled into a large roll with a carrier material interlaid between the mat layers. These non-woven mats utilize fibers with aspect ratios exceeding 500. Typical aspect ratios currently used range from 40 up to 100 and special handling procedures may be required as the aspect ratio approaches 100. Since the mat is already in the preformed shape, handling problems are minimized and balling does not become a factor (Technical Manual, ICFRC-TM4, 1997).

This steel fiber mat which is a new concept in concrete reinforcement will be better suited for thin shell or thin layer concrete reinforcement such as thin overlays for bridge decks and industrial floors and thin faced tilt wall panels (Technical Manual, ICFRC-TM4, 1997).

1.10.5 Low Carbon Steel Fibres

The low carbon steel fibres are more corrosive and its strength is less as compared with mild steel. Also, its cost is high. So they are rarely used.

1.10.6 Galvanized Iron Fibres

The typical properties of galvanized iron fibres are more ductility and more shock absorbent capacity. These are very useful properties while dealing with some special structures such as blast resistance structures.

1.10.7 Aluminium Fibres

These fibres are light in weight and highly ductile. But their strength is less and cost is high as compared with steel fibres.

1.10.8 Durability

Steel fibre corrosion may be a major concern of durability of fibre reinforced concrete. Guidelines set in AS3600 stated that corrosion in conventional steel reinforcement could be avoided if suitable cover is provided. However, these guidelines are only applicable at particular position for conventional steel reinforcement. On fibre reinforced concrete, the steel fibres were randomly distributed throughout the matrix, as some corrosion can happen at the surface of the concrete, where it is very difficult for each fibres cover with the cement. However, with cement cover more than 1mm, the fibres are safe from corrosion.
Thus, corrosion of steel fibre was considered a minor problem, as it does not affect much on the mechanical properties of the fibre reinforced concrete (Chuan Mein Wong, 2004).

a. Formation of Steel Balls or Balling Effect

When the fibres are being mixed in concrete they get clumped into one another, this clumping of fibres forms steel balls, which affects the strength and structural properties of the concrete as proper distribution, is not possible (Prakash, K.B. 1998). The typical balling effect is shown in the fig 2.1

Fig 1.11: Formation of Balling (Source: World Intellectual Property Organization)

b. Corrosion

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 the material, thus aiding the tendency for electrochemical corrosion. This results in reduction of strength of fibres and thus the strength of concrete. But it has been observed that the fibres exposed to the surface show evidence of corrosion whereas internal fibres are not at all affected.

These problems can be overcome by-

- Proper and careful mixing
- Optimum use of water in concrete mix

1.10.9 Mineral Fibres

1.10.9.1 Asbestos

It is naturally occurring fibrous silicate derived from rocks as cross fibres seams or veins. The asbestos fibres are commonly used in the manufacture of asbestos cement. Volume fraction of up to 15% of asbestos fibres can be mixed with Portland cement to give quite successful commercial product i.e. asbestos cement.
a. Properties of Asbestos Fibres

Asbestos fibres are made of natural crystalline fibrous minerals. Asbestos/cement was the first fibre-reinforced composite in modern times and still use more than any other fibre-reinforced materials. These fibres are largely in success for fibre-reinforce materials result form the compatibility between the fibres and cement matrix. Asbestos fibres relatively have high modulus of elasticity and strength, which permits effective dispersion of large fibre volume and enhance the bond between cement matrixes. These fibres are utilized with fibre-reinforced materials suitable in low cost housing and infrastructure (Chuan Mein Wong, 2004). Since these fibres absorb more water, greater w/c is required in production of FRC. These fibres try to cling with each other resulting in accumulation of fibres at one place. Due to this balls of fibres are formed and proper distribution of fibres becomes a problem.

The inhalation of asbestos dust leads to a health hazard known as “ASBESTOSIS” which is actually a lung cancer. Even though these fibres create problems when used on the field, it is observed that for composite concrete construction, the asbestos fibres bring about better results.

1.10.9.2 Glass Fibres

Soviet research in late 1950’s explores low alkali of glass fibres in cement system, which having a low value of pH. It is until 1960’s, glass fibres were classified as possible reinforcement to high pH value of cement systems (James, 1990). Glass fibres is a strong, lightweight material, which stands with tremendous fracture toughness, posses high tensile (280 to 3500MPa) and modulus of elasticity (3.1 to 3.5 GPa) in high alkaline cement systems (Chuan Mein Wong, 2004).

a. Development of glass fibre

Glass fibres have been developed mainly in the production of thin sheet components, using glass as reinforcing bars, impregnated and saturated plastics. Glass fibres are produced in the process in which molten glass extracted by the form of filaments, at the bottom of a heated platinum tank. As filaments are extracted at the same time, they coagulated while cooling outside the tank. The filaments are collected as strands in a drum. Finally, the filaments are chopped into short strands to take random positions and applications on a cement matrix (Chuan Mein Wong, 2004).

b. Durability

Special technologies and development are required for glass fibres as a feature of alkali-resistant glass. The problem is that a low alkali resistant of E-type of glass fibres (made of borosilicate), which is
commonly used to reinforcing plastic, will weaken promptly in high alkali-environment of cement matrix. The alkaline nature of concrete takes place and cause damaging chemical reaction between cement and glass fibre. To inhibit this problem, a special type of alkali resistant glass, the AR type of glass fibres (made of soda-lime silicate) was developed, which reduces corrosion of glass fibre in the cement matrix (Bentur et. al, 1990). The development and research of glass fibres in a cement matrix ensures long-term durability and effectiveness of load bearing capacity when embedded in the highly alkaline environment (Chuan Mein Wong, 2004).

It is an amorphous substance having silicate of sodium and other materials. Glass fibres can be manufactured by blowing the compressed air into the molten glass or by centrifugal the molten glass.

Glass fibers are primarily used for glass fiber-reinforced cement (GFRC) sheets. Regular E-glass fibers were found to deteriorate in concrete. This observation led to the development of alkali-resistant, AR-glass fibers.

Glass fibres are produced commercially in three basic forms, namely, roovings, strands and woven or chopped strand mat. The individual filaments vary from 10 to 20 micron, and are coated with sizing to protect the fibre from surface abrasion as well as to bind them into a strand (Rafat Siddique, 2002).

Commonly used glass fibers are round and straight and have diameters of 0.005 to 0.015 mm, but these fibers may be bonded together to produce glass fiber elements with diameters of 0.013 to 1.3 mm. The strength of glass fiber is comparable to that of steel fiber, its density is lower, and its elastic modulus is about one third of steel. A major disadvantage of glass fiber is its vulnerability in the alkaline cementitious environment, which seriously damages the long-term properties of glass fiber reinforced concrete. Attempts have been made in recent years to develop alkali resistant glass fibers (Technical Manual, ICFRC-TM4, 1997).

The major application of glass fiber has been the spray-up process in which the glass fibers and a cement rich mortar are sprayed simultaneously on a surface.

There are however, two main problems in the use of glass fibres in Portland cement products, namely, the breakage of fibres, and the surface degradation of the glass in the highly alkaline of the hydrated cement paste. There are now several manufacturing processes that show promise of producing glass fibre reinforced cement products without the severe shattering of fibres associated with conventional asbestos cement manufacturing from chemical processes. To prevent the glass fibres from chemical attack, corrosion
resistant coatings, usually resin based, have been applied, and after this, alkali-resistant glasses have been produced that appear to be satisfactory for use with Portland cement. Fabrication techniques play an important part in the strength of glass-fibre reinforced elements. The use of a high water binder ratio is essential so that the slurry can be worked, the excess water being removed by suction or pressing techniques.

While the spray suction technique produces a two dimensional random array of fibre reinforcement, conventional mixing with random dispersion of fibres can also be used. In both the techniques, glass fibre lengths of 10 to 50 mm can be used. Both these methods have been used to produce cladding panels, window frames, and other building and bridge components. There is considerable improvement in impact strength $20-25 \times 10^3 \text{J/m}^2$ compared to $3-5 \times 10^3 \text{J/m}^2$ for asbestos cement. It has also good resistance to thermal shock, and improved fire resistance, which makes it usable as cladding or permanent shuttering for structural concrete. Long term modulus of rupture and impact strength test on GRC samples show that considerable improvement in durability can be achieved by the use of alkali-resistant glass compared with conventional E glass (Borosilicate). There is still a reduction in strength with time, of storage in air, and a still greater fall when stored under water. However, such reductions in strength do not lead to total loss of strength. The use of high alumina cement and pulverized fuel ash in the matrix can further improve durability. The cheaper borosilicate or E-glass has been extensively used with high alumina cement (Elkalite) and gypsum plaster without danger of alkali attack on the fibres (Rafat Siddique, 2002).


- Glass fibres are very light. Their weight is less than 30% of the weight of steel fibres for a given volume percentage.
- They do not stain or discolor on weathering.
- They mix easily into concrete with a little evidence of balling.
- They are non-magnetic which maybe useful in future electrically controlled highway system.
- It has got high degree of flexibility

d. Disadvantages of Glass Fibres

The glass fibres get affected by the high alkaline surrounding of cement concrete. This causes in the gradual decrease in the strength of fibres, which ultimately affects the strength of the concrete.

a. Research carried out in England by the Building Research Station in collaboration with Pilkington Brothers Limited over the last few years has resulted in the development of a new glass fibre which
is inherently alkali-resistant because of its chemical composition, and is therefore suitable for reinforcing matrices based on Portland cement. This fibre has been given the generic name “CEM-FIL”, and is now being exploited commercially under license from the National Research and Development Corporation of Britain.

b. Excessive mixing may lead to damage and abrasion of these fibres and subsequently reduction in strength of concrete.

1.10.9.3 Carbon Fibres

Carbon fibres are limiting their use in cementitious material because of its high cost in mid 1980's. Recently, low cost carbon fibres have been manufactured using petroleum and coal pitch. These two processes of making carbon fibres involve heat treatments and various grade of carbon in its chemicals. These fibres find their application to substitute cement-based pipe and wood in structural. Carbon fibres have specialized applications in high tensile and flexural strength. Typically, they have an elastic modulus as high as steel, yet they are very light. Its common uses are applications in sheeting and wrap as externally reinforced degrading concrete structures (Chuan Mein Wong, 2004).

These fibres are produced by the carbonization of certain organic fibres. A Carbon fibre is a recent development. Research is in progress to investigate the application of carbon fibre selective reinforcement to the military structures. As it is well known that low weight is very important characteristic in all-military structures, for the army and particularly in military bridges. Effective use of transport requires that bridge components should be as light and compact, as possible and also tactical conditions often require that these bridges should be launched under assault conditions.

Carbon fibers produced from petroleum pitches in large volumes are low-cost and low-modulus. These fibers are very small in diameter and are generally used in shorter lengths. They are also manufactured as continuous mats and continuous straight fibers. They can be manufactured in strength as high as steel with a density only one-fifth that of steel. Carbon fibers are inert in aggressive environments, abrasion resistant and stable at high temperatures with relatively high stiffness. The uniform dispersion of carbon fibers in concrete is more difficult than the other fiber types (Technical Manual, ICFRC-TM4, 1997).

Until the mid-1980s the high cost of carbon fibers limited their use in Portland cement composites. More recently, low cost carbon fibers have been manufactured using petroleum and coal pitch. Even though
their cost is still higher than polymeric fibers, carbon fibers have potential for special applications that require high tensile and flexural strength (Balaguru and Surendra. P.Shah, 1992).

Carbon fibers have elastic moduli as high as steel and are two to three times stronger than steel, yet they are very light, with a specific gravity of about 1.9. They are inert to most chemicals (Balaguru and Surendra. P.Shah, 1992).

Carbon fibers are typically produced in strands (tows) that can contain up to 12,000 individual filaments. These strands are normally spread before incorporation into cement matrices. Carbon fibres have high tensile strength and young's modulus, but also a high specific strength compared to steel and glass fibres(Balaguru and Surendra. P.Shah, 1992).

Carbon fibre reinforced composite has linear stress-strain characteristics, and appears to possess adequate fatigue resistance and acceptable creep. Increase in flexural strength, and stiffness are about 21.42 N/mm² and 2142 N/mm² respectively for the one percent of fibre (Raft Siddique, 2002).

Carbon fibre composites have shown 20% reduction in strength over a period of one year, when cured continuously in water at 50°C. With about 4% volume fraction of continuous unidirectional aligned fibres, CFC has about 1.5 times the modulus of elasticity of the matrix.

At low fibre fractions, the fracture toughness of CFC is low and not much higher than that of the matrix and is considerably lower than that of GRC. Test results show that a combination of carbon fibres with other fibres shows a substantial improvement in impact resistance.

The suitability of these fibres is not confirmed but experiments are going on to use these fibres in Deck-slabs.

a. Properties of carbon fibres

- They have good fatigue strength.
- They have greater stability than glass fibres.
- These fibres have good bonding characteristic with the matrix.
- The main advantage of carbon fibres as a reinforcement is its low density, high strength and high modulus of elasticity along the fibres.

The main drawback is that the strength of fibre reinforced concrete is in transverse direction of fibres. So this concrete is used in the form of thin laminations. These laminations are used only at those
places where the load is unidirectional. So the laminations are used in cladding panels, shells and bridge

1.10.10 Synthetic or Plastic or Polymeric or Organic fibres

In recent years, synthetic fibres have become more attractive for reinforcement of cement and
concrete material. According to James (1990), Shell Chemical Co. started the investigation on the use of
polypropylene fibres in concrete around 1965. The developments of synthetic fibres were successfully
utilized bonding and reinforcement in cement matrix (James, 1990). Synthetic fibres have very high tensile
strength, but fibres can be differentiating into two categories, either by high or low modulus of elasticity.
Most of fibres fall in the categories of low modulus of elasticity, such as polypropylene, polyester,
polyethylene, and nylon. The main advantages of these fibres are alkali resistance, high melting point (up to
165°C) and low cost of the raw material. Disadvantages are poor fire resistance, poor bond with cement
matrix and sensitive with sunlight and oxygen. Low modulus elasticity of synthetic fibres shows the
usefulness in increasing in toughness and shrinkage cracking. However, they seem less application in
increase in flexural strength and ductility of concrete (Bentur et. al, 1990).

a. Properties and Geometry of Synthetic Fibres

Synthetic fibres have high molecular isotropic and regular atomic arrangement of structure,
allowing them to stretch into high degree of orientation. This type of fibres is a linear hydrocarbon polymer
with a methyl group attached to alternate carbon atoms on the chain backbone (James, 1990). However, the
methyl groups can affect the chemical behaviour, which can produce oxidation of the fibres. As a result, this
will cause in the change of the crystallization and bulk properties of the polymer itself. Therefore, an
'isotactic index' (measures the percentage of polymer insoluble in the methyl compound) provides a
measurement on the isotactacity, where it presents a general effects on the modulus of elasticity and the
yield stress of the fibres. Synthetic fibres can be made in three different geometries: monofilaments, films
and tapes. The first two forms of geometry of synthetic fibres commonly used in concrete and mortar for
their mechanical anchorage effects. The filaments and fabrications provide a better bond between cement
matrix, increasing the performance of cement and concrete matrix.

b. Durability

The synthetic fibres have been described as chemically inert and non-toxic in the cement
environment (James, 1990), as these fibres were free from environmental stress cracking problems.
However, it is suspected that the oxidation of synthetic fibres may occur at elevated temperature. To encounter this problem, it was suggested that with sufficient concrete cover and synthetic fibres at 25°C will not cause any oxidation, where it can exceed the lifetime of 30 years with this temperature. Synthetic fibres may degrade when exposed to the ultraviolet radiation. Additionally, exposure of natural sunlight will also cause loss in the strength of the synthetic fibres. The synthetic fibre reinforced composites quickly degrade under fire, as standard ‘flame spread tests’ done in United Kingdom identified the composite belongs to the lowest class fire protection.

Cotton, resin, polyester, nylon, polypropylene and polyethylene are organic fibres. Out of this cotton, polyester are susceptible to alkali attack. Nylon, polypropylene and polyethylene are not subjected to any chemical attack in cement paste.

Synthetic polymeric fibers are derived from organic polymers and the following have been tested in Portland cement concrete: acrylic, aramid, kevlar, nylon, polyester and polypropylene. Among these, the polypropylene has the most successful commercial application so far. The common forms of these fibers are smooth-monofilamented, twisted, fibrillated and tri-dimensional mat. The monofilaments were of geometry, size and shape similar to that of which were commercially available in steel and glass; approximate diameter 0.25 mm and 12 to 50 mm long, with an aspect ratio of 50 to 100. Dosage rates varied from 0.1 to 2.0-volume %. Polypropylene has a low density and is also chemically inert. It has a hydrophobic surface, which does not absorb part of the mixing water.

The major shortcomings of polymeric fibers are low modulus of elasticity, poor bond with cement matrix, combustibility and low melting point. Their bond to cement matrix is improved by twisting several fibers together or by treating the fiber surface. The long-term properties of polymeric fibers are not available.

Synthetic polymeric fibers have been produced as a result of research aid development in the petrochemical and textile industries. Fiber types that have been tried with cement matrices include acrylic, aramid, nylon, polyester polyethylene, and polypropylene. They all have a very high tensile strength, but most of these fibers (except for aramids) have a relatively low modulus of elasticity. The quality of polymeric fibers that makes them useful in FRC is their very high length-to-diameter ratios; their diameters are on the order of micrometers. Table 1.4 presents a summary of physical properties of various polymeric fibers. (Balaguru and Surendra P Shah, 1992)
Polymeric fibers are available in single filament or fibrillated form. The lengths used in FRC range from 12 to 50 mm. Some types of fibers are available in very short lengths (pulp form) of only a few millimeters. On the other end of the spectrum, very long fibers are available for applications that require continuous fiber reinforcement. The following sections provide a brief description of the commercially available polymeric fibers (Balaguru and Surendra P Shah, 1992).

Table 1.4: Physical Properties of Polymeric Fibers (Balaguru and Surendra P Shah, 1992)

<table>
<thead>
<tr>
<th>Fibre type</th>
<th>Eff. dia x 10^-2 (mm)</th>
<th>Specific gravity</th>
<th>Tensile Strength (GPa)</th>
<th>Modulus of elasticity (GPa)</th>
<th>Ultimate elongation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acrylic</td>
<td>13-104</td>
<td>1.17</td>
<td>207-1000</td>
<td>14.6-19.6</td>
<td>7.5-50.0</td>
</tr>
<tr>
<td>Aramid I</td>
<td>12</td>
<td>1.44</td>
<td>3620</td>
<td>62</td>
<td>4.4</td>
</tr>
<tr>
<td>Aramid II</td>
<td>10</td>
<td>1.44</td>
<td>3620</td>
<td>117</td>
<td>2.5</td>
</tr>
<tr>
<td>Nylon</td>
<td>-</td>
<td>1.16</td>
<td>965</td>
<td>5.17</td>
<td>20.0</td>
</tr>
<tr>
<td>Polyester</td>
<td>-</td>
<td>1.34-1.39</td>
<td>896-1100</td>
<td>17.5</td>
<td>-</td>
</tr>
<tr>
<td>Polyethylene</td>
<td>25-1020</td>
<td>0.96</td>
<td>200-300</td>
<td>5.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Polypropylene</td>
<td>0.90-0.91</td>
<td>310-760</td>
<td>3.5-4.9</td>
<td>15.0</td>
<td></td>
</tr>
</tbody>
</table>

Plastic fibres such as nylon and polypropylene have high tensile strength, 561.0-867.0 N/mm², but their low modulus precludes any reinforcing effect. However, their high elongation (15-25%) enables the composite to absorb 10 to 25 times more energy than unreinforced mortar and concrete. In applications requiring high-energy absorption, plastic fibres have a special advantage (Balaguru and Surendra P Shah, 1992).

The most successful form of polypropylene for use as fibre reinforcement is the fibrillated film fibres which are used extensively as reinforcement in piles and for non load bearing elements. Polypropylene is essentially a thermoplastic resin or polymer of the polyolefin family, which softens when heated, and therefore does not possess a high temperature resistance. It has the advantage of chemical stability of the cement paste and is not attacked by acids and alkalis (Balaguru and Surendra P Shah, 1992).

The most extensive use of polypropylene fibres is in concrete piles. The superior impact resistance properties of the fibres arise from purely mechanical bond between the fibre and the matrix. The fibres are made up from a number of fine fibrils the matrix creeps and interacts among fibrils, and because of the absence of a physicochemical bond only minimum contact between fibre and matrix is necessary during mixing to ensure even distribution through out the mix. The reinforcing properties of the fibres are influenced by its diameter, the length of the fibre, and the number of twists per unit length twine. The amount of fibre content and the condition of mixing. Length shorter than 40mm are found to be shared in the mixer, and become ineffective as reinforcement. The degree of the mechanical bond achieved depends on
the wire, the tightness of twist, the mixing time to give adequate dispersion and the abrasive action of the aggregate. In addition to pile shells, polypropylene fibres are used extensively in non-load bearing corrosion-proof members (under the trade name caricrete) (Balaguru and Surendra P Shah, 1992).

1.10.10.1 Aramid

Because of their high modulus of elasticity, aramid fibers can enhance the mechanical properties of FRC, including tensile and bending strength. The primary limitation to the use of these fibers in concrete is their high cost compared with other fibers. These fibers are also available in strand form (Balaguru and Surendra P Shah, 1992).

1.10.10.2 Acrylic

Fibers that contain at least 85% by weight of acrylonitrile are classified as acrylic fibers. These fibers are denser than water and have a slightly higher modulus of elasticity than other polymeric fibers except for aramid fibers (Balaguru and Surendra P Shah, 1992).

1.10.10.3 Nylon

Commercially available nylon fibers are made of Nylon 6. They are available in various lengths in single-filament form. Since these fibers are very thin, the number of fibers per pound (fiber count) is in the range of 35 million per pound (0.45 kg) for a fiber length of 19mm (Balaguru and Surendra P Shah, 1992).

1.10.10.4 Polyester

Polyester fibers are made of ethyl acetate monomers. Their physical and chemical properties can be changed substantially by altering manufacturing techniques. The higher modulus of elasticity and better bonding to concrete that is important for FRC applications can be achieved by some of these modifications (Balaguru and Surendra P Shah, 1992).

1.10.10.5 Polyethylene

Polyethylene fibers are available both in standard lengths 12 to 50 mm and in pulp form. The longer fibers available in the market have wart-like surface deformations, enabling better bond to concrete. The fibers that are available in pulp form have been promoted as a replacement for asbestos fibers in concrete. These short fibers can also be used in cement matrix to improve ductility, impact resistance, and fatigue strength (Balaguru and Surendra P Shah, 1992).
Table 1.5 gives typical properties of various types of fibres

**Table 1.5: Typical Properties of Fibres**

<table>
<thead>
<tr>
<th>Type of Fibre</th>
<th>Diameter (mm)</th>
<th>Tensile strength (N/mm²)</th>
<th>Young's modulus, (N/mm²)</th>
<th>Ultimate elongation, Percent</th>
<th>Specific gravity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acrylic</td>
<td>-</td>
<td>209.1-423.3</td>
<td>211.0</td>
<td>25-45</td>
<td>1.1</td>
</tr>
<tr>
<td>Asbestos</td>
<td>-</td>
<td>561.0-984.2</td>
<td>81.60 - 142.8 x 10⁵</td>
<td>0.6</td>
<td>3.2</td>
</tr>
<tr>
<td>Cotton</td>
<td>-</td>
<td>423.3-703.7</td>
<td>51 x 10²</td>
<td>3-10</td>
<td>1.5</td>
</tr>
<tr>
<td>Glass</td>
<td>9-15</td>
<td>1020.0-4081.0</td>
<td>71.41 x 10⁵</td>
<td>1.5-3.5</td>
<td>2.5</td>
</tr>
<tr>
<td>Nylon</td>
<td>-</td>
<td>765.0-867.0</td>
<td>40.80 x 10⁵</td>
<td>16-20</td>
<td>1.1</td>
</tr>
<tr>
<td>Polyester</td>
<td>-</td>
<td>739.0-882.2</td>
<td>81.60 x 10⁵</td>
<td>11-13</td>
<td>1.4</td>
</tr>
<tr>
<td>Polyethylene</td>
<td>-</td>
<td>708.9-830.6</td>
<td>142.8 - 428.4</td>
<td>10</td>
<td>0.95</td>
</tr>
<tr>
<td>Polypropylene</td>
<td>20 - 200</td>
<td>561.0-705.0</td>
<td>35.71 x 10⁵</td>
<td>25</td>
<td>0.90</td>
</tr>
<tr>
<td>Rayon</td>
<td>-</td>
<td>423.3-632.4</td>
<td>71.41 x 10⁵</td>
<td>10-25</td>
<td>1.5</td>
</tr>
<tr>
<td>Steel</td>
<td>5 - 500</td>
<td>280.5-4233.0</td>
<td>204.0 x 10⁵</td>
<td>0.5-3.5</td>
<td>7.8</td>
</tr>
</tbody>
</table>

1.10.10.6 Polypropylene

Polypropylene and Polypropylene fibers- structure and properties

Introduction and Structure (Brown et al., 2002)

Polypropylene fibers are available both in single-filament and fibrillated form in lengths ranging from 6 to 50 mm. Short fibers in the form of pulp are also available. Polypropylene pulps seem to have lower strength than polyethylene pulp made with oriented molecules.

Polypropylene (PP) is a versatile thermoplastic material, which is produced by polymerizing monomer units of polypropylene molecules into very long polymer molecules or chains in the presence of a catalyst under carefully, controlled heat and pressure. Propylene is an unsaturated hydrocarbon, containing only carbon and hydrogen atoms:

\[
\text{CH}_2=\text{CH}_3
\]

(Propylene)

There are many ways of polymerization of the monomer units, but PP as a commercially used material in its most widely used form is produced with catalysts that produce crystallizable polymer chains. With Ziegler-Natta or metallocene catalysts, the polymerization reaction is stereo-specific. Propylene molecules add to the polymer chain only in a particular orientation, depending on the chemical and crystal structure of the catalyst, and a regular, repeating three-dimensional structure is produced in the polymer chain. Propylene molecules are added to the main polymer chain, increasing the chain length, and not to one of the methyl groups attached to alternating carbon atoms that are termed as pendant methyl groups.
A typical structure of polypropylene chain is shown below.

\[
\cdots \text{CH}_2 \cdots \text{CH} \cdots \text{CH}_2 \cdots \text{CH} \cdots \text{CH}_2 \cdots \text{CH}_2 \cdots
\]

Polypropylene is one of the fastest growing classes of commodity thermoplastics, with a market share growth of 6-7% per year and the volume of polypropylene produced is exceeded only by polyethylene and polyvinyl chloride. The moderate cost and favorable properties of polypropylene contribute to its strong growth rate. Polypropylene is one of the lightest of all thermoplastics (0.9 g/cc). The reason for the popularity of the polypropylene fibers is because of the versatility of the material. It has a good combination of properties, cheaper than many other materials that belong to the family of polyolefins and it can be manufactured using various techniques. These benefits are derived from the very nature and the structure of polypropylene (Brown et al., 2002)

**Mechanical, Thermal Properties and Chemical resistance:**

**a. Mechanical Properties**

Traditional materials tend to be relatively little affected by temperature and time within the normal service conditions. But thermoplastics exhibit a different behavior. Stresses and strains that a thermoplastic can withstand when they are applied slowly may be quite sufficient to shatter when they are applied rapidly. A stress that creates no problem for a short period may cause the material to deform or creep over a longer period of time. These are instances of the time-dependency of plastics.

The mechanical properties of polypropylene are strongly dependent on time, temperature and stress. Furthermore, it is a semi-crystalline material, so the degree of crystallinity and orientation also affects the mechanical properties. Also the material can exist as homopolymer, block copolymer and random copolymer and can be extensively modified by fillers, reinforcements and modifiers. These factors also affect the mechanical properties (Brown et al., 2002)

A summary of the mechanical properties are given below,

- **Tensile Strength:** 25-33 Mpa
- **Flexural Modulus:** 1.2-1.5 Gpa
- **Elongation at break:** 150-300%
- **Strain at yield:** 10-12%
b. Thermal properties

Polypropylene is a thermoplastic and hence softens when heated and hardens when cooled. It is hard at ambient temperatures and this inherent property allows permits economical processing techniques such as injection molding or extrusion. The softening point or resistance to deformation under heat limits its service temperature range. Melting point and the glass transition temperature control the operating range. If the product has a wide working temperature range, then the co-efficient of linear expansion becomes significant. The coefficient of linear expansion of polypropylene is higher than most commodity plastics but is less than that of polyethylenes. Its coefficient of linear expansion varies with temperature, unlike those of metals that are substantially independent of temperature (Brown et al., 2002).

"When polypropylene is exposed to high temperatures within its maximum operating temperatures a gradual deterioration takes place. This effect is known as thermal ageing. It is an oxidation process and hence it is related to weathering. Polypropylene is more susceptible to oxidation by oxidizing agents and by air at elevated temperatures. Normally all polypropylenes are stabilized against oxidation by adding stabilizers. Copper, manganese, cobalt and carbon black additives decrease resistance of polypropylene to heat ageing.

Thermal ageing resistance is measured using an "induction" technique. In this method samples are held at a particular temperature for some days to degrade the samples to a particular extent. Ageing temperature varies from 70°C to 135°C were used, depending upon the degree of stability of the fiber and the expediency of the test. A 50 percent loss in fiber strength and elongation or the toughness factor is generally taken as the end of the induction period and is considered as a relative measure of polymer stability at test temperature. The resulting data make it possible to estimate the service life of polypropylene at elevated temperatures. For example, a polypropylene with an induction period of 20 days would have a service life of about 6 years at 80°C, while one with an induction period of at the same temperature days would have a life of about 1,000 days (Brown et al., 2002).

c. Chemical resistance

Chemical resistance refers to inertness and compatibility with other ingredients present within the compounded polymer as well as resistance to external environment. It is often associated with heat stability because reaction may take place during high temperature processing. Polypropylene has a high resistance to attack due to its non-polar nature. The term non-polar refers to the bond between atoms. The atoms
of each element have specific electro-negativity values of the atoms in a bond. If the electro-negativity value is greater the polarity of the bond will be higher. When this difference is small the material is said to be non-polar. In other words, the solubility of a polymer is related to the forces holding the molecule together, and one measure of this is the solubility parameter. Vulnerability is said to occur when the solubility parameter of the polymer and solvent are similar. It is understood that lower the value of the solubility parameter, the more resistant will be the polymer. Normally in chemical solutions polymers are not dissolved outright but soften and also may swell. These changes can be reversible when the chemical is driven off, but changes that are caused by chemical reaction are irreversible. Many chemical attacks are more severe at higher temperatures and at higher concentrations of the chemical reagent (Brown et al., 2002).

In general, polypropylene is resistant to alcohols, organic acids, esters and ketones. It is swollen by aliphatic and aromatic hydrocarbons, and by halogenated hydrocarbons but is highly resistant to most inorganic acids and alkalis. However, it is readily attacked by strong, oxidizing acids and halogens. Contact with copper and copper alloys accelerates oxidation, particularly in the presence of fillers and reinforcements. Also the water absorption is very low and this is again because of the non-polar nature of the material (Brown et al., 2002).

1.10.10.7 New Development in Synthetic Fibres

3M Company, St. Paul, Minnesota, USA, has developed synthetic (polyolefin) fibers with low aspect ratios similar to steel fibers for use in concrete. These fibers would be available in various lengths and diameters and they are added to improve the structural properties of concrete like steel fibers. These fibers could be mixed with concrete in large quantities, as much as 20% by volume without causing any balling, segregation or increase in air entrainment in concrete. The amount of fibers that could be added depends on the length and diameter of the fibers. However, the performance of these fibers in fresh and hardened concrete depends on the aspect ratio of the fibers. Therefore, it is possible to produce high volume fiber reinforced concrete using the regular concrete mixture proportions including coarse aggregates whereas high volume fiber concrete using steel fibers are produced using cement slurry instead of regular concrete. There are a number of advantages such as no corrosion potential, chemical inertness and no hazardous or nuisance conditions when fibers become loose or protrude from the concrete surface. Unlike steel fibers, these fibers are nonmagnetic and non-corrosive (Technical manual, ICFRC- TM4, 1997). Table 1.6 below demonstrates the physical differences between polyolefin and other currently used fibers.
1.10.1 Natural Fibres

Natural fibres are produced almost in all countries. Their processing requires very low degree of industrialization. The energy requirements and cost for their production is also very low. Further random mixing of fibres in cement-concrete requires semi-skilled personnel in construction work. This makes natural fibres a very attractive material for improving and reducing the cost of cement concrete. The oldest forms of fibre-reinforced composites were made with naturally occurring fibers such as straw and horsehair. Modern technology has made it possible to extract fibers economically from various plants, such as jute and bamboo, to be used in cement composites. A unique aspect of these fibers is the low amount of energy required to extract these fibers. The primary problem with the use of these fibers in concrete is their tendency to disintegrate in an alkaline environment (Balaguru and Surendra P Shah, 1992 and Rafat Siddique, 2002).

Efforts are being made to improve the durability of these fibers in concrete by using admixtures to make the concrete less alkaline and by subjecting the fibers to special treatment. This, natural fibre-reinforced composite commonly uses for thin sheet and cement products, as well as in the application for cement cladding.

Natural fibers used in Portland cement composite include akwara, bamboo, coconut, flax, jute, sisal, sugarcane bagasse, wood, and others.

Mechanical properties of some of these fibers are presented in table 1.6

The following sections provide a brief description of these fibers.

The natural fibres are basically of four types:

1. Bast or stem fibres (e.g. Jute, Flax, Hemp, Kenaf, San)
2. Leaf fibres (e.g. Sisal, Henqueen)
3. Fruit Fibres' (e.g. Coir)
4. Wood fibres (e.g. Bamboo, Reeds etc.)
However, their low elastic modulus, high water absorption susceptibility to fungal and insect attack, alkali attack from the cement concrete are the disadvantages of using natural fibres. Table 1.7 gives important physical and properties of some natural fibres.

### Table 1.7: Physical and Mechanical Properties of Natural Fibres

<table>
<thead>
<tr>
<th>Type of Fibre</th>
<th>Specific gravity</th>
<th>Tensile Strength (N/mm²)</th>
<th>Elongation, at break (%)</th>
<th>Water Absorption (%)</th>
<th>Modulus of elasticity (N/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elephant Grass</td>
<td>-</td>
<td>178.0</td>
<td>3.6</td>
<td>-</td>
<td>4936</td>
</tr>
<tr>
<td>Water Reed</td>
<td>-</td>
<td>70.0</td>
<td>1.19</td>
<td>-</td>
<td>5193</td>
</tr>
<tr>
<td>Plantain</td>
<td>-</td>
<td>93.0</td>
<td>5.9</td>
<td>-</td>
<td>1436</td>
</tr>
<tr>
<td>Musamba</td>
<td>-</td>
<td>85.0</td>
<td>9.70</td>
<td>-</td>
<td>941</td>
</tr>
<tr>
<td>Maquey</td>
<td>1.24</td>
<td>390.0</td>
<td>0.5</td>
<td>65-70</td>
<td>NA</td>
</tr>
<tr>
<td>Lechuguilla</td>
<td>1.36</td>
<td>390.0</td>
<td>0.5</td>
<td>95-105</td>
<td>NA</td>
</tr>
<tr>
<td>Kenaf</td>
<td>-</td>
<td>295.0</td>
<td>-</td>
<td>-</td>
<td>NA</td>
</tr>
<tr>
<td>Jute</td>
<td>1.5</td>
<td>227.0</td>
<td>1.3</td>
<td>120</td>
<td>NA</td>
</tr>
<tr>
<td>Coir</td>
<td>1.6</td>
<td>180.0</td>
<td>26.5</td>
<td>110</td>
<td>2600</td>
</tr>
<tr>
<td>Sisal</td>
<td>1.5</td>
<td>300-820</td>
<td>3.2</td>
<td>-</td>
<td>2500</td>
</tr>
<tr>
<td>San</td>
<td>1.02</td>
<td>195-235</td>
<td>1.19</td>
<td>100-120</td>
<td>NA</td>
</tr>
<tr>
<td>Sugarcane</td>
<td>1.2-1.3</td>
<td>17.0-290</td>
<td>NA</td>
<td>70-75</td>
<td>15-19</td>
</tr>
<tr>
<td>Bagasse</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>NA</td>
</tr>
<tr>
<td>Bamboo</td>
<td>1.5</td>
<td>350-500</td>
<td>NA</td>
<td>40-45</td>
<td>33-40</td>
</tr>
<tr>
<td>Flax</td>
<td>NA</td>
<td>1000</td>
<td>1.8-2.2</td>
<td>NA</td>
<td>100</td>
</tr>
<tr>
<td>Wood fiber</td>
<td>1.5</td>
<td>700</td>
<td>NA</td>
<td>50-75</td>
<td>NA</td>
</tr>
</tbody>
</table>

NA- Properties are not readily available or not applicable

#### 1.10.11.1 Elephant Grass

Elephant grass is found near by watercourses, and is common in sandy soil conditions. Its length is between 2 to 3 meter, and most common length being 2.4 meter. The diameter at the base is around 18 to 22 millimeter. The stem, which is not hollow but contains pith made of soft fibres, is pale or dark purple. Load bearing stem, of the plant are packed with fibres arranged parallel to each other in a matrix of lignin. The crust is thin and fibrous, and the fibre itself is tough and sharp, so that extraction by hand is not easy. It is available in India.

#### 1.10.11.2 Water Reed

It is commonly found on the banks of lakes and streams. It grows in bushes and its length is between 2 to 3 meter. When it is mature, the diameter of the stem may be as much as 20 millimeter. The stem consists of an empty interior and a strong fibrous crust about 5mm thick.

#### 1.10.11.3 Plantain

The trunk of this plant is fibrous and fibres can be easily extracted by hand. Fibres of the plant are strong and flexible. It is widely grown in India.
1.10.11.4 Musamba

This is a hardwood tree common to savannah lands. It's well known use is for making twines as ropes substitute. The back of the tree is fibrous and extraction of the fibres is very difficult.

1.10.11.5 Akwara Fibers

Akwara is a natural fiber derived from a plant stem grown in large-quantities in Nigeria. They are made of a cellular core covered with a smooth sheath. Akwara fibers were found to be durable in alkaline environment of cement matrix, and they are also dimensionally stable under wetting and drying conditions. The disadvantages are their low elastic modulus and brittleness. Akwara has two shades of colors. The more matured and stronger end is dark brown, while other end is whitish. The fibre geometry is variable. The diameter varies from 1 millimeter to 4 millimeter and the length of the fibres is around 1.5 meter.

1.10.11.6 Maguey and Lechuguilla Fibres

Both these fibres are of agave family. Both the fibres look identical. Their surfaces are covered by a natural substance like wax, which if placed in water would dissolve, producing a kind of foam similar to the commercial soap. The length of fibre varies from 30 to 50 centimeter.

1.10.11.7 Bamboo Fibres

Bamboo, a member of the grass family, grows in tropical and subtropical regions. Plants can grow up to a height of 14 to 16 m. Their hollow stalks have intermediate joints; the diameters of these stalks range from 15 to 110 mm. Special techniques are required to extract the fibres from bamboo. They are strong in tension, but have a relatively low modulus of elasticity. Their tendency to absorb water adversely affects the bonding between the fibres and the matrix during the curing process.

1.10.11.8 Flax and Vegetable Fibers

Flax is grown mainly for its fiber. Flax fibers are strong under tension and also possess a high modulus of elasticity.

1.10.11.9 Jute and Coir or Coconut Fibres

These fibres are also showing great promise in terms of strength. When incorporated in concrete, the composite has shown considerable increase in tensile strength over conventional concrete.

Jute fibers are relatively strong in tension. Traditionally these fibers were used for making ropes and for weaving into gunny cloth used in bags to transport grains.
Jute grown solely for fibre content is cultivated mainly in Indian sub-continent. Jute plants can grow to a height of 2.2 to 25m with stalk diameters normally less than 25mm. The bark of these plants contains the fibres, which are extracted from the stalk by soaking them in water for about four weeks, thereby loosening the fibres. The fibres are then removed manually and dried. Jute fibres are relatively strong in tension. Traditionally these fibres are being used for making ropes and for weaving into gunny cloth used in bags to transport grains.

A mature coconut has an outer fibrous husk. Coconut fibers, called coir can be extracted simply by soaking the husk in water or, alternatively, by using mechanical processes. These short (only a few inches) stiff fibers have been used for making rope for centuries. Coir has a low elastic modulus and is also sensitive to moisture changes.

1.10.10 Sisal Fibres

A number of investigators in Australia and Sweden have studied the properties of cement composites made with sisal fibres. These fibres, extracted from the leaves of Agave sisalana, are basically made of hemicellulose, lignin, and pectin. Sisal fibres are relatively strong but are not durable in alkaline environments.

1.10.11 San Fibres

San fibre is extracted from San plant which grows to about 1.0 to 2.5m in height and is light green in colour. The diameter of the plant varies from 10mm to 30mm. The stem of the plant is fully covered with a thin layer of fibrous skin, which can be removed from the stem in long longitudinal pieces, even at the green stage but with some difficulty. To make extraction of fibres easy, the uprooted plants are placed under water for a period of 3 to 4 weeks, after which they are taken out of the water, the fibrous skin is separated easily. The fibres by this time are found to have acquired a light yellowish colour.

1.10.12 Sugarcane Bagasse Fibres

Sugarcane bagasse is the fibrous material left after the extraction of juice from sugarcane. In most of the cases, bagasse has about 45-55% fibre content. The physical properties of the fibres depend on the variety of the sugarcane, its maturity, and the efficiency of the milling plant.

1.10.13 Wood Fibres or Cellulose Fibres or Craft fibre

Wood fibres constitute the major portion of the natural fibres used in concrete throughout the world. Their use in cement composite has gained popularity as a replacement for asbestos fibres. The
advantages are their availability, good tensile strength, high modulus of elasticity and well-established methods of extracting the fibres. The disadvantages are their vulnerability to decomposition in the alkaline medium present in concrete. However, methods and processes have been identified to minimize the disintegration of fibres in an alkaline environment. The process of extracting fibres from wood is known as pulping. The process may be mechanical, chemical, or semi-chemical. The properties of the resultant fibres depend to a large extent on the pulping process. The basic parts of wood are cellulose, hemicellulose, and lignin. Lignin has an adverse effect on the strength of the fibers; hence the pulping process that removes most of lignin provides the best fibres. Tensile strengths of delignified cellulose fibres have been recorded up to 1960 N/mm² whereas cellulose a fibre from which lignin has not been removed has tensile strengths of the order of 1500 N/mm². Chemical pulping processes reduce the lignin content in wood fibres more effectively than mechanical or semi-chemical processes. The two common chemical methods are the kraft or sulfate process. Removal of more and more lignin provides better fibres. However, lignin removal can limit the amount of fibres that can be extracted from certain woods, hence; lignin free fibres are normally more expensive (Balaguru and Surendra P Shah, 1992 and Rafat Siddique, 2002).
1.11 Production of Fibre Reinforced Concrete

Quality control used to produce sound, durable conventional concrete applies also to fibre reinforced concrete. Not only the various ingredients used but also the proportioning, mixing, transporting, placing, curing etc. are responsible for attributing good as well as bad concrete.

1.11.1 Mix Proportions

The constituent materials used for fibre reinforced concrete are cement, fine aggregates, coarse aggregates, water, admixtures, and fibres. The water-cement ratio is the main controlling factor for compressive strength. The other factors that control strength and workability are cement content, maximum aggregate size and gradation, air entrained air. In FRC the factors controlling workability are the fibre content and the fibre aspect ratio. Generally the aim is to obtain a mix that produces the required compressive strength, is workable, and has the minimum amount of cement. Since cement is the most expensive component in plain concrete, reduction of cement content usually results in better economy (Rafat Siddique, 2002).

1.11.2 Proportioning

The proportioning of concrete mixes, most commonly referred to as “mix design” consists of two interrelated steps.

a) Selection of suitable ingredients (i.e. cement, aggregates, fibres water etc) of concrete and

b) Determining their relative quantities

The water requirement varies with the type and nature of fibres. Water cement ratio of 0.4 to 0.6 and cement content of 2500 to 4300 N per metre cube are required to ensure proper dispersion of fibre and adequate paste content to coat large surface of fibres Methods for obtaining the mix proportion of plain concrete are well established. The mix design procedure recommended by Indian Standard Code can be used (Shetty, 2002).

1.11.3 Mixing

The primary object in mixing is the uniform distribution of fibres throughout the matrix. A collection of long thin steel fibres, usually with aspect ratios higher than 100, will interlock to form a mat or a ball, during mixing. Once these balls have been formed, separation of these fibres becomes extremely difficult. Clumping is one of the main reasons of straight smooth fibres not being successfully used. Higher aspect ratios are needed to develop sufficient bond strength between fibre and metric. Even with aspect ratios of 100 or more, about 1.75-
2% volume fraction of fibres are needed to develop sufficient ductility. The combination of higher aspect ratio and higher volume fraction required for straight fibres makes mixing a very difficult task. Besides the aspect ratio, balling of fibres is a function of fibre content, gradation of aggregates used in the mix, fibre shape, and the method and procedure used for the addition of fibres in the mixer. Larger aspect ratios and larger maximum-size aggregates reduce the volume fraction of fibres that can be added without balling. For a given fibre type, mixing becomes more difficult for fibres with higher aspect ratios. For a given aspect ratio, strong stiff fibres allow better mixing because they do not clump so easily (Rafat Siddique, 2002).

In the 1970's the development of deformed fibres with better anchoring characteristics gave boost to the use of these fibres in concrete. The deformations gave better bonding. As a result, shorter length fibres could be used. Since anchoring was better and efficient, a smaller volume fraction of fibres could help in generating enough ductility. Clumped fibres should not be fed into the mixer. The possibility for clumping of fibres exists whenever (a) fibres are dropped from one conveyor belt to another, (b) the conveyor belts carrying the fibres bounce over rollers, (c) an overload of fibres reaches the sides of the mixing drum (Rafat Siddique, 2002).

The mixing of fibres in concrete can be done by various methods. The most commonly used methods are a) Dry mix process b) Wet mix process (Prakash K.B, 1998).

1.11.3.1 Dry mix process

To ensure proper dispersion, fibres are added before water, in mixing phase. This is done by blending the fibres and aggregates prior to charging the mixer or blending fine and coarse aggregates in mixer and then adding the fibres at maximum speed (12 rpm) followed by cement water and additives (Prakash K.B, 1998).

1.11.3.2 Wet mix process

This process consists of adding the fibres after the conventional concrete has been produced.

The fibres, in both processes may be added in small increments by hand or by “French fry basket” or by mechanical means using a steel fibre dispenser unit.

The workability of fibre mix would depend on the volume of fibres and their aspect ratios. The mix is considered “unworkable” when “balling” of fibres occurs. This is the most common and serious problem in which the fibres knit themselves in the form of balls with little or no concrete between them (Prakash K.B. 1998).
Several mixing sequences have been successfully used both in the laboratory and in the field. The following mixing sequences have been found to work efficiently for most of the mix proportions.

Fibres can be added directly to the mixer once the other ingredients have been uniformly mixed. The fibres can be added manually, by emptying the containers into the truck hopper, or via a conveyor belt or blower either at the batch plant or at the job site. The mixer should rotate at full speed when the addition of fibres is in progress. After the fibre addition is complete, the contents should be mixed for at least another 45-55 revolutions (Rafat Siddique, 2002).

Fibres can be added to the aggregates before charging into the mixer. The general practice is to add the fibres to the aggregates as they are moving on the charging belt. They can either be placed directly on top of the aggregates or be carried on a separate belt that empties onto the charging belt. Fibres should be spread out as much as possible to avoid heavy concentrations.

Fibres can be mixed by feeding them simultaneously with aggregates, cement, admixtures and about 70-85 percent of water. This can be achieved by slowing down the aggregate feed and adding the other ingredients.

The most common mixing method for polymer fibre reinforced concrete is batch mixing. The fibres can be added simply to the wet mix directly from bags or feeders. It is recommended that concrete be mixed for at least 6-9 minutes after the addition of fibres.

Transporting, placing and finishing techniques for polymeric fibre-reinforced concrete are the same as those used for plain concrete. For some fibre types the slump values may be slightly less, but if vibration is used for compaction there should be no workability problems. The fibre concrete can be pumped using conventional equipment used for plain concrete. Excess water should be avoided because fibres that are lighter than water may tend to float. Occasionally, certain fibres tend to produce a hairy finish. This can be avoided with proper finishing techniques (Rafat Siddique, 2002).

1.11.4 Transporting

Transportation and placement of FRC with steel fibres can be done with conventional equipment.

Trucks carrying concrete with higher fibre contents should not be loaded to their full capacity, and it should be limited to about 75-85 percent. Fibre reinforced concrete is more cohesive than plain concrete and
more power is needed to rotate the drum. Hence, the reduced load will help not only to reduce the total weight but will maintain proper rotation of the drum. The same is true for pan mixers used in plants making precast concrete.

A good quality FRC mix barely slides down the chute when discharged from the mixer. Slope of the chute is increased slightly for easy discharge. When the mix is stiff, it has to be pulled down manually. The addition of high-range water-reducing admixture (HRWRA) solves this problem to a great extent.

If concrete buckets are used, they should have steep hopper slopes and large gate openings. When fibres block the opening, FRC may not fall freely when the buckets are opened. This can be tackled by attaching a vibrator to the side of the bucket that is activated when the bucket opens, facilitating the discharge of the concrete.

When FRC is transported through long vertical access shafts, concrete cannot be dumped on the hopper. Fibre may totally block the pipe. Vibrating the concrete in the hopper with an immersion vibrator will make the concrete fluid enough to facilitate flow. This method has been successfully used in the field (Rafat Siddique, 2002).

1.1.5 Placing

The fibrous concrete should be placed as nearly as possible in its final position. It should not be placed in bulk at one point and allowed to be worked over a long distance as it results in fibre and aggregate segregation. Fixed- form and slope-form paving machines can also be used for the placement of fibrous concrete.

For consolidating FRC, usual methods of compaction such as shutter or table vibrator can be used. However needle vibration is not recommended with higher volume content of fibres since the holes left by needle may remain unfulfilled due to the interlocking effect of the fibres. Table vibration has been shown to be beneficial in the sense that the fibres tend to align themselves in planes perpendicular to the direction of vibration. This gives a random planar orientation which is more efficient than a three dimensional random orientation. This type of behavior under table vibration can be put to good use in pre-cast products by arranging the compaction such that the fibres are arranged in the most beneficial direction. Consolidation can also be done by spinning, as in the case of poles and piles or by using spray suction technique as in the production of thin roofing elements and wall panels.
Fibrous concrete placed should be screened to consolidate. The excess concrete may be striken off by manual and mechanical means are used. Soon after the screeding, the concrete surface should be floated by conventional steel.

Brooming the concrete with steel hairbrush can scare the concrete surface. In no case wet brush should be used as the fibres may stick to the brush and come out.

1.11.6 Finishing

Minor adjustments are required in finishing FRC compared with plain concrete. Open slab surfaces should be struck off with a vibrating metals screed with slightly round edges. A "jitterbug" can be used in areas inaccessible to vibrating screeds. Chamfers or rounds are provided at edges and corners to prevent protrusion of fibre ends. Magnesium floats can be effectively used to close the open areas caused by the screeds. Wood floats normally leave rough surfaces with some fibres on the surface. For certain applications such as pavements further finishing is generally required, if a texture is required for skid resistance, a broom or roller is used before initial set. Larger floats provide flatter and better finishes and should not be moved on edges when finishing. Otherwise they will pick up and move the fibres. Loose fibres on the finished surface should be removed because they are a potential hazard, especially on airport runways used by high-speed jets. The fibres may become airborne missiles that result in injuries. With very careful workmanship, FRC can be finished to any desired smooth and flat surface (Rafat siddique, 2002).

1.11.7 Curing

The standard methods and techniques of curing should be used for fibrous concrete products. Concrete can be kept moist by sprinkling and ponding, use of moisture retention covers, or by a steel coat of curing compound.

1.11.8 Quality control

All the ingredients are carefully and accurately measured to ensure uniform batches of fibrous concrete of proper proportion and consistency. Workability characteristic of a properly designed fibrous concrete are almost same as conventional concrete with equal slump. If varying amount of moisture is present in the aggregate proper allowance is made. Special care is taken to remove all water from the mixer before re-batching. High cement factors normally used for fibrous concrete will accelerate the setting time and should be accounting
for, during mixing and placing. Uniformity of fibre distribution is assessed by taking random samples washing and collecting fibres in the samples.

1.1.8.1 FRC with Coarse Aggregates

This composite contains fine and coarse aggregates and discontinuous fibers. The matrix is usually proportioned following the procedures used for plain concrete. The volume fraction of fibers ranges from 0.4% to 2% (300 to 1500 N/m³) for steel fibers and 0.06% to 0.5% (6 to 48 N/m³) for polymeric fibers. The mix proportions obtained for plain concrete are slightly modified to maintain workability, easy fiber mixing, and good fiber distribution (Balaguru and Surendra.p.Shah, 1992).

1.1.8.2 Fiber Reinforced Cement Mortar

This term applies to a wide variety of manufactured products such as glass fiber-reinforced cement sheets (GFRC) as well as panels and tiles made using other fibers such as naturally occurring and polymeric fibers. The manufacturing process for this composite (which contains cement and fine aggregate) is quite different from the procedures used for FRC with coarse aggregates. The fiber volume fraction ranges from 1% to 5% (Balaguru and Surendra.p.Shah, 1992).

1.1.8.3 Fiber Reinforced Cement Products

These are similar to fiber reinforced cement mortar but contain little or no fine aggregate. The widely known asbestos cement sheets fall into this category. These products are usually manufactured using the Hatschek process, in which a mat of fibers is dipped into cement slurry and then dewatered to form the fiber-cement sheets. These can be formed into a variety of products such as corrugated sheets and pipes. Since the use of asbestos fibers is restricted in most countries, a large number of replacement fibers are being investigated. These fibers are relatively short (a few millimeters long) and have very high length-to-diameter ratios. These fibers also help to retain cement during the manufacturing process. Fibers that have been marketed to replace asbestos include polyethylene, polypropylene, polyvinyl alcohol, aramid, cellulose, and carbon. The fiber volume fraction ranges from 3% to 6%. In the case of asbestos cement sheets, up to 20% of fibers have been used (Balaguru and Surendra.p.Shah, 1984).

Recently, cement composites containing a high volume of steel fibers have been developed. These are categorized as slurry infiltrated fiber concrete (SIFCON). This composite is cast by infiltrating a bed of fibers
with cement or mortar slurry. The fiber volume fraction used ranges from 4% to 22% (Balaguru and Surendra.p.Shah, 1992).

1.11.9 ACI method of Mixture Proportioning for FRC

The mix design procedure recommended by ACI Committee 211 is one of the common methods used. It involves selection of the various constituent materials using a set of tables. The major steps involved are as follows (Balaguru and Surendra.p.Shah, 1992):

Step 1. If slump is not specified, choose a slump suitable for the type of construction. Recommended slumps vary from 25 to 50 mm for mass concrete, and up to 100 mm for beams and columns. Slump (or workability) can be increased, by using water-reducing admixtures. Nevertheless, it is advisable to choose a base-slump value that is independent of admixture for mix design.

Step 2. Choose the maximum size of aggregate. The maximum size should be smaller than One-fifth of the narrowest dimension between forms, One-third of the depth of slab, and Three-fourths of the clear spacing between reinforcing bars.

The maximum size is limited to 38 mm except for thick sections or mass concrete.

Step 3. Decide on the amount of water and entrained air. A table is provided in Reference for choosing these quantities. The amount of water required is presented as a function of slump, maximum aggregate size, and amount of entrained air. Higher slump values, smaller aggregate sizes, and lower air contents lead to more water demand. The amount of air required depends on the type of exposure. For structures subjected to severe conditions of freezing and thawing, wetting and drying, more entrained air is recommended. More entrained air provides better workability but may reduce the compressive strength. Addition of fibres affects both workability and entrained air. Hence, these qualities must be readjusted based on trial mixes.

Step 4. Choose the amount of cement needed to obtain the specified compressive strength. Typically water-cement ratio is chosen to obtain the required strength. Since the water content is already estimated in Step 3, the water-cement ratio can be used to obtain the cement content.
Step 5. Choose the volume of coarse and fine aggregates. The ratio of coarse-to-fine-aggregate again decided based on workability requirements. Slightly higher sand content than that used for plain concrete seems to provide better results for fiber-reinforced concrete.

Step 6. Make adjustments in the amount of water to be added based on the moisture present in the coarse and fine aggregates.

For a given project, trial mixes based on the mix design have to be made to ascertain the workability and the strength requirements. If the ready-mix plant supplying the concrete has already supplied concrete in the strength range required, their proportions can be used for trials.

The mix has to be designed to obtain an average compressive strength \( f'_{cr} \) that is higher than the specified compressive strength \( f'_c \). The term \( f'_{cr} \) is defined as the average required compressive strength in the ACI Code. Guidelines to estimate \( f'_{cr} \) are provided in the ACI Code 318. The over design (difference between \( f'_{cr} \) and \( f'_c \)) depends mainly on the level of quality control maintained at the ready mix plant (Balaguru and Surendra.p.Shah, 1992).

1.11.10 Special Requirements for FRC with Steel Fibers

The slump test is not a reliable test to obtain the workability of SFRC. Since SFRC should be vibrated in place for proper compaction, either the inverted slump cone test or V-B test should be used for measuring workability. Consequently, after the trial proportion is established, the water or water reducing admixture has to be adjusted to obtain the required inverted slump cone (or V-B) time.

Typically, SFRC mixtures require higher cement and higher fine aggregate content for maintaining the strength and workability. Characteristics such as length, length diameter ratio, and shape play an important role. Trial batches are needed for any fiber types to be used. Most fiber manufacturers maintain records and provide trial mix proportions for their fibers. Table 1.8 presents the general range for the mix proportion with steel fibers (Balaguru and Surendra.p.Shah, 1992). Table 1.9 presents mix proportions for two typical mixes using high-range water-reducing admixtures (Balaguru and Surendra.p.Shah, 1984).
Table 1.8: General Range of Proportions for Normal-Weight Steel Fiber-Reinforced Concrete

<table>
<thead>
<tr>
<th></th>
<th>3/8 in. max sized aggregate</th>
<th>3/4 in. max sized aggregate</th>
<th>1 1/2 in. max sized aggregate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement (N/m³)</td>
<td>3600-6000</td>
<td>3000-5400</td>
<td>2820-4200</td>
</tr>
<tr>
<td>W/C ratio</td>
<td>0.35-0.45</td>
<td>0.35-0.50</td>
<td>0.35-0.55</td>
</tr>
<tr>
<td>Percentage of fine to coarse aggregate</td>
<td>45-60</td>
<td>45-55</td>
<td>40-55</td>
</tr>
<tr>
<td>Entrained air content (%)</td>
<td>4-8</td>
<td>4-6</td>
<td>4-5</td>
</tr>
<tr>
<td>Deformed fibre</td>
<td>0.4-1.0</td>
<td>0.3-0.8</td>
<td>0.2-0.7</td>
</tr>
<tr>
<td>Smooth fibre</td>
<td>0.7-2.0</td>
<td>0.6-1.6</td>
<td>0.40-1.4</td>
</tr>
</tbody>
</table>

Table 1.9: No Mixture Proportions for Two Typical Mixes Using Fibers with Hooked Ends

<table>
<thead>
<tr>
<th></th>
<th>Mix 1</th>
<th>Mix 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement (N/m³)</td>
<td>3600</td>
<td>4800</td>
</tr>
<tr>
<td>Ratio of fine to coarse aggregate</td>
<td>50/50</td>
<td>50/50</td>
</tr>
<tr>
<td>Max. coarse aggregate size (in)</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Water-cement ratio</td>
<td>0.40</td>
<td>0.30</td>
</tr>
<tr>
<td>High-range water-reducing admixture percent by weight of cement</td>
<td>1.0</td>
<td>1.2</td>
</tr>
<tr>
<td>Air-entraining agent percent by weight of cement</td>
<td>0.15</td>
<td>0.20</td>
</tr>
<tr>
<td>Fibre content (N/m³)</td>
<td>450</td>
<td>450</td>
</tr>
<tr>
<td>28 days Compressive strength (MPa)</td>
<td>45.71</td>
<td>53.57</td>
</tr>
</tbody>
</table>

1.11.11 Mixes with Lightweight Aggregate

Mix design procedures for lightweight aggregate concrete are different compared with normal-weight concrete. ACI Committee 211 has presented a set of recommendations for selecting proportions for structural lightweight concrete. A few researchers have investigated the performance of fiber-reinforced lightweight concrete and have reported details regarding mix composition, workability, special precautions, and strength development (Balaguru and Surendra.p.Shah, 1992).

1.11.12 Special Requirements for Concrete Reinforced with Polymeric Fibres

The volume fraction of polymeric fibers currently used in the field is very low. In most cases it is limited to 0.1%. This translates to about 10 N/m³ of concrete. At this fiber-loading level, the change in workability is minimal. Still, slight modifications may be needed to maintain workability and air content level. Fibers can be added at the ready-mix plant or at the site. Mixing for at least 10 minutes is recommended after the addition of fibers.
Researchers have used up to 2 percent volume fraction of fibers (lengths 12 to 50 mm) with conventional mixing. For volume fractions above 0.2%, special precautions are necessary because the workability is reduced considerably and the amount of entrapped air increases. The latter can cause severe problems with respect to consolidation and strength reduction. Using higher dosages of high-range water-reducing admixtures may solve workability problems. Aggregate gradation and mixing sequences have to be adjusted to control the amount of entrapped air.

Single-filament fibers tend to reduce the workability more than fibrillated fibers. Smaller fiber diameters that result in higher fiber count also reduce workability more than larger diameters. Fiber length also plays an important role. Fibers in pulp form with lengths limited to a few millimeters can be mixed up to a volume fraction of 5%. In general, fiber lengths used in the field vary from 12 to 50 mm.

Only fiber-reinforced concrete containing steel and polymeric fibers in the volume fraction range of 0.1% to 2% are presented here. In most concrete applications the fibers used predominantly are steel and synthetic polymers (Balaguru and Surendra.Shah, 1992).
1.12 Factors Affecting the Properties of FRC

Fibre reinforced concrete as already stated is defined as a composite material consisting of cement based material containing an ordered or random distribution of fibres. The fibres act as crack arresters that resist the growth of the flaws in the matrix, restraining them from enlarging under stress into cracks, which eventually cause failure. By inhibiting the propagation of cracks, originating from internal flaws, improvement in static and dynamic properties can be obtained and thus fibres impart to the composite qualities of crack control toughness, ductility and impact resistance (Rafat Siddique, 2002).

The use of continuous aligned fibres in a cement material is fundamentally not different from conventional reinforced or prestressed concrete where the larger diameter reinforcing bars or the smaller diameter prestressing wires behaves analogously to the continuous aligned fibres. The phenomenon of multiple cracking and of composite action in such materials has been well established. Obviously, the highest strength characteristics are obtained when the fibres are aligned to resist the critical stresses, but then material becomes markedly anisotropic (Rafat Siddique, 2002).

A more exciting challenging arrangement, which has found a wider application, is the use of short discontinuous fibres that are uniformly distributed in the matrix. It is true that with random orientation not all the fibres are equally effective in crack control or in their strengthening and stiffening roles, nevertheless if sufficient strength and crack control improvement could otherwise be obtained, the other practical advantages of discontinuous fibres will outweigh the strength advantages of continuous aligned fibres (Rafat Siddique, 2002).

The effective reinforcement of the matrix and the efficient transfer of stress between the matrix and the fibres depend upon many factors, some of which are intimately interdependent and exercise a profound but complex influence on the properties of the composite. These factors can be effectively considered in the following categories:

1. Relative fibre matrix stiffness.
2. Fibre-matrix interfacial bond.
3. Strain compatibility between the fibres and the matrix.
4. Volume of fibres
5. Aspect Ratio
1.2.1 Relative Fibre-Matrix Stiffness

For efficient stress transfer to the fibres the elastic modulus of the matrix must be lower than that of the fibres. Low modulus fibres such as natural fibres, nylon and polypropylene are not likely to give much strength improvement. High modulus fibres such as metallic fibres (e.g. steel), glass, or crystalline inorganic fibres (e.g. asbestos) normally lead to strong composites. High strength high modulus fibres impart characteristics of strength and stiffness to the composite, whereas low modulus high elongation fibres are capable of large energy absorption characteristics and impart a greater degree of toughness and resistance to impact and explosive loading. The former also contribute to these dynamic properties but to a lesser extent (Rafat Siddique, 2002).

1.12.2 Fibre-Matrix Interfacial Bond

The interfacial bond between the matrix and the fibres determines the effectiveness of stress transfer from the matrix to the fibres. With randomly oriented, short discrete fibres the interfacial bond that develops between the fibres and the matrix is not continuous and becomes critical in defining the optimum fibre length-diameter ratio (the aspect ratio), and indeed, the volume content of the fibres for maximum improvement in tensile resistance. But a poorer interfacial bonding would show greater improvement of fracture toughness and impact resistance through energy dissipation and damping at the interfacial discontinuities. Fibre length and fibre diameter are thus critical in influencing static and dynamic properties (Rafat Siddique, 2002).

If the interfacial bond is such that the composite failure occurs by fibre pullout then the matrix becomes the principal tensile load-carrying element, and then only modest increase in tensile strength can be obtained. To achieve a truly two-phase composite action, the matrix must be so designed as to transfer load to the fibres so that they contribute fully to the composite strength. For short discontinuous fibres there is the additional criterion
that the interfacial bond must be such that anchorage length on anyone side of the crack does not result in fibre pullout.

**1.12.3 Fibre-Matrix Strain Compatibility**

Associated with the relative fibre-matrix stiffness and the interfacial bond is the need for strain compatibility between the fibres and the matrix. With cement-based matrices the cracking and often the ultimate strain is of the order of 250 to 500 x 10^{-4} m/m, and since most fibres have far greater extensibility bond failure occurs early and hinders the efficient use of fibre reinforcement. The low cracking strain of the cement material implies that reinforcement of the matrix can be achieved at fairly low volume fractions of the fibre (Rafat Siddique, 2002).

**1.12.4 Volume of Fibres**

The strength of composite largely depends on the quantity of fibres used in it. The effect of increase in volume fibres increases the tensile strength and toughness of the composite. Use of higher percentage of fibres is likely to cause segregation and hardness of concrete and mortar.

**1.12.5 Aspect Ratio**

It is the important factor, which influences the property and behavior of composite. It is defined as the ratio of effective length of fibre to the diameter of the fibre. The length of the fibre influences the crack arresting mechanism while the diameter of the fibre determines the strength of the fibre (Shetty, 2002)

Figure 2.2 shows the graph between the strength and aspect ratio. It is clear from the graph that as the aspect ratio increases the strength of FRC also increases. However there is not much increase in strength after an aspect ratio of 80 due to their shorter length.

**1.12.6 Orientation of Fibres**

One of the differences between conventional reinforcement and fibre reinforcement is that in conventional reinforcement fibre are in the desired direction while in FRC fibres are randomly oriented. It was observed that fibres aligned parallel to applied load offer more tensile strength and toughness than that randomly distributed and perpendicular fibres (Shetty, 2002).
1.12.6 Orientation of Fibres

One of the differences between conventional reinforcement and fibre reinforcement is that in conventional reinforcement fibre are in the desired direction while in FRC fibres are randomly oriented. It was observed that fibres aligned parallel to applied load offer more tensile strength and toughness than that randomly distributed and perpendicular fibres (Shetty, 2002).

1.12.7 Workability and Compaction of Concrete

Incorporation of steel fibres decreases the workability considerably. This situation adversely affects the consolidation of fresh mix. Even prolonged external vibration fails to compact the concrete. This situation depends on the length to diameter of fibre. Generally, the workability and compaction are improved through increased w/c ratio (Shetty, 2002).

1.12.8 Size of Coarse Aggregates

Maximum size is restricted to 10mm to avoid appreciable reduction in strength of composite. Fibres also in effect, act as aggregate. Although they have a simple geometry, their influence on property of fresh concrete is complex. The inter-particle friction between fibres and aggregate controls the orientation and distribution of fibre and consequently the composite. Friction reducing admixtures and that improve the cohesiveness of mix can significantly improve the mix (Shetty, 2002).
1.12.9 Mixing

It needs careful conditions to avoid balling of fibres segregation and in general difficulty of mixing of materials uniformly. Increase in the aspect ratio, volume percentage, size and quantity of coarse aggregate intensifies the difficulties and balling tendencies (Shetty, 2002).

1.12.10 The Typical Proportioning of FRC

a) Cement content: 3250-5500 N/m³.

b) Water cement ratio: 0.4-0.6.

c) Percentage of sand to total aggregate: 50-100%.

d) Maximum aggregate size: 10mm.

e) Air content: 6.0-9.0%.

f) Fibre content: 0.5-2.5% by volume of mix.

When mixing in a laboratory mixer introducing the fibres through a wire mesh basket will help even distribution of fibres. For field use, other suitable methods must be adopted (Shetty, 2002).

1.12.11 Other Factors

Other factors such as the volume fraction of fibres and the orientation of fibres also influence the behaviour of fibre reinforced cementitious composites. The minimum or critical volume fraction below which increase in tensile strength cannot be expected is with respect to static strength only. Even with low fibre volume fractions the impact strength and resistance to crack propagation are considerably improved. The efficiency of the fibres depends on their orientation in space. With complete random orientation only about 41 percent of the fibres are effective in reinforcing (Rafat Siddique, 2002).

A major difficulty in fibre-reinforced cementitious systems is in incorporating quantities of fibres sufficient to achieve improvements in strength and at the same time making it economically viable. With conventional mixing techniques the maximum volume of fibres that can be introduced is limited to 2 to 3 percent by volume, which in turn limits the strength properties that can then be achieved. New techniques of fibre incorporation such as spraying the fibres simultaneously with the matrix modifying mixing techniques using fibre-dispensing equipment using special admixtures etc. may offer considerable improvements (Rafat Siddique, 2002).
Traditional concrete mixes cannot be used with fibres. The size, shape, surface geometry and volume fraction of the coarse aggregate all very much influence not only the rheological properties of the fibrous concrete but also its properties in the hardened state (Siddique, 2002).
1.13 Steel Fibre Reinforced Concrete

1.13.1 Salient Features of Steel Fibre Reinforced Concrete

The outstanding property of cement-based steel fibre concrete is the crack-arrest and crack control mechanism of the fibres. This directly leads to improvement in all other properties linked with cracking, such as strength, stiffness, ductility, energy-absorption, and resistance to impact, fatigue and thermal loading (Parmeswaran, 1988).

It must be understood that the real value of steel fibre reinforcement lies not so much in strength, but in crack control and associated properties. This crack controlling property of the fibre has three major effects on the behaviour of the concrete composite. First, the steel fibres delay the onset of flexural cracking, the increase in tensile strain at first crack being as much as 100%. The ultimate tensile strain may be as large as 20 to 50 times that of plain concrete. Secondly, the fibres impart well-defined post-cracking behaviour to the composite. Thirdly, the crack-arresting property and the consequent increase in ductility imparts greater energy-absorbing property to the composite prior to failure. With a 2.5% fibre content, the energy-absorption capacity is increased by more than 10 times as compared to un-reinforced matrix (Parmeswaran, 1988). A typical stress-strain relation ship for fibre reinforced concrete is shown in fig. 1.13

![Stress-strain curves for fibre reinforced concrete](image)
These properties of steel fibres can be advantageously made use of in concrete structures having conventional steel bar reinforcement. The fibres improve the serviceability conditions substantially by controlling cracking and deflection, besides increasing the flexural strength marginally. The crack-controlling role of the fibres enables the permissible stress in the steel reinforcement to be raised to a much higher value for a given crack width. Higher-strength steel bars may thus be used which will also meet the serviceability requirements. Control of shear cracking and improvement of shear resistance in concrete beams and slabs are also possible (Parmeswaran, 1988).

The distinctive properties of steel fibre reinforced concrete can be summarized as follows:

Steel fibres up to about 5% by volume, are found to increase the cracking resistance (at first crack) of concrete up to 2.5 times the strength of the unreinforced materials and slightly increase the compressive strength, splitting tensile strength as well as direct tensile strength are also increased by about 2.5 and 1.5 times, respectively. Steel fibre reinforcement increases the elastic modulus of the composite. Adding about 10% of steel fibres by volume may double the young's modulus of concrete.

The ultimate load-carrying capacity of steel fibre reinforced concrete beam depends mainly on the adequacy of bond. Unless there is excellent bond at the interface between the fibres and the concrete surrounding them, the fibres will get pulled out (debonded), as soon as the load is transferred on to them immediately after cracking. The ultimate load of beams in which the fibres failed by pulling out will be no greater than the ultimate load of unreinforced beams. If the inter-facial bond is excellent, the fibres can withstand the load further after a cracking of the matrix and would ultimately fracture leading to a very great increases in ultimate strength. Increase in bond has been achieved by the introduction of indented, crimped, or bent fibres, which are now being produced commercially in several countries.

Apart from improvement of ductility and strengths at first crack and ultimate stage, fibre reinforcement has also been found to improve the shear strength, tensile stiffness, bearing strength, fatigue strength, torsional strength, spalling resistance, energy-absorption, resistance to wear, resistance to freeze-thaw damage, resistance to wear, resistance to freeze-thaw damage, resistance to shock and dynamic loading, impact and fatigue strength, and friction and skid resistances. Table 1.10 gives the improvement in properties shown by steel fibre concrete as compared to plain concrete.
Table 1.10: Improvement in properties of steel fibre concrete as compared to plain concrete

<table>
<thead>
<tr>
<th>Property</th>
<th>Fibre reinforced concrete</th>
<th>Advantages over plain concrete</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexural strength (Proportional limit)</td>
<td>Upto 12.5 N/mm²</td>
<td>Can be more than 2 times higher</td>
</tr>
<tr>
<td>Flexural strength (Ultimate)</td>
<td>Upto 17.5 N/mm²</td>
<td>Can be more than 3 times higher</td>
</tr>
<tr>
<td>Compressive strength</td>
<td>Upto 90 N/mm²</td>
<td>Significant increase</td>
</tr>
<tr>
<td>Impact resistance</td>
<td>1367</td>
<td>Nearly 3 times higher</td>
</tr>
<tr>
<td>Ductility</td>
<td>Very much more</td>
<td></td>
</tr>
<tr>
<td>Fatigue endurance limit ratio</td>
<td>0.80-0.95</td>
<td>More than 70% higher</td>
</tr>
<tr>
<td>Abrasion resistance Index (Sand blast test)</td>
<td>2</td>
<td>Twice as resistance</td>
</tr>
<tr>
<td>Spalling resistance index (heat test)</td>
<td>1</td>
<td>Several times greater</td>
</tr>
<tr>
<td>Freeze-thaw damage (durability index)</td>
<td>1.9</td>
<td>90% greater resistance</td>
</tr>
<tr>
<td>Shear strength (Per Battelle)</td>
<td>Upto 5.1 N/mm²</td>
<td>Nearly 2 times higher</td>
</tr>
<tr>
<td>Deflection</td>
<td>Very much less</td>
<td></td>
</tr>
</tbody>
</table>

1.13.2 Strength of Steel fibre reinforced concrete

Several theories have been formulated to predict the strength of steel fibre reinforced concrete in axial compression, tension and bending based on assumed stress strain relationship for fibres and matrix, fibre spacing and orientation, critical fibre volume, critical aspect ratio, and interfacial bond between the fibres and the matrix. Among these, the two most important factors, which influence the ultimate load, are the volume percentage of fibres and their aspect ratios (Parmesan, 1988).

If the fibres do not pull out, then the flexural strength of a beam reinforced with fibres can be predicated by assuming appropriate tensile/compression stress blocks, as given by Edgington, Hannant and Williams (1974), Swamy (1975), or Rajagoplan and Parameshwaran (1974). By using partial safety factors, the flexural strength equations for steel fibre reinforced concrete, which are sufficiently lower bond, were proposed by Swamy( ) as under:

\[
f_{cr} = 0.843f_m (1-V_r) + 2.00 V_r (l/d)
\]

\[
f_{ut} = 0.970f_m (1-V_r) + 2.00 V_r (l/d)
\]

Where, \( f_{cr} \) and \( f_{ut} \) are the cracking and ultimate stresses of the composite, \( f_m \) are the volume fraction of the fibres and 'l' and 'd' are the length and diameter of the fibres.
The ultimate moment of resistance of steel fibre reinforced concrete in which the fibres are uniformly dispersed and randomly oriented may be computed using the expression given below which is based on the stress-strain profiles suggested by Rajagopalan, Parameswaran, and Ramaswamy (1974). In arriving at the expression, it is assumed that the fibres do not pull out before their ultimate resistance is realized.

\[ M_u = 0.4154 (K_1 D)^2 b f'c + 0.33 \lambda b \sigma_{fu} (K_2 D)^2 b + 0.5 \lambda \sigma_{fu} b V_f D^2 (1 + K_3^2 - 2K_3 - 2K_1) \]

Where \( K_1 = \lambda b \sigma_{fu} V_f (0.7225 f'c + \lambda \sigma_{fu} V_f (1 + 0.5\alpha) \)

\[ \alpha = K_2/K_1 = \varepsilon_u/\varepsilon_{cu} \]

\( \lambda \) = Orientation factors other variables are given in fig. 1.14.

**Strain profile**

**Stress distribution**

Fig.1.14: Assumed Strain and Stress Profiles (Source: Parmeswaran, 1988).

1.13.3 Properties of FRC

The properties of FRC depend on the type of fibre, fibre geometry, fibre content, orientation and distribution of fibres. The manufacturing process also influences them.

The outstanding property of cement based fibre concrete is the crack-arrest and crack control mechanism of the fibres. This directly leads to improvement in, all other properties linked with cracking, such as strength, stiffness, ductility, energy absorption, resistance to impact and fatigue and thermal loading. The real
value of fibre reinforcement lies not so much in strength but in crack control and associated properties. The crack controlling property of fibre has three major efforts on the behavior of the concrete composite. The fibres delay the onset of flexural cracking, the increase in tensile strain at first crack being as much as 100%. The ultimate tensile strain may be as large as 20 to 50 times that of plain concrete. The fibre imparts a well-defined post-cracking behavior to the composite (Parmeswaran, 1988).

The crack arrest property and the consequent increase in ductility impart greater energy absorbing property to the composite prior to failure. With 2.5% fibre content, the energy absorption capacity is increased by more than 10 times as compared to un-reinforced matrix.

1.13.4 Rheology of Fibre-reinforced concrete

The Rheological properties of FRC depend on the size and type of fibre and on the method of production. Since fibres tend to have relatively large surface areas, they have a large water requirement, as well as exhibiting a tendency to interlock or, 'ball'. Glass fibres may have a particularly high water requirement, because water is absorbed between the filaments making up each individual fibre. In addition, the w/c ratio and ratio of fine to coarse aggregate must be considered, as with conventional concrete. As a general rule, the workability is decreased as the fibre content increases, as the aspect ratio of the fibres increases, or as the coarse aggregate content increases. It is however, difficult to define a satisfactory method of testing the workability. At present, the vee-bee test is considered to be most suitable (Parmeswaran, 1988). Some results indicating the effect of aspect ratio and type of matrix on the workability of steel fibre reinforced concrete are shown in fig. 1.15 and 1.16.

Apart from difficulties with workability it is also harder to compact FRC although again not very satisfactory test is available. However, it is known that increase in the coarse aggregate content can greatly decrease the compatibility. This is shown in fig. 1.17. For most fibre mixes, external vibration is preferred; however, it may not be practical in the field. In general, fibres tend also to reduce the bleeding and improve the cohesion of a mix.
Fig. 1.15: Effect fibre aspect ratio on V-B time of fibre-reinforced mortar (Source: Parmeswaran, 1988)

Fig. 1.16: Compaction time against fibre content for matrices with different maximum aggregate size (Source: Parmeswaran, 1988)
1.13.5 Properties of steel fibre reinforced concrete

The distinctive properties of SFRC are given below:

Steel fibres up to about 5% by volume, are found to increase the cracking resistance of concrete up to 2.5 times the strength of the un-reinforced materials and slightly increase the compressive strength.

Splitting tensile strength as well as direct tensile strength is also increased by about 2.5 and 1.5 times respectively (Parmeswaran, 1988)

Fibre reinforcement increases the ductility of the members also enormously increase the elastic modulus of the composite. Adding about 10% of steel fibre by volume may double the young's modulus.

1.13.6 Properties of Freshly Mixed FRC

The significant problem with the fiber concrete mixes is a practical one that of ensuring adequate workability (flowability and compact ability) that will facilitate the concrete to be placed, compacted and finished with ease and also ensuring a uniform fiber distribution. The balling of fibers, segregation of mix, and excessive bleeding during placing and compaction should also be avoided. For a given mix proportion, the
degree of compaction seriously affects the strength and other properties. Therefore, the knowledge of fresh concrete properties is essential for proper design of the mix. The energy required for consolidation is more for fiber concrete than for plain concrete. The energy needed is proportional to the fiber content in the concrete (Ramakrishnan et al., 1983).

The quality control parameters often used for fresh concrete are workability, and air content. The other parameters to be measured include unit weight, temperature, and relative humidity. The workability can be measured using a standard slump cone test, inverted slump cone test or Vee-Bee test, and also compaction factor test.

The significant problem with fibre concrete mixes is a practical one that of ensuring adequate workability. The balling of fibres, segregation of the mix, and excessive bleeding during placing and compaction should be avoided. For a given proportion, the degree of compaction affects the strength and other properties.

1.13.7 Workability Tests

Adequate workability is required for proper placement, consolidation, and finishing. Only the minimum amount of water that is required should be in the mix because excess water results in segregation and bleeding. The following test methods are used for estimating the workability and for controlling the amount of water in the mix (Rafat Siddique, 2002).

1.13.7.1 Slump Cone Test

The slump test is the most commonly used method. This test can be used for FRC only when slump values exceed 40 to 50mm. It can also be used to monitor the FRC consistency from batch to batch.

1.13.7.2 Compaction Factor Test

This test gives behaviour of concrete under the action of external forces. If measures the compactability of concrete, by measuring the amount of compaction. This test is suitable for mixes having medium and low workabilities i.e. compaction factor between 0.91 to 0.81 but is not suitable for concretes with very low workabilities the compaction factors below 0.71.
1.13.7.3 Inverted Slump Cone Test

In this test, the time, in seconds, required by the concrete to flow through a standard slump cone kept in the inverted position is determined. The flow of concrete is aided by an immersion vibrator to simulate the workability of concrete compacted by vibration. This test is not suitable for concrete with more than 90-100mm slump made using water-reducing admixtures because the concrete will flow through the cone too quickly. For such a fluid mix, the standard slump test is recommended. Fig.1.18 shows the relationship between standard and inverted slump cone test results for plain and fibre reinforced concrete. It can be concluded that when standard slump is less than 75mm, FRC flows better under vibration than plain concrete. For mixes with slump of more than 75mm, the difference between FRC and plain concrete is negligible. The variations are similar to polymeric fibre concrete except that the standard slump value is reduced drastically if the fibre volume fraction exceeds 0.22 percent.

![Graph showing slump vs time for different concrete types](image)

Fig.1.18: Slump as measured in slump cone test, Vs time, as measured in the inverted cone test (Source: Rafat Siddique, 2002).
1.13.7.4 Vee-Bee Test

In this test, the concrete is subjected to external vibration. The consistency of the mix is determined by the time, in seconds, needed for a certain amount of concrete to flow. The Vee-Bee consistometer is not suitable for field use because of its size and weight. Fig. 1.19 shows the relations between standard slump, inverted slump, and Vee-Bee time. From this figure it can be concluded that inverted cone and Vee-Bee tests provide comparable results. Their relation with respect to standard slump is parabolic even though a concrete with a slump of 50mm has an inverted cone time of about 7 seconds compared with 3 seconds in Vee-Bee time. Inverted slump cone times are typically higher than Vee-Bee times for all levels of consistency.

The relationship between slump and flow table spread for plain and steel fibre reinforced superplasticized concretes is shown in fig. 1.20. There is only a small difference between them.

In fig. 1.21 the continuous and broken curve show the relations between slump and vee-bee time for superplasticized concretes with and without fibres. The increase in fibre content from 326.3 N/m$^3$ to 563.6-N/m$^3$ had negligible effect on the slump and flow table. However, increase in fibre content caused an increase in Vee-bee time.

1.13.7.5 Tests for Air Content, Yield, and Unit Weight

Air content can be measured using gravimetric (ASTM138), volumetric (ASTM173), or pressure (ASTM231), methods. When testing FRC, consolidation using internal or external vibration is recommended rather than rodding. Some vibration is essential when the mix is stiff and cannot be compacted properly using rodding. Use of vibration is permitted in ASTM Standard C138. The determination of unit weight and yield are covered in ASTM C138. These are simple tests common to both plain and fiber-reinforced concrete (Balaguru and Surendra. P. Shah, 2002).
Fig 1.19: Relationship between slump, Vee-Bee time, and inverted cone time (Source: Rafat Siddique, 2002).

Fig 1.20: Relationship between slump and flow table spread (Source: Rafat Siddique, 2002).
Factors that influence the behavior of freshly mixed steel fiber reinforced concrete include matrix composition, fiber type, fiber geometry, fiber volume fraction, and fiber-matrix interfacial bond characteristics. As mentioned earlier, addition of fibers will make the composite look stiffer. However, the mix can be highly workable if vibrators are used for placement and compaction.

All fiber geometries have been used in concrete. Typically, longer fibers and fibers with higher aspect (length/diameter) ratios tend to reduce workability. Balling during mixing and placing may be eliminated for certain fiber configurations by using smaller maximum-size aggregates, lower aspect ratios, and lower volume fractions.

Balaguru and Ramakrishnan have reported the results of an extensive investigation using fibers with hooked ends. Variations in slump, air content, and V-B time were studied for various cement and fiber contents. The water-cement ratio was varied from 0.28 to 0.50. A large number of mixtures with and without fibers were evaluated. Slump, V-B time depends on air content values as well as air temperatures since workability is sensitive to air temperatures. These results reflected the influences of water-cement ratio, cement content, fiber content, and high-range water-reducing admixture dosage. Extensive details are presented because these are field usable, realistic mixtures.
The factors that influence slump are the following:

- Water-cement ratio
- Combined effect of water-cement ratio and cement content
- Cement content
- High-range water-reducing admixture content
- Fiber content
- A combination of water-cement ratio, cement content, and fiber content

Within the range of the test variables, especially cement and fiber contents, the influence of fiber content was found to be 1000 times less than the water-cement ratio and 300 times less influential than the combination of cement content and water-cement ratio. This result leads to the observation that fiber contents in the range of 550 to 320 to $600 \text{ N/m}^3$ have very little influence on slump if high-range water-reducing admixtures are used.

Variance analysis for V-B time showed the following variables to be influential. Again the variables are listed in descending order of importance.

- Water-cement ratio
- Combined effect of water-cement ratio and cement content
- Cement content
- High-range water-reducing admixture content
- Fiber content
- A combination of water-cement ratio, cement content, and fiber content

Within the range of the test variables, especially cement and fiber contents, the influence of fiber content was found to be 1000 times less than the water-cement ratio and 300 times less influential than the combination of cement content and water-cement ratio. This result leads to the observation that fiber contents in the range of 550 to 320 to $600 \text{ N/m}^3$ have very little influence on slump if high-range water-reducing admixtures are used.
Variance analysis for V-B time showed the following are variables to be influential:

- High-range water-reducing admixture content
- Water-cement ratio
- Cement content
- Fiber content
- A combination of water-cement ratio, cement content, and fiber content

The factors that influence air content were found to be the following:

- Water-cement ratio
- Combination of water-cement ratio and cement content
- Cement content
- High-range water-reducer dosage
- Fiber content
- Combination of water-cement ratio, cement content, and fiber content

Note that air-entraining agent dosage was not used as a variable. It had already been found that a larger dosage of air-entraining admixture is needed to produce the same amount of air content in the presence of fibers.

The loss of workability with time is a problem in the construction field. The problem is more acute when a high-range water-reducing admixture is used, because these admixtures lose their effectiveness with time. Loss of slump and reduction in air content with time, measured for comparable plain and fiber concretes. The fibers used, which had hooked ends, were 50 mm long, 0.5 mm in diameter and were made of low-carbon steel. The slump values fall considerably after about 30-60 minutes. The rate of drop for fiber and plain concrete is about the same, but the absolute values decrease much faster for fiber concrete.

The reduction in air content seems to be less dramatic. While the values drop considerably in the first 30 minutes, they tend to stabilize after 60 minutes. The variation with time can be considered about the same for fiber and plain concretes.

It has been shown that concrete can be retempered using a high range water-reducing admixture without adversely affecting its mechanical properties. Retempering is a process in which either water or admixtures are
added to improve workability. Retempering more than once is not recommended even though experimental results show that retempering can be done twice (Balaguru and Surendra. P. Shah, 2002).

1.13.9 Effect of Fibre and Aggregate Parameters on Workability

1.13.9.1 Fibre Length and Diameter

A collection of long thin fibres of length/diameter greater than 100 will, if shaken together, tend to interlock in some fashion to form a mat, or a type of bird's nest from which it is very difficult to dislodge them by vibration alone. Short stubby fibres on the other hand of length/diameter less than 50 are not able to interlock and can easily be dispersed by vibration.

Similar effects are observed when fibres are dispersed in mortar or concrete and the ease with which the fibres can move relative to each other under vibration is shown in fig.1.15 for mortars, with a particle size less than 5 mm.

It can be seen from fig.1.15 that the l/d ratio has a crucial influence on the volume of fibres, which can be included in the mix with relatively easy compaction (say V-B < 20 seconds). It is shown that the critical fibre volume for strengthening in direct tension may be about 1.7 per cent at an l/d of 100 and fig.1.15 indicates that practically this may only just be achieved with mortars, let alone with concretes. However, the fibre volume required for strengthening in flexure can be achieved much more easily with acceptable compaction characteristics (Balaguru and Surendra. P. Shah, 2002).

1.13.9.2 Aggregate Size and Volume

The problem is more complicated when fibres are introduced into a concrete rather than a mortar matrix because they are separated not by a fine grained material which can move easily between them, but by particles which will often be of a larger size than the average fibre spacing if the fibres were uniformly distributed. This leads to bunching and greater interaction of fibres between the large aggregate particles and the effect becomes more pronounced as the volume and maximum size of the particles increases. The principle is demonstrated in figure.

Fig.1.22 shows diagrammatically that uniform fibre dispersion is more difficult to achieve as the aggregate size increases from 5 mm to 10 mm to 20 mm. However, this is a simplified picture because, in reality, the fibre and aggregate dispersion is three-dimensional and there may be up to 200 fibres in any given cube of
mortar of side length equal to the fibre length before fibre interaction becomes excessive. Nevertheless, it is apparent from fig.1.22 that the greater the volume and size of the coarse aggregate, the more fibre interaction will occur.

![Diagram showing fibre distribution](image)

Fig. 1.22: Effect of aggregate size on fibre distribution within a square of side length = fibre length (40mm)

In a normal concrete mix the particles finer than 5 mm occupy about 54 per cent of the volume, the 10 mm aggregate about 20 percent and the 20 mm aggregate about 20 per cent of the volume. Thus only about 54 per cent of the real volume (i.e. the mortar fraction) is available for free fibre movement during Compaction. Experience has shown that a satisfactory mix for fibre concrete should contain a mortar volume of about 70 per cent with only about 30 percent consisting of particles between 5 mm and 10 mm.

The effect of a range of aggregate sizes and volumes on the compaction times of composites made with wires of $l/d = 100$ is shown on Fig.1.16.

Fig.1.16 indicates that for a V-B time of 20 seconds the 10 mm concrete will only accept about 50 per cent of the fibre volume compared with mortar and the 20 mm concrete will carry less then the 10 mm concrete. These particular results are due to orientation of fibres, aggregate size and aggregate volume because the mortar fraction is lowest for the 20 mm mix. However, Mangat who has obtained a similar trend has examined the effect of coarse aggregate volume alone (Balaguru and Surendra. P. Shah, 2002).

1.13.10 Properties of Hardened Concrete

The significant influence of incorporation of steel fibers is to delay and control the tensile cracking of the composite material. Thus inherently unstable tensile crack propagation in concrete is transformed to a slow
controlled crack growth. The fibers provide a ductile member in a brittle matrix and the resultant composite has ductile properties, which are significantly different from plain concrete.

All modes of failure are affected by fibers. The strengthening mechanism of fibers involves transfer of stress from matrix to the fiber by interfacial shear or by interlock between the fiber and matrix if the fiber surface is deformed. The fiber and matrix share the tensile force until the matrix cracks and then the total force is transferred to the fibers. This change in the mechanism of failure causes significant improvement in the following properties: ductility, toughness, impact resistance, tensile and flexural strengths, fatigue life, abrasion resistance, shrinkage, durability, and cavitations resistance (Parameswaran, 1988).

1.13.10.1 Behaviour of Fibre Reinforced Concrete under Compression

The increase in compressive strength due to addition of fibers is variable ranging from negligible to 20 percent. However, there is a substantial change in the compressive stress strain response. This change is generally characterized by a noticeable increase in strain at peak load and a significant increase in ductility resulting in substantially higher toughness. This increased toughness is useful in preventing sudden and explosive failure under static loading and in absorbing energy in dynamic loading. A typical increase in the compressive toughness index varies from 200 to 300 percent. The toughness increases with the volume fraction of fibers and the aspect ratio. The available test data indicates that steel fibers lead to a higher toughness than glass or polypropylene fibers (Technical Manual ICFRC-TM 4, 1997).

Matrix properties also have influence on the effectiveness of fibers in improving the compressive behavior of concrete. The improvements due to the fiber addition are relatively more significant at lower matrix compressive strengths. Addition of silica fume increases the compressive strength and toughness of steel fiber reinforced concrete through increase of the fiber-matrix interfacial bond (Ramakrishna n et al., 1985).

Extensive research had indicated that there was no appreciable change in the linear part of the stress-strain curve in compression when randomly oriented fibers are added to concrete in different volume fractions. The modulus of elasticity values calculated was almost the same for plain and FRC specimens with various volume fractions.

As explained by Rafat Siddque (2002) the increase in strength provided by steel fibres very rarely exceeds 23-28 percent. With the increase in the use of deformed fibres, the fibre quantity is generally limited to
550-650 N/m$^3$ or less than 1.0 percent. At this volume fraction, the increase in strength can be considered negligible for all design purposes.

Other factors that are considered in design are the modulus of elasticity, strain at peak load and post cracking behaviour. The change in modulus of elasticity is taken as negligible. However, fibres make a considerable contribution to ductility. Fibre addition increases the strain at peak load and results in a less steep and more reproducible descending branch as shown in fig 1.23. Overall, FRC can absorb much more energy before failure compared to plain concrete.

The increase ductility provided by the fibres depends on a number of factors, (i) fibre content (ii) fibre geometry and (iii) matrix.

An increase in fibre content results in an increase in the energy absorption capacity. However the relative magnitude of energy increase with 0 to 0.7 percent fibre content, by volume is much greater than any further energy increase at higher fibre contents. With regards to fibre shape aspect ratio is important for the performance of smooth straight fibres. As the aspect ratio is increased the ductility increases. In the case of deformed fibres, hooked ends fibres provide good energy absorption.

The composition of the matrix contributes to strength and energy absorption in two ways. The first is its bonding characteristics with the fibres. Second is the brittleness of the matrix which itself plays an important role in behaviour of FRC. Normal strength concrete is brittle than high strength concrete and the incorporation of fibres makes the composite more ductile. Britteness is more pronounced for concrete containing flyash and silica fume. Hence a higher fibre volume fraction is required for high strength concrete to produce ductile failure. The contrast can be seen in stress-strain curves in fig. 1.24 and 1.25. For normal strength concrete about 550-650 N/m$^3$ of steel fibres with hooked ends is sufficient to produce a reasonably flat descending part. Whereas for higher strength concrete a fibre content of 1100-1300 N/m$^3$ is required to obtain a ductile behaviour.

Compressive strength seems to govern the brittleness of both plain and fibre-reinforced concrete. Higher compressive strength always results in brittle mode of failure for both normal weight and lightweight concrete.
Fig. 1.23: Compressive stress-strain behaviour of FRC containing 50mm hooked end steel fibres (Source: Rafat Siddique, 2002).

Fig. 1.24: Compressive stress-strain behaviour of FRC containing 30 mm hooked end steel fibres (Source: Rafat Siddique, 2002).
1.13.10.2 Split Tensile Strength of Fibre Reinforced Concrete

There are two types of tension tests used for concrete: direct tension and splitting tension. In the former, dog-bone shape specimens are subjected to axial tension. Such tests are not normally used in the splitting tension test, which is often used; a cylindrical specimen is subjected to a splitting tension along its axis. Cubes can also be used for this test (Technical Manual ICFRC-TM 4, 1997).

Deformations are not normally measured in splitting tensile tests. Therefore ductility under this type of loading is difficult to measure.

1.13.10.3 Behaviour of Fibre Reinforced Concrete under Flexure

A significant difference in the behavior of plain and fiber reinforced concrete is found in the flexure test (Ramakrishnan, et al., 1980). When the fiber concrete beams are loaded in flexure, two stages of behavior have been generally observed in the load-deflection curve (fig.1.26). The behavior is more or less linear up to the first crack and then the curve is significantly non-linear and reaches its peak at the ultimate strength or at the maximum sustainable static load.
Two factors that significantly influence the flexure test are the fiber type and fiber volume. Fig.1.26 presents the flexural load deflection curves for two types of steel (straight and hooked) fibers (Ramakrishnan, et al., 1980). Fig.1.27 shows the comparison of load deflection curves for different volume fractions of hooked fibers (Ramakrishnan, et al., 1989).

The hooked fiber proved its capacity as a crack arrester. The cracks are prevented from propagating until the composite ultimate stress is reached. The mode of failure was a simultaneous yielding of the fibers and the matrix. During the test, one could actually hear the popping sound of the fibers failing in tension. It seems obvious that the deformed end of these fibers contribute significantly to the increase in bond between the fiber and matrix. The significance of good bond can be seen from the load-deflection curves of fig 1.27, which are typical curves. These curves indicate a ductile behavior and large energy absorption. The two fiber concentrations used gave similar strength results. For the specimens reinforced with straight fibers due to the sudden failure, the load dropped from the maximum value at point A to the load indicated by point C with a considerable increase in deflection as shown in Figure. Therefore line ABC is an apparent load deflection curve whereas the actual curve may be closer to the line ADC as shown in fig.1.27. Observation of the failure and the inspection of the failed specimens have shown that the mode of failure for the straight fiber specimens was strictly a bond failure. Comparison of the load deflection curves shows that the straight fiber reinforced concrete has a lower load carrying capacity, than hooked fiber reinforced concrete. However, it has higher ultimate strength and higher toughness than plain concrete (Technical Manual ICFRC-TM 4, 1997).

Fibers, when added in significant volume fractions, increase the first crack and ultimate flexural strengths of concrete. The effect of steel fibers on the ultimate strength is significant and with its better pullout performance, it is especially effective at large deformations and crack widths.

Behaviour under flexure is the most important aspect of FRC because in most practical applications the composite is subjected to some kind of bending load. Moreover the addition of fibre improves the flexural toughness of plain concrete. Tests are usually done by using 100 x 100 x 500 mm beams under third point loading. In all cases, the increases in flexural strength are normally higher than increases in either compressive or splitting tensile strength.
Fig. 1.26: Load-Deflection curves for static loading at 28 days
(Technical Manual ICFRC-TM 4, 1997)

Air Supr

WIC

Cmont

Fig. 1.27: Comparison of Load-Deflection curves for mixes with different fibre contents (7 days)
(Technical Manual ICFRC-TM 4, 1997)

<table>
<thead>
<tr>
<th>Mix</th>
<th>W/C</th>
<th>Cement (Kg/m³)</th>
<th>Fiber (Kg/m³)</th>
<th>Air content (%)</th>
<th>Super plastic dosage</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.36</td>
<td>362.51</td>
<td>32.63</td>
<td>5.70</td>
<td>1.00%</td>
</tr>
<tr>
<td>B</td>
<td>0.36</td>
<td>362.51</td>
<td>44.48</td>
<td>4.50</td>
<td>1.00%</td>
</tr>
<tr>
<td>C</td>
<td>0.36</td>
<td>362.51</td>
<td>56.34</td>
<td>4.60</td>
<td>1.00%</td>
</tr>
</tbody>
</table>
Both the fibre volume fraction and aspect ratio play a significant role. Longer fibres tend to provide preferred orientations along the length of the specimen, resulting in higher strength increase. For a given fibre geometry, higher aspect ratios result in greater strength increase if the composite is compacted properly (Technical Manual ICFRC-TM 4, 1997).

a. Influence of Fibre Content

The influence of fibre content on load-deflection curves fraction is shown in fig.1.28 and it shows the load-deflection curve obtained by using 100 x 100 x 500 mm beams tested over a simply supported span of 400 mm on third point loading. The compressive strength of the matrix was 29 MPa. The fibres, which had hooked-ends, were 51 mm long and had a diameter of 0.51 mm. The load-deflection curve is almost linear upto 90 percent of first crack load. The post crack increase in load is significant for 900 and 1200 N/m fibre content. This increase provides the increase in flexural strength of concrete and stable post crack behaviour (Rafat Siddique, 2002).

Fig. 1.28: Influence of fibre content on load-deflection curves: 51mm long hooked-end fibres(Source: Rafat Siddique, 2002).

b. Influence of Fibre Length

The influence of fibre length is very significant for straight fibres. It has been established that longer fibres with higher aspect ratios provide better performance in both strength increase and energy absorption as long as they are mixed, placed, compacted and finished properly. The test results obtained with hooked-end
fibres in concrete that had a compressive strength of 29 MPa, are based on 100 x 100 x 500 mm beams tested under third-point loading. The three fibre lengths were 30, 50 and 60 mm and the corresponding diameters were 0.51, 0.52 and 0.8 mm (Rafat Siddique, 2002). The load deflection curves of two fibre contents and three fibre lengths are shown in fig. 1.29.

![Load-deflection curves with hooked end fibres](image)

**Fig. 1.29:** Effect fibre length on load-deflection curves with hooked end fibres (Source: Rafat Siddique, 2002).

c. Influence of fiber geometry

As described by (Balaguru and Surendra, P. Shah (2002) the influence of fiber geometry is shown in fig. 1.29, 1.30 presents load-deflection curves for three fiber geometries, namely, hooked-end fibers, corrugated fibers, and deformed-end fibers. The hooked-end fibers were 30 mm long, whereas corrugated and deformed-end fibers were 25 and 30 mm, respectively. Concrete with hooked-end fibers had a higher tensile strength and a better post crack response than the other two types. The drop after the first peak is much more pronounced for corrugated and deformed-end fibers.

The differences in behavior among the three fiber types can be seen even more clearly in fig. 1.29, which shows the toughness indices of $I_{30}$, $I_{50}$, and $I_{100}$. Hooked-end fibers perform better in almost all cases. The differences are more significant at larger deflections. For example, $I_{100}$, which is calculated using the area under the load-deflection curve up to 50.5 times the first-crack deflection, is much larger for hooked end fibers. The results reported in Reference dealing with hooked end and corrugated fibers show similar trends.
d. Influence of matrix composition

Within concrete containing coarse aggregates, the major variables are compressive strength, aggregate size, and presence of admixtures such as fly ash and silica fume, and type of aggregate. Typically, as the matrix strength increases, concrete becomes more brittle and, hence, more fibers are needed to achieve the same amount
of ductility. The addition of silica fume makes the matrix more brittle and, hence, for the same fiber type and volume fraction, silica fume concrete beams have lower toughness. Fig. 1.31 clearly shows a larger drop in the post crack load-deflection curve for silica fume concrete than for concrete without silica fume. The total energy absorbed by the high-strength silica fume concrete could be higher than that of normal strength concrete but the toughness index values calculated using ASTM procedures are lower.

Concretes containing lightweight aggregates were found to behave similarly to normal weight concrete. Here again, high-strength concrete containing silica fume shows a greater drop in load capacity after the first crack than concrete without silica fume. The use of longer fibers is recommended for concretes made with large-size aggregates.

A matrix consisting of non Portland cement containing fibers behaves quite similarly to Portland cement concrete with fibers. The toughness indices of magnesium phosphate quickset concrete reinforced with hooked-end, crimped, and deformed-end fibers are compared in fig. 1.32. From this figure one can see that hooked-end fibers provide the best performance. As for Portland cement concrete, the differences in behavior become more significant at large deflections reflected in 130 and 150. The results were based on 50 x 50 x 330 mm beams tested using third-point loading (Balaguru and Surendra, P. Shah, 2002).

![Graph showing effect of added silica fume on load-deflection curves](Source: Balaguru and Surendra, P. Shah, 2002).
Toughness or energy absorption of concrete is increased considerably by the addition of fibers. The toughness index is the measure of the amount of energy required to deflect the 102 mm beam in the modulus of rupture test, a given amount compared to the energy required to bring the beam to the point of first break (Gopalaratnam et al., 1991). It is calculated as the area under the load deflection curve up to 1.9 mm divided by the area under the load deflection curve of the fibrous beam up to the first crack strength (proportional limit defined as first deviation from linear). A flexural toughness index may also be calculated as the ratio of the toughness of the steel fiber concrete at specified deflection to the toughness up to the first crack as shown in ASTM C 1 0 18-89 or up to maximum stress or to the toughness of the unreinforced matrix.

The first crack load, the maximum load and the area under the load deflection curve up to 1-9 mm center point deflection, is shown in fig.1.27. All specimens made of plain concrete failed immediately after the first crack and hence the toughness index for these specimens is equal to 1. In general, the toughness index for FRe varied greatly depending on the position of the crack, the type, aspect ratio, and volume fraction of the fibers and the distribution of fibers. However, the average toughness index for beams with hooked fibers was two to three times greater than for those beams reinforced with straight fibers (Gopalaratnam et al., 1991).

1.13.12 Direct Tension

There is no standard test to determine the stress-strain curve of FRC in direct tension. Various parameters, like the size of the specimen, method of testing, stiffness of the testing machine, gage length and the unpredictable crack pattern will influence curves and the tensile strength. The strength in direct tension is
generally the same as that of plain concrete. However, the toughness of SFRC is one or two orders of magnitude higher due to the large frictional energy developed during fiber pullout (Technical Manual ICFRC-TM 4, 1997).

1.13.13 Impact Strength

A simple impact test proposed by ACI Committee 544 (1982) consists of a 4.54 kg hammer dropped on to a steel ball resting on the test specimen, which are 64 mm high and 152 mm in diameter. The hammer is dropped consecutively and the number of blows required to cause first crack and ultimate failure are recorded. First crack is defined as the first visible crack. Ultimate failure is reached when the cracks have opened sufficiently to make the specimen touch three of the four lugs at the base plate. A test result from a comparative study of different fiber types is shown in fig. 1.33. Fibers with good anchorage (hooked fibers) provide a superior impact resistance to the concrete (500 percent more than straight fibers). The higher energy required to pull the fibers out of the matrix provides the impact strength, Steel fiber reinforced beams have been subjected to impact loading in instrumented drop weight and Charpy type systems by Suaris, Shah, Naaman and Gopalaratnam. They have reported that the total energy absorbed (measured from the load deflection curves) by SFRC beams could be as much as 40-100 times more than that for unreinforced beams (ACI Committee, 1982).

In general, the dynamic strength of FRC subjected to explosive charges, dropped weights and dynamic flexural, tensile and a compressive load is 3 to 10 times greater than that for plain concrete.

1.13.14 Fatigue Strength

Fatigue strength is an important property of SFRC because it is the behavior of the material under dynamic loading that clearly distinguishes the material from plain concrete. In many applications, particularly in pavements and bridge deck overlays, the flexural fatigue strength and the endurance limit are important design parameters because these structures are designed on the basis of fatigue load cycles. The greatest advantage of adding fibers to concrete is the improvement in flexural strength in both static and fatigue loading (Technical Manual ICFRC-TM 4, 1997).
In an extensive investigation of the behavior of FRC subjected to fatigue loading, using various types of steel and polypropylene fibers (Ramakrishna, et al., 1987, 1989, 1991, Vodron et al., 1990, Nagbhushanam, et al., 1989), the author has shown that the flexural fatigue strength of FRC is significantly higher than that of non-reinforced concrete. Fibers restrain the growth of microcracks and flaws under repetitive stress. A properly designed SFRC can achieve 90 to 95 percent endurance limit. With a higher endurance limit the concrete cross sections could be reduced. Alternatively using the same cross section would result in a much longer life span or higher load carrying capacity or both.

An analytical investigation (Ramakrishnan, et al., 1991) resulted in the flexural fatigue models and the prediction of fatigue life expectancy for four different FRC (hooked-end steel, straight steel, corrugated steel, and polypropylene) with two different fiber quantities (0.5 and 1.0% by volume) as shown in fig.1.34. The same basic mixture proportions were used for all the concretes. For a better accuracy in generating the S-N curves, statistical and probabilistic concepts were introduced to predict the flexural fatigue model. It was found that the fatigue life model (S-N curve) was more accurate when presented on a log-log scale than on a lognormal scale,
as commonly assumed. It was also found that fiber reinforced concrete reaches an endurance limit at about two million cycles.

Fig. 1.34: Regression lines for flexural fatigue strength of fibre reinforced concretes (Technical Manual ICFRC-TM 4, 1997).
1.13.15 Structural Properties

As yet, a set of standard tests to determine the structural properties of either fresh or hardened FRC does not exist, although many tests have been proposed. In general, many of the tests, particularly those for strength, which have been developed for ordinary concrete, may be applied. However, FRC has not been developed for its ultimate static strength properties. Although some improvement in strength can be obtained with fibres, similar strengths can often be obtained simply by making the appropriate changes in cement content and w/c ratio. Thus simple strength comparisons may be rather misleading (Parmeswaran, 1988).

For adequately compacted specimens, the addition of fibres has very little effect on the compressive strength of FRC. Moreover, it would appear that fibre reinforcing has little effect on the elastic modulus of FRC. Typical compressive stress-strain curves for steel fiber concretes are shown in fig.1.35. Moreover, it would appear that fibre reinforcing has little effect on the elastic modulus of FRC.

![Fig. 1.35: Stress-strain deformation in compression of steel fibre concrete (Source: Parmeswaran, 1988)](image)

The direct tensile strength of FRC can be increased considerably by the addition of high modulus fibres. The increase is, however dependent on the aspect ratio of the fibres, as shown in fig. 1.36. It appears that the tensile strength can be adequately predicted by the ‘law of mixtures’ applicable to composite materials as under.

\[ \sigma_t = \sigma_m (1 - V_f) + 2 \tau (l/d) V_f \]

Where \( \sigma_t \) and \( \sigma_m \) are tensile strengths of the composite and the matrix, respectively, \( V_f \) the percent of the fibres by volume, \( l/d \) the aspect ratio; and \( \tau \) the average interfacial bond strength. Tensile strengthening occurs at all fibre contents as long as \( 2 \tau (l/d) > 6m \). However it should be noted that some investigations have shown very little
increase in direct tensile strength due to fibre additions. Torsional strength of FRC is also very little affected by the additions (Parmeswaran, 1988).

The effects of fibre additions on the flexural strength of FRC have been investigated extensively. Some investigations have found an increase in both the first-crack strength and in the ultimate strength, the later increase being up to 3 times the strength of the plain concrete as shown in fig. 1.37. However some investigators have shown little or no appreciable improvement in flexural strength much seems to depend upon the details of the tests carried out, both the coarse aggregate volume and methods of fabrication being important. The real advantage of FRC to be that a certain amount of flexural strength can be relied upon, even after some cracking of the matrix occurs (Parmeswaran, 1988).

![Fig. 1.36: Relation between fibre volume and tensile strength (Source: Parmeswaran, 1988)](image)

Although a few data are available, it appears that steel fibre reinforcement can improve the shear strength of concrete. Some research has been carried out in replacing conventional shear reinforcement in the reinforced concrete beams with steel fibres. Although the fibres were found to be less effective than conventional shear reinforcement, the increase in shear, moment and energy absorption capacity of beams with fibre reinforcement suggests that they may have structural applications, particularly for earthquake and blast resistant structures. More work in this area is in progress (Parmeswaran, 1988).
The bearing strength of fibre reinforced concrete is also much higher than that of plain concrete.

The greatest advantage of using FRC is that fiber additions improve the toughness (the total energy absorbed in breaking a specimen), i.e. fibre additions give concrete a considerable amount of apparent ductility. However, there is no standard test for ordinary concrete to measure the toughness, and to date, no satisfactory test has been developed for FRC, although several have been suggested. It seems likely that some measure of the area under the stress-strain curve is necessary to characterize the effectiveness of the fibres. If we define toughness as the area under the stress-strain (or load-deflection) curves, it may be seen in the fig. 1.39, that increasing the fibre content has little effect on the ultimate strength, but vastly increases the toughness. Basically, toughness refers to the ease with which cracks can propagate within a material and is particularly significant property of
brittle materials such as concrete. Since plain concrete is limited by its brittle behaviour, any measure taken to improve its toughness will be useful (Parmeswaran, 1988).

Polypropylene fibres significantly increase concrete toughness but have little effect on the tensile strength. Mixtures of polypropylene and glass fibres, on the other hand, produce concrete with a high degree of both toughness and flexural strength (Tables 1.11 and 1.12).

![Graph showing effect of volume fibres in flexure](image)

**Fig. 1.39:** Effect of volume fibres in flexure (Source: Parmeswaran, 1988)

**Table 1.11:** Ratio of Toughness values of some fibre reinforced cementitious materials with respect to unreinforced materials

<table>
<thead>
<tr>
<th>Composite</th>
<th>Volume percent (%) of fibre</th>
<th>Relative Toughness*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Steel</td>
<td>0.5</td>
<td>2.5-4.0</td>
</tr>
<tr>
<td>Steel</td>
<td>1.0</td>
<td>4.0-5.5</td>
</tr>
<tr>
<td>Steel</td>
<td>1.5</td>
<td>10-25</td>
</tr>
<tr>
<td>Glass</td>
<td>1.0</td>
<td>1.7-2.0</td>
</tr>
<tr>
<td>Polypropylene</td>
<td>0.5</td>
<td>1.5-2.0</td>
</tr>
<tr>
<td>Polypropylene</td>
<td>1.0</td>
<td>2.0-3.5</td>
</tr>
<tr>
<td>Polypropylene</td>
<td>1.5</td>
<td>3.5-5.0</td>
</tr>
<tr>
<td>Nylon</td>
<td>1.0</td>
<td>1.5-1.7</td>
</tr>
<tr>
<td>Mortar</td>
<td>1.3</td>
<td>15.0</td>
</tr>
<tr>
<td>Asbestos</td>
<td>3-10</td>
<td>1.0-1.5</td>
</tr>
<tr>
<td>Cement paste</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Glass</td>
<td>4.5</td>
<td>1.0-3.0</td>
</tr>
<tr>
<td>Mica flakes</td>
<td>2.0-3.0</td>
<td>3.0-3.5</td>
</tr>
</tbody>
</table>
* These values are representative values only and may vary additionally due to difference in test methods and specific process and mix variables.

Table 1.12: Ratio of Flexural strength of some fibre reinforced cementitious materials with respect to unreinforced materials

<table>
<thead>
<tr>
<th>Composite</th>
<th>Volume percent (%) of Fibre</th>
<th>Relative Flexural strength*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steel</td>
<td>1-2</td>
<td>2.0</td>
</tr>
<tr>
<td>Glass</td>
<td>1-2</td>
<td>2.5-3.5</td>
</tr>
<tr>
<td>Mortar</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steel</td>
<td>1.3</td>
<td>1.5-1.7</td>
</tr>
<tr>
<td>Glass</td>
<td>2</td>
<td>1.4-2.3</td>
</tr>
<tr>
<td>Asbestos</td>
<td>3-10</td>
<td>2.0-4.0</td>
</tr>
<tr>
<td>Cement paste</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Glass</td>
<td>4.5</td>
<td>1.7-2.0</td>
</tr>
<tr>
<td>Mica flakes</td>
<td>2-4</td>
<td>2.2-5</td>
</tr>
<tr>
<td>Polypropylene</td>
<td>1-2</td>
<td>1.0</td>
</tr>
</tbody>
</table>

* These values are representative values only and may vary additionally due to difference in test methods and specific process and mix variables.

Related to the concept of toughness is the impact resistance of FRC. Many studies have shown that the impact resistance of concrete can increase dramatically (by more than an order of magnitude) with the addition of fibres. Low-modulus fibres like nylon and polypropylene seem to be particularly effective in this regard. The fiber effectiveness for impact resistance is also related to the bond characteristics, fibres with different shapes can give quite different results, as shown in fig.1.40. Unfortunately, no satisfactory test for the impact strength of FRC has yet been developed which makes it impossible to compare the results obtained in different investigations. Finally, fibres will not only improve the impact strength of FRC but also help prevent the shattering of the mass into fragments under shock loading. In addition, there are indications that fibre reinforcement improves the ability of concrete to withstand abrasion and cavitation damage (Parmeswaran, 1988).

Fatigue resistance is also related to the ability of cracks to propagate. Laboratory tests have proved that fatigue strength of concrete in flexure increases with increasing fibre content; however, fibres have little effect on fatigue in compression.

The presence of steel fibres is also known to increase the abrasion and erosion resistance of fibre composites.
very effective in reducing shrinkage cracking and this should have a very beneficial effect on the durability of the concrete.

1.13.16 Shrinkage and Creep

Knowledge of shrinkage, creep and creep recovery characteristics of structural concrete is essential for the analysis and design of concrete structures. The total shrinkage and creep strains measured according to the ASTM standards over a period of more than a year had shown that these strains were less than those obtained for the generally used structural concrete (Ramakrishnan et al., 1983). Similar to plain concrete, the shrinkage and specific creep strains of SFRC increased with an increase in water cement ratio and the concrete that exhibited higher shrinkage had also higher creep.

1.13.17 Freeze-Thaw Resistance

Durability is an essential property of most building materials and components. It becomes even more important if the material is subjected to freezing and thawing. A study (Ramakrishnan et al., 1983) was conducted to determine the major factors that may affect the behavior of SFRC and influence its durability under freezing and thawing conditions. A better performance was shown by FRC in three out of five cases. However the difference is not significant, considering the variation that may be possible in experimental results.

In general, it is concluded that as in the case of plain concrete, air content is the most significant factor. Comparison of SFRC and plain concrete indicates that their behavior under freeze-thaw loading is essentially similar. An increase of cement content and a reduction of water cement ratio improve the durability. The toughness index of SFRC does not change appreciably with freezing and thawing. An inspection of the specimens indicated that (Ramakrishnan et al., 1983) in SFRC specimens the severity of visible cracking and spalling as a result of freeze-thaw was reduced when inadequate air void system was present. Based on the results it was recommended that at least 8.0 percent air content should be specified for SFRC exposed to severe freeze-thaw conditions.

1.13.18 Durability

Durability is as important as strength in determining the suitability of concrete for any specific application. Durable concrete should generally be dense and impermeable. However, although the porosity of FRC appears to be higher than that of plain concrete, probably due to the difficulties in fully compacting the mix,
the effects of fibres on the permeability have not yet been determined. Since the study of FRC is fairly recent
development, many long-term durability data are not yet available.

If the steel FRC is made with an appropriate paste content and water-cement ratio for the exposure
condition in question, the alkaline environment provides adequate protection for the fibres in the uncracked state. However once the concrete cracks, particularly in a marine or acid environment, the rate of corrosion and carbonation will increase considerably. Surface rusting will occur, but this is only a cosmetics effects. Ordinary glass cannot be used in the production of FRC because of attack by the alkaline Portland cement. Special alkali-resistant glass fibres (called CEMFIL) are better, but even they may show a loss of strength with time, coupled with increased brittleness of the composite, the rate of corrosion depends on the availability of moisture. Asbestos cements are very durable chemically, however, because of the short fibre length, asbestos cement is fairly brittle and subject to damage in handling. Carbon and polymeric fibres can also be expected to be durable, but natural organic fibre may suffer from alkaline, bacterial, or fungus degradation (Parmeswaran, 1988).
1.14 Applications and Case studies of FRC

1.14.1 Advantages of FRC

Fibres, which are randomly distributed throughout the concrete, can overcome cracks and control shrinkage more effectively. These materials have outstanding combinations of strength and energy absorption capacity. In general, the fibre reinforcement is not a substitution for conventional steel reinforcement. The fibres and steel reinforcement have their own role in concrete technology (Parameswaran, 1988, and Chuan Mein Wong, 2004).

Benefits of using fibres-reinforced concrete are

- Increase impact and shock resistance, fatigue endurance and shear strength of concrete.
- Requires no special equipments to install reinforcement
- Increase crack resistance, long-term ductility, energy absorption capacity and toughness of concrete.
- Reduce labour and material costs in concrete applications.
- Provides multi-directional concrete reinforcement.
- Compatible with admixtures, all types of cement and concrete mixtures.
- Reduce plastic shrinkage and crack width formation.
- Restrictions and limitations of using fibre-reinforced concrete are
- Control crack as result of external stresses.
- Reduction in curing and creep.
- Justification for a reduction in the size of support columns.
- Higher structural strength development.
- Replacement of any moment for structural steel reinforcement.
- Decreasing the thickness of slab on grade.
- An assurance of minimum quality

If the materials used in making concrete are of low grade or if the concrete produced is of substandard, then even if the same concrete is used, were assured of a minimum quality which is required for any construction purpose.

- Reinforcement positioned where it is needed to do the most good
- Extra amount of fibres can be added to any part of the member. When it is found that excess load would be coming on that particular part.
- As the fibres are uniformly dispersed all over the member, the surface wear characteristics of concrete are considerably improved.
- The joint edges of a FRC member do not spall and chip away easily under heavy service.
- FRC products give more resistance to impact from heavy loads.
- FRC can be pumped and sprayed like ordinary concrete with less tracking which occurs in this section of sprayed ordinary concrete.
- Being light, it requires less less for carriage for lifting. Being thin, they give greater usable floor area.
- It has greater explosion resistance.
- It cracks less extensively in severe fires that ordinary concrete.
- A wide range of surface finishes are possible

1.14.2 Disadvantages of FRC.

- Steel fibres, being costlier at present FRC becomes very expensive compared to RCC in terms of materials only.
- The balling phenomenon as explained earlier is very undesirable.

1.14.3 General Problems and Suggestions

Although nearly every conceivable type of fibre has been tried out in cement or concrete matrix at one time or another, not all of them can be effectively and economically used with cement-based matrix. Obviously each fibre is characterized by its own particular properties and limitations, and the properties of concrete will be modified accordingly. Naturally, many applications can benefit from concrete having improved properties due to the fibre reinforcement (Parameswaran, 1988).

Fibrous concrete used for slab and pavement applications generally perform better than comparable plain concrete having identical thickness, foundation (sub grade) condition, and concrete flexural strength.

In the early applications, the thickness of the slabs was reduced, taking into account the improved flexural strength of FRC. The reduction in thickness resulted in problems for some applications. The primary problem was found to be the curling and breaking of corners. Other than these external loads, micro stresses resulting from drying shrinkage, stresses developed because of temperature gradient, are also to be considered...
at the joints were assumed to contribute to this problem. Slab movement owing to temperature change was also found to cause more problems in thinner sections. The solutions suggested to avoid this problem include the use of double polyethylene sheeting, other types of induced debonding with the existing layer, and the use of sliding dowels to join adjacent slabs.

Another general problem is the development of full-depth transverse cracks. The primary suspected cause for this is the use of higher cement and sand contents, thereby increasing the shrinkage. Successful techniques used to eliminate or minimize this problem are

- Reducing the cement content and using the highest possible coarse aggregate content,
- Replacing part of the cement by fly ash, and
- Using admixtures to reduce shrinkage. Reduction in the water-to-cement ratio is also very effective.

The workability of concrete with low water-cement ratio could be easily improved using high-range water reducing admixtures.

Other problems encountered in the use of FRC are

- Loose fibers on the surface
- Protruding fibers
- Load transfer to adjacent slabs
- Extension of existing cracks (or joints) in the case of overlays
- Rusting of exposed fibers

Loose and protruding fibers became a major problem when FRC was used in residential streets and at naval air stations. At naval air stations it was reported that fibers were sometimes sucked in by the aircraft, causing major problems. Besides that, the fibers were blown out onto people by aircraft exhaust. On residential streets, exposed and protruding fibres were causing problems for children and pedestrians for obvious reasons. Techniques have been developed to avoid this problem; for example, a "roller bug" was found to be very effective in pressing down the fibers at the surface. A thin protective coat applied right after the final grading was also found to be very effective.

In some instances, FRC slabs were cast to span existing joints and cracks, and it was assumed that the FRC would transfer the stresses across. In most cases, it was found that thin overlays cannot provide this function.
Proper load-transfer mechanisms should be provided using keyways and dowels. The omission of such provisions leads to warping, curling, and breaking at corners. In some cases long cracks have also developed.

The slabs that measure about 250 mm thick and that were designed conservatively in terms of load transfer and the spacing of construction joints are performing very well. Some of these slabs were subjected to heavy aircraft loads. In spite of the heavy loads, the pavements needed little or no maintenance (Parameswaran, 1988).

1.14.4 Applications, Case Studies and Field Performance of FRC

1.14.4.1 Steel Fibre Reinforced Concrete

Its applications can be broadly classified under two sub heads

I. In-Situ Structures

The superior structural properties of steel fibre reinforced concrete make it an ideal material for overlays and over slabling of roads, pavements of air fields, bridge decks, industrial and other floorings, particularly those subjected to wear and tear and chemical attack. Guniting has been successfully used with steel fibres and thus, has opened up an entirely new field of applications in tunneling, coastal construction, dams cooling towers, racket launching pads and liquid retaining structures as well as in remedial works (Parameswaran, 1988).

II. Pre-cast Products

Unlike conventional reinforced concrete, there is no problem of providing adequate cover to reinforcing bars, which reinforced concrete be cast in thin sections. Pre-cast products include pipes, hulls of ships, railway sleepers, beams stairways, wall panels, roof panels, roof and floor tile, floating dock modules, manhole covers and end blocks of pre-stressed concrete beams. Steel fibre reinforced concrete can be a boon for pre-cast manufacturing industries on account of its wide range of application (Parameswaran, 1988).

1.14.4.2 Applications and Benefits of Steel fibre reinforced concrete (Parameswaran, 1988)

a. Steel fibre reinforced concrete is being used

- To give improved mechanical performance over un reinforced concrete
- To replace or enhance other types of reinforced concrete
- To create new products, sometimes in competition with other (non-concrete) materials
b. Concrete Pipes

- Improvement in manufacturing process. Less surface crazing and fewer in-plant breaks
- Creator strength makes possible the use of thinner, lighter sections
- Easier handling on site through lighter weight.

c. Roads/Air field Runways

- Thinner overlays can be quickly laid by slip forming or paving train techniques-less disturbance to existing services and adjacent areas.
- Cost competitive with bituminous products in areas where curing period can be tolerated

d. Pre-cast Products

- Cost Savings of the order 50% were recorded in a fibre reinforced concrete product alternatively manufactured in cast iron (manhole cover)
- Thinner sections mean easier handling through reduction in weight
- Mechanized production through hydraulic pressing techniques
- Improvements in serviceability through physical properties

e. Flooring

i. Total Depth Slab

- Reduced slab thickness offers material savings

ii. Monolithic Wearing Surface

- More durable surface with greater impact and abrasion-resistance, because of smaller aggregate mix with higher cement content and steel fibres
- Less jointing. Fibre reinforced concrete slabs can be laid in larger bays thus reducing laying costs, and jointing materials
- Reinforcement extends to top edges of slab and controls surface spalling which results in less cracking and breaking up at the edge of joints
- Steeper temperature gradient reduces effect of temperature change
- need for granolithic surfacing often eliminated

f. Pipe coating

- Greater flexural strength and impact resistance give increased performance characteristics
Mechanized manufacturing process offers overall economy in comparison with traditional reinforcement techniques.

g. Refractory Concrete
Extended high temperature service life through crack control and spall resistance.
- Reduction on maintenance and replacement costs
- More predictable life particularly under thermal shock conditions

1.14.4.3 Case Studies and its Field Performance (Parameswaran, 1988)

Fiber-reinforced concrete has been in use for almost more than three decades. The field performance and case studies are representing the wide spectrum applications and detailed information for a particular type of project.

The following is the gist of reports available on the performance of FRC that was placed as early as 1971

1. Case studies of use of "WIRAND"® concrete
* Trade name for steel fibre reinforced concrete using National-Standard Duo form steel fibres manufactured in UK

a. A.P.C.M. Footbridge, Reema construction Ltd., Northfleet, UK

1500 mm long x 300 mm wide pre-cast deck units in wirand Concrete are used in this footbridge. Reema construction Ltd., The manufacturers, used a 10mm maximum aggregate size concrete mix incorporating 3% addition by weight of 0.30 x 25mm ‘Duo form’ fibre wire, to produce a light-weight unit, capable of handling all the proposed pedestrian loads imposed (Parameswaran, 1988).

b. Wexham Manhole Cover, Cement and Concrete Association, UK

Developed by C and CA to provide a cover and frame suitable for modern paved areas, the Wexham cover has been awarded Agreement Certificate No.120. The hydraulically pressed units are capable of carrying a load in excess of 5 tons and are expected to live a service life in excess of 20 years. N-S Duo form fibre wire 0.40 x 25mm is used in a mortar mix, specially developed to achieve the desired product performance (Parameswaran, 1988).

Note: SERC, Madras, has developed the technical design and production of similar manhole covers suitable for light, medium, and heavy-duty applications for commercial exploitation in eight in India.
c. Manhole Riser Units: British Airport Authority, Heathrow

In 1973, approximately 1000 manholes were brought up to the level of the resurfaced runway at London’s International airport using a modular system of riser units to a specification prepared by B. A. A. Engineers, and in conjunction with National-Standard Concrete Laboratory. A mix was established with an aggregate cement ratio of 4.39:1 with fines/coarse ratio of 63 - 47 and 3% by weight of 0.38 x 25mm Duo form fibre wire. The window frame units, 125mm wide x 50mm thick, were manufactured by Elthorne Construction Limited by means of a turbo mixer, incorporating the wire through an N-S wire-dispenser mounts directly over the pan. The elimination of conventional reinforcement simplified the pre-casting operation and enabled the production of a manhandle able unit (Parameswaran, 1988).

d. Ingot Support Blocks Jessop Saville Limited, Brightside Works, Sheffield

A Lumb re-heater soaking pit, operating at 1100°C-1150°C has eight pre-cast blocks each weighing 14 cwts which are used to support 6 tone ingots. Average life to date of the fibre reinforced blocks has been 10 weeks, compared with the previous life with a conventional cast able of 5-6 weeks. Estimates of cost savings of approx. £100.00 per installation are quoted (Parameswaran, 1988).

e. Wall and Roof Units

A number of wall and roof panel’s for gas compressor stations were constructed in 1973/4 by Aberdeen Concrete Company Limited and Girling’s, Ferro-concrete Company Limited. The pre-cast units were designed by Ove Arup and Partners and utilize a composite construction of rod reinforcement and ‘Wirand’ concrete located on site on to a structural steel frame. The crack control properties of the Wirand, which utilizes N-S Duo form fibre wire, together with the inherent strengths of the conventional reinforcement, has facilitated the production of a complex unit which has so far met the required high service demands (Parameswaran, 1988).

f. Pipe Coating, Bredero price, Immingham, UK

The “Hevicote plus” process of pipe coating, developed by Bredero price, is widely used to provide corrosion and high impact resistance and to overcome buoyancy in locations where pipelines have to cross rivers, swamps, or pass along the sea bed. At their Immingham, UK plant, Bredero price are using National-Standard fibre wire in impinging process to coat 400mm-915mm diameter steel pipes for various installations in the North Sea 0.35 x 20mm Duo form wire is incorporated by mechanical dispenser into a pug mill mixer blending special concrete mixes using conventional or iron ore aggregate, the latter to
provide a minimum of volume with a maximum of weight. The fibre wire imparts extra high impact resistance and important gains in flexural strength to the “Hevicote plus” Coating, both of critical importance when laying in the extremely severe North Sea conditions (Parameswaran, 1988).

g. Warehouse Floor, Joy Lock Limited, Cardiff

In this 3-storey warehouse block, constructed in 1972, 6.6m span suspended floors are subjected to deflection through the use of stacker trucks and abrasion from the movement of pallets. The architects, Holder and Mathias, through P. Trentham Limited, the main contractor, specified 13mm of Wirand topping to provide flexural strength and crack resistance. 0.38 x 25mm Duo form wire was incorporated at 3% by weight on to a 38mm pea gravel concrete base (Parameswaran, 1988).

h. Factory Car Park, Caledonian Mining Company Ltd, Telford

1800m² of Wirand concrete have been laid to an average depth of 70mm. 1/3 of this total was gunited by Caledonian Mining Company Ltd. between forms laid 5m apart and provided with a top tamped finish. The mortar mix was 1:3.5 with 3% addition by weight of 0.38 x 25mm Duo form wire. The remainder was truck mixed and laid by Derrick Moragn (Construction) Ltd., the mix being 1: 4.5 with 10 mm aggregate and similar quantity of Duoform wire (Parameswaran, 1988).

i. Bridges

The attributes of Wirand make the material particularly appropriate for use on bridge overlays. Because of improved performance characteristics in respect of crack control and resistance to thermal shock and abrasion, caused by the application of de-icing salts and the use of studded tyres in winter, much thinner overlays can be used with resultant weight and material savings.

There are also numerous applications in the USA where Wirand concrete has been used for bridge carriageways with considerable success (Parameswaran, 1988).

j. Airports

The first Wirand concrete overlay on an airport runway was installed in May 1974 at the John.F. Kennedy International Airport, New York. Here, three separate but continuous slab sections were laid requiring a total of 415m³ of Wirand concrete. Performance to data has been satisfactory and further installations at this airport and else where are currently envisaged.
In the United Kingdom, an experimental area of taxiway at the East Midlands Airport, castle Donnington, was laid in 1974, using 3% by weight of 0.50 x 38mm N-S Duo form fibre wire and incorporated in a 4.5:1 mix with 4% air content.

Also at Birmingham airport, a hard standing for refueling tankers has given good service since 1972. Here, the area of 250m² and 45mm thick. Wirand concrete has replaced asphalt in an area subject to possible damage by fuel spillage (Parameswaran, 1988).

k. Rock Stabilization, Union Pacific Railroad, Whitman Country, Washington, USA

Some 6250m² of sprayed fibrous concrete was applied by the contractor. The method was chosen in preference to conventional concrete over steel mesh, because of the difficult and costly operations of fixing the mesh to the rock surface within the confined space of the railway right-of-way, and the need to apply up to 225mm of concrete to fill behind and cover the reinforcement (Parameswaran, 1988).

l. Tunnels and Bridge Arch Repairs

British rail Spray concrete using N-S Duo form fibre wire has been used by various contractors for a number of repairs to installations in several regions of British Rail. A typical installation is the relining of a tunnel on the Leeds/Newcastle line. Approximately 1700m² were sprayed to a depth of 65 mm with wirand, and 8-10mm of plain screen coat. A hand-floated finish was tooled. 0.40 x 25mm Duo form fibre wire was used at an addition of 2% by weight of dry material. Using 0.25 x 12mm N-S fibres, mixed dry and applied at a rate of 4.6 m³/hr an average depth of 100mm effectively followed the rock profile. It was reported that rebound was kept below 13%. In addition, to these technical and contractual advantages, a cost saving of 16% was achieved. As a result, Wirand concrete is being specified for similar applications (Parameswaran, 1988).

m. Lockbourne Air Force Base, Ohio, USA, Airport runway 1970

Two FRC slabs were cast on a concrete base of 225 mm thickness. A 150 mm thick, 10.7 x 14 m slab was placed as a paving apron, and a 150 mm thick, 1.5 x 6.7 m slab was cast for use as a taxiway. Steel fibers that were 0.25 x 0.5 x 25 mm were used at 1060 N/m². The slabs were cast over a 0.2 mm thick polyethylene sheet placed on the base, thus producing an unbonded overlay.

The fiber-reinforced slabs were found to perform much better than the adjacent plain concrete slabs, which developed a longitudinal crack and a number of short traverse cracks (Balaguru and Surendra P. Shah, 1992).
n. Detroit, Michigan, USA, Airport runway 1971

A 200 mm thick, 6.1 x 9.1 m steel fiber-reinforced concrete slab was cast near the gate area used by Boeing 747 aircraft. The FRC slab was cast adjacent to a 300 mm thick plain concrete slab and tied to it by deformed rebars. The slabs were reported to be performing well, after a period of nine months (Balaguru and Surendra P.Shah, 1992).

o. Tampa, Florida, USA, Taxiway 1971

In this project two FRC overlays were constructed on a taxiway parallel to one of the primary runways. The overlays that were 100 and 150 mm were cast on a base pavement with a minimum of surface preparation. No attempts were made to either bond or debond the pavement. The concrete mixture had a fly ash content of 1330 N/m³ supplementing a cement content of 3060 N/m³. The fiber content was 1200 N/m³. The steel fibers had a cross section of 0.25 x 5.5 mm and were 19 mm long.

In this application, reflecting cracking was observed over the existing cracks. Cracks also occurred over the joints of the base pavement. The cracks over the base pavement cracks did not widen significantly, whereas the cracks over the joints opened considerably, causing fiber fracture or pull-out. The overlays were reported to be in service until 1984 (Balaguru and Surendra P.Shah, 1992).

p. US Army Waterway Experiment Station, Vicksburg, Mississippi, USA, 1972

The US Army Construction Engineering Research Laboratory (CERL) Champaign, Illinois performed controlled testing of FRC runway slabs at the US Army Waterway Experiment Station, Vicksburg, Mississippi, USA was constructed in ‘Wired’ concrete in Feb 1972 using a slip form pavers. The mix contained 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 were developed in the 150mm slabs, which were hairline and non-working (Balaguru and Surendra P.Shah, 1992).

q. Cedar Rapids, Iowa, USA, Airport 1972

The overlay used in this application had a thickness varying from 25 to 100 mm. The FRC was cast over previously existing cracks and joints. Two fiber lengths, 25 and 62 mm, were used at fiber contents of 2000 and 1500, 1180 and 890 N/m³ respectively. Since the overlay was relatively thin, reflective cracks developed over the existing cracks and joints (Balaguru and Surendra P.Shah, 1992).
r. New York, New York, USA, Airport 1974

The overlay constructed in this project was 138 mm thick. The overlay was completely debonded from the existing pavements using two 0.15 mm thick polyethylene sheets. The construction joints were either keyed or doweled. The fiber content used was 1000 N/m³. The fibers were 0.62 mm in diameter and 62 mm long. The overlays provided good service even though some cracking and, shattering occurred at the intersections (Balaguru and Surendra P.Shah, 1992).

s. Las Vegas, Nevada, USA, Airport 1976 and 1979

Two aprons, 150 and 175 mm thick, were built in 1976 and 1979 using steel fibers. Lanes were 7.5 m and had transverse joints at 15 m intervals. No dowels, keyways, or tie bars were placed across the joints. About 10 percent of the panels were reported to have developed corner breaks in the 175 mm thick apron. Some of the corner breaks in the 150 mm slab developed spalling. Some of the transverse joints also opened up considerably. For the 1976 project, straight steel fibers with dimensions of 0.25 x 0.55 x 25 mm were used at 950 N/m³. For the 1979 project-hooked end steel fibers were used at 500 N/m³. These fibers were 0.5 mm in diameter and 50 mm long (Balaguru and Surendra P.Shah, 1992).

t. Fallon Naval Air Station, Nevada, USA, 1980 and 1981

In these projects, FRC was placed over a bituminous bond breaker and was found to perform extremely well. A grid roller was used to push the fibers that were near the surface, thus creating a smooth (mortar) top surface (Balaguru and Surendra P.Shah, 1992).

u. Frankfurt Airport, Germany, 1983

In this application, deformed (HAREX) fibers were used at a dosage of 600 N/m³. The pavements were reported to be in good condition (Balaguru and Surendra P.Shah, 1992).

v. Taoyuan Air Base, Taiwan, 1984

In this project, a 150 mm thick bonded overlay was placed using 50 mm long crimped steel fiber. All the joints in the old pavement were matched in the overlay. Performance data are not available for this project.

w. Palam airport, New Delhi, INDIA

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

1.14.4.4 Highway and street pavements

a. Fayetteville, Arkansas, USA, 1971

A 62 mm thick overlay was placed in different locations using 19 mm long fibers. The fiber dosage was 600 N/m$^3$. Two of the five sections developed some failure zones after 10 years of service (Balaguru and Surendra P. Shah, 1992).

b. Detroit, Michigan, USA, 1971

In this project, a minimum 75 mm thick FRC overlay was cast over an existing reinforced concrete pavement. The slab was cast without any special surface preparations. Two fiber dosages of 710 and 1200 N/m$^3$ were tried. The resurfaced lanes were opened to traffic in two days. In addition, the curing temperatures were considerably lower than the optimum.

The lanes were subjected to heavy urban traffic. The higher fiber content FRC performed well, whereas the one with the lower fiber content developed serious problems. However, the problems were attributed to poor construction practices resulting in thicknesses as low as 31 mm instead of 75 mm (Balaguru and Surendra P. Shah, 1992).

c. Cedar Rapids, Iowa, USA, 1972

Two residential streets were overlaid using FRC over badly cracked and spalled 175 mm thick reinforced-concrete pavement. The surface preparation involved only broom cleaning and wetting. The thickness of the slab varied from 62 to 100 mm. One 25 mm long steel fibers were used at a dosage of 1040, 1200, or 1500 N/m$^3$. The slabs developed minor cracks within a few months. Other than these cracks, the slabs were reported to be providing good service. One street was repaved because of complaints about abrasions suffered by children (Balaguru and Surendra P. Shah, 1992).

d. Greene County, Iowa, USA, 1973

Thirty-three 120 x 6.0 m sections were resurfaced using 50 to 75 mm thick FRC sections. In addition, four and five sections were overlaid, respectively, with 75 to 100 mm and 100 to 125 mm thick sections. The variables evaluated were fiber sizes, cement and fiber content, and bonding between old and new surfaces. The fiber contents and lengths were 360, 600, and 950 N/m$^3$ and 25 and 62 mm. fully bonded, partially bonded, and unbonded conditions were studied.
The debonding techniques were found to decrease the formation of transverse cracks considerably. Unbonded sections developed fewer than 2 cracks, whereas partially or fully bonded sections developed from 8 to 15 cracks. The 50 mm thick section was found to develop more problems in terms of cracking and curling than the thicker sections. Sections with higher fiber content were also found to perform better than the slabs with lower fiber content (Balaguru and Surendra P.Shah, 1992).


Three test sections were constructed in 1973, 1976, and 1977 using steel fiber reinforced concrete. The first section, which was 75 to 175 mm thick, was constructed over a granular sub base. Two fiber contents of 400 and 790 N/m³ were compared with plain concrete. These fiber contents worked out to be 0.5% and 1.0% in volume. The fibers were 19 mm long and 0.25 mm in diameter.

Fiber-reinforced concrete containing 0.5% fiber was judged to have a life four times that of plain concrete. Concrete with 1% fiber was found to be four times better than the concrete with 0.5% fiber.

In the second project, 12 steel fiber-reinforced, 3 conventionally reinforced, and 3 unreinforced sections were cast. Three fiber types, namely, 25 mm long slit-sheet, 31 mm long melt extract, and 19 mm long wavy-cut fibers were used at fiber dosages of 440 and 740 N/m³. The comparative evaluation indicated that greater joint spacings are possible with fiber reinforced concrete. In addition, a higher flexural strength was found to enhance the performance of fiber-reinforced concrete.

The third project consisted of a 50 mm thick overlay on 275 mm thick lean concrete. Brass-coated wire and two types of slit sheets were used for reinforcement. The fiber content was 740 N/m³. Some sections were cast without causing a cold joint (Balaguru and Surendra P.Shah, 1992).

f. Motorway, M10, United Kingdom

Two overlays, 60 and 80 mm thick, were constructed over a 15 year old concrete slab using 1.3%, 2.2%, and 2.7% (by weight) steel fiber. The fibers were 0.5 mm in diameter and 38 mm long. Expansion joints were placed at 36 m intervals to match the existing joints. Transverse joints were spaced at 12 m. No tie or dowel bars were used for the joints.

Hairline and reflective cracks were developed on both fully and partially bonded overlays. Longitudinal cracks were found to be more pronounced in partially bonded sections. Thinner sections were found to provide better overall performance (Balaguru and Surendra P.Shah, 1992).
g. Deck slab construction: Heathrow Airport London

Decking slab of a 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 a live load of 2500N/m². The mix used was 1:1.5:3 with a w/c ratio of 0.65 and 3% fibres by weight were dispersed uniformly (Prakash K.B., 1998).

h. Wall and Roof Units: Fenrith, Australia

Isotropic strength properties obtained by the uniform dispersion of fibres throughout the volume of the concrete will permit thinner flat and curved plate structural elements, resulting in significant weight reduction for small structures. A residential building with a total floor area of 11.7 m² was erected within a day using about 39 m³ of fibrous concrete at Fenrith in Australia, small steel fibres of about 150mm lengths were used and the entire concrete was poured in one stretch, the process on cheap, less time consuming and does not require close site supervision. The system is recommended mainly for hospitals, schools, houses and other buildings in developing countries (Prakash K.B., 1998).

II. Industrial floors and pavements used by heavy trucks

Industrial floors can also be considered as pavements subjected to heavy traffic. In some instances, the presence of chemicals and higher amounts of abrasion can result in faster deterioration (Prakash K.B., 1998).

a. Niles, Michigan, USA, 1968, 1970

A 100 mm thick fiber reinforced concrete was placed on one lane of a roadway leading to an industrial plant and a 180 mm thick plain concrete was placed on the other. The plain concrete section developed transverse cracks, but the FRC was crack-free.

Thirteen test sections constructed in 1970 involved the use of various slab thicknesses and fiber contents. A minimum thickness of 100 mm and a (straight steel) fiber content of 1200 N/m³ were needed for crack-free surfaces. Thinner sections developed cracks to various extents. The inspection was done after a period of two years (Balaguru and Surendra P. Shah, 1992)

b. Kashima Works, Japan

A 150 mm thick fiber-reinforced section was used to carry forklifts with a gross weight of 47 tonnes (52 tons). 25 mm long fibers were used at a dosage of 1310 N/m³. An 200 mm thick conventional plain concrete section was used for comparative evaluation.
After one year, one large and several minor cracks developed in the plain concrete, and the FRC had only one hairline crack. It was concluded that FRC provides much longer pavement life and that larger spacings could be used for expansion joints when fibers are used in concrete (Balaguru and Surendra P. Shah, 1992).

c. Midlothian, Texas, USA

Concrete reinforced with steel bars and glass fiber was evaluated for use in the road leading to a quarry of a cement plant. The plain concrete slab was 200 mm thick. The reinforcement consisted of 9 mm diameter bars spaced at 600 mm. The glass fiber-reinforced sections were 100 and 150 mm thick. The volume fraction of 25 mm long fibers ranged from 0.97% to 1.34%. It was concluded that glass fibers do not provide effective reinforcement (Balaguru and Surendra P. Shah, 1992).

d. Burnassum Project, Holland

A large area of 250,000 m² was paved with 175 mm thick steel fiber-reinforced concrete. A relatively low fiber content of 300 N/m³ was used because the fibers were bent at the ends to provide better efficiency. The slab was found to perform well and hence replaced 198 mm thick reinforced-concrete sections (Balaguru and Surendra P. Shah, 1992).

e. Kidston Gold Mine Shop, Australia

A 120 mm thick steel fiber-reinforced section was successfully used for a gold mine shop and maintenance building floor that carried heavy equipment. The floor replaced a wire-reinforced 150 mm thick concrete floor (Balaguru and Surendra P. Shah, 1992).

III. Bridge Deck Overlays

Fiber-reinforced concrete has also been used extensively for bridge deck overlays. Some of these applications are briefly described in the following sections.

a. Winona, Minnesota, USA, 1971

One of the first uses of FRC for a bridge deck overlay was on a precast bridge in Winona. The 61 to 100 mm overlay was placed on a severely deteriorated precast deck after removing the surface scale to a depth of 38 mm. The fiber content for the 13 mm long, 0.25 mm diameter fibers was 1200 N/m³. The overlay was reported to be in good condition in spite of deicing salts and studded tires (Balaguru and Surendra P. Shah, 1992).
b. New Cumberland, Pennsylvania, USA, 1971

FRC was used to replace asphalt overlays on a steel truss bridge that was 47 m long and 12 m wide. The overlay, which was 50 to 125 mm thick, consisted of concrete containing 1200 N/m$^3$ straight steel fibers. The fibers were 25 mm long and 0.25 mm in diameter. After one year of service, a few minor cracks were observed at locations where the overlay thickness varied abruptly. The overlay was still in service in 1984 in spite of the heavy traffic involving about 13,700 vehicles per day (Balaguru and Surendra P. Shah, 1992).

c. Cedar Rapids, Iowa, USA, 1971

In this project, FRC was cast on wood plank decking. The overlay was separated from the deck using two polyethylene sheets. The slab, which was 46 m long and 3.3 m wide, had no joints. The 62 mm long, 0.62 mm diameter fibers were used at a dosage of 900 N/m$^3$. The overlay was reported to be essentially crack-free after three years (Balaguru and Surendra P. Shah, 1992).

d. New York City, New York, USA, 1973

A relatively thick 250 to 300 mm FRC bonded overlay was placed over the existing deck. The deck was reinforced with a 100 x 300 mm wire mesh at the mid height of slab and with 900 to 1200 N/m$^3$, 62 mm long fibers (Balaguru and Surendra P. Shah, 1992).

e. Pittsburgh, Pennsylvania, USA, 1973

In this project the FRC overlay was bonded to the old deck using an epoxy bonding agent. The 75 mm thick overlay contained 1200 N/m$^3$, 25 mm long fibers. Some shrinkage cracks appeared after curing. These cracks did not open further. In 1984 the overlay was reported to be in service in satisfactory condition even though some crazing and spalling existed in a small area (Balaguru and Surendra P. Shah, 1992).

f. Jefferson, Iowa, USA, 1973

The 75 mm thick overlay containing 950 N/m$^3$, 25 mm long fibers was bonded to the old deck using cement paste. An inspection in 1983 revealed that the overlay was completely debonded but was still in good service condition (Balaguru and Surendra P. Shah, 1992).

g. Rome, Georgia, USA, 1974

A 50 mm thick FRC overlay was used in order to stiffen a 7.1 x 180 m long bridge deck. The fiber content was 1030 N/m$^3$. The overlay did not stiffen the bridge but provided good service in spite of oscillatory deflections and vibrations (Balaguru and Surendra P. Shah, 1992).
5. Concrete Pipes

SFRC can be considered of great promise in pipes manufacture as delay can be avoided. The pipes can also take occasional overloads without failure. Since the entire volume is fibre reinforced including the pipe edges, the chances of accidental damage during loading, unloading and handling operations are considerably reduced. This is particularly important at the ends of the pipes, since the cracking and damage in these areas can cause delay in the laying of joining process.

IV. Water retaining Structures

Water retaining structures like surface and overhead circular as well as rectangular tanks, can be prepared with fibrous concrete in conjunction with conventional reinforcement. The structures will not only be thinner in section but also are more waterproof.

V. Marine Structures

Waterfront 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. Investigations have shown insignificant corrosion by salt water on Portland cement mortar reinforced with 2% of steel fibres by volume and no change in flexural strength was observed after 90 days of immersion in or out of a saturated salt water solution. The energy absorption capacity of fibrous concrete also imparts high impact strength to it, which is a significant requirement in marine structures.

VI. Breakwater Armour Units

SFRC can be used as an ideal material for breakwater armor units as it possess good physical properties such as density, strength, toughness, resistance to impact, abrasion and resistance to deterioration in marine environment. Other potential applications are under water storage structures, waterfront warehouses floors and decking.

VII. Blast Resistant Structures

The design of blast resistant structures made from concrete requires that they should be capable of resisting the blast wave. Blast waves causes complex stressing of the structure in compression tension and shear. FRC in conjunction with conventional reinforcement could provide the necessary strength. Fibre reinforcement can advantageously be used in foundations for machinery where shock vibratory loads are encountered.
VIII. Refractory Applications

Wherever a thermal gradient exists with temperature up to $1595^\circ C$, a stainless steel FRC refractory may be used. FRC can also successfully be used for linings of cement kilns and open earth furnace doors.

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

IX. Shear Reinforcement

Steel fibres can be used partly in place of stirrups for shear reinforcement in beams. The other application can be in multi-storey frames. The ductility of SFRC would permit the development of plastic hinges from overload conditions.

X. Partially Prestressed Composite Concrete beams

It is found that steel fibres improve the flexural strength of partially pre-stressed concrete members and there is also a reduction of the mid point deflection and maximum crack width of the member, generally, at loads above working loads. Fibre reinforcement can be added to selected zones of pre-stressed concrete members.

XI. Patching

Patching is similar to overlay except that these repairs are applied in small areas and must be compatible with the existing concrete to provide long service life. Fiber-reinforced concrete patching has been tried for cast, in-situ repair and in the form of precast slabs. In most cases, the composite provided good service.

Eleven small patches were installed along a key joint on a runway used by Boeing 747s at Chicago's O'Hare International Airport. The patch sizes varied from $0.6 \times 0.9$ to $0.3 \times 3.3$ m. They were 75 to 150 mm deep. The patches were sawed and cleaned with forced air. The repair, done using 1 in. long and 0.40 mm diameter fibers, was performing well even though similar patches filled with epoxy proved unsatisfactory.

Precast steel fiber-reinforced slabs were used in a number of instances for quick repairs in New York City. The slabs were $0.9$ m square and $50$ mm thick. The mortar matrix was reinforced with 1450 N/m$^2$, 25 mm long, 0.25 mm diameter straight steel fibers. In some cases, the slabs were set on a base made of quickset materials. Most of the time, the slabs were open to traffic in less than five hours (Balaguru and Surendra P. Shah, 1992)
XII. The Use of FRC in Precast Form

Here again, FRCs are used to take advantage of their improved impact resistance. In some cases, fibers are also used as a replacement for continuous (bar) reinforcement (Balaguru and Surendra P. Shah, 1992)

a. Tetrapods (Dolosse)

Steel fibers were used in lieu of conventional reinforcing bars to improve the wave-impact resistance of the tetra pods. More than 1500 units weighing 42 tons (38 tonnes) were manufactured using 22,900 m$^3$ of FRC between 1982 and 1985.

b. Mine Crib Blocks

This is a unique application in which the ductility of FRC in compression is utilized to avoid catastrophic failure. The blocks made with fibers were found to provide much better ductility when used for roof support structures in coal mines.

c. Vaults and Safes

Fibers are being used extensively for precast panels used for vaults and safes. By using fibers, the thickness can be reduced by as much as two-thirds. Fiber volume fractions for this application range from 1% to 3%.

d. Tilt-Up Panels

Panels up to 7.2 m high have been cast without using conventional reinforcement; FRC was found to provide considerable savings in labor cost.

e. Precast Garages

Steel fiber-reinforced concrete has also been used to precast complete automobile garages in Europe.

f. Manhole Covers

Both steel and synthetic fiber-reinforced concrete have been successfully used for manhole covers

XIII. Applications of FRC in Dams

a. Libby Dam (USA).

Libby Dam is a concrete gravity structure 127 x 103 mm high with three rectangular low-level outlets and two spillway bays. The outlets were constructed with conventional concrete walls and inverts. The concrete mix achieved an ultimate compressive strength of 40 N/mm$^2$ at 90 days and about 70 N/mm$^2$ at
the time the cavitation damage occurred. The concrete surface gradually showed roughening similar to a sandblasted texture in some areas until September 1983 when sudden severe cavitation damage occurred after about 12,000 hours of total use at intake heads varying from $8.5 \times 10^3$ mm to $66 \times 10^3$ mm.

The damage was extensive. Large amounts of reinforcing steel were exposed or lost, with up to 460 mm deep holes in concrete. The damage covered about $46 \times 10^6$ mm$^2$ ($46$ m$^2$) of wall and invert area. The damage was repaired with steel fibre reinforced concrete, which is reported to have performed well in the years with no further damage.

The stilling basin also developed severe erosion, which exposed and removed large volumes of reinforcement. Approximately $1,500$ m$^3$ of high strength concrete was lost. In 1977, the basin was repaired with conventional concrete fill topped with $380$ mm of steel fibre reinforced concrete. The joint areas were polymer impregnated. Some minor erosion is reported to have occurred at the repaired areas since being put into service but no additional repairs are called for (Sudindra et al., 1987).

b. Dworshak Dam (USA)

Debris (primarily from construction) was trapped in the stilling basin and caused severe erosion damage. After a few years of intermittent use of stilling basin, approximately $1,200$ m$^3$ of high-strength concrete and reinforcement were eroded from the basin. When dewatered for repairs, only about $20$ m$^3$ of loose debris was found in the basin. The debris included gravel, sand, rocks, pipe, reinforcing steel, angle iron and steel plates. Repair measures are:

- Shotcreting over minor damage in the walls (maximum depth about 150 mm)
- Epoxy mortar over about $465\times10^6$ mm$^3$ of floor and lower spillway area (12 mm to 75 mm deep).
- Filling deep erosion (maximum depth about $2.5\times10^3$ mm) with structural grade un reinforced fill concrete.
- Placing an anchored topping slab of fibrous concrete (380 mm thick) over all areas of the floor except where epoxy had been used.
- Polymer impregnating the right side of the basin floor.

Overall evaluation at this time can be summarized thus:

- The epoxy repairs have failed.
- The stilling basin draws material backs into it and traps it during operation. The fibrous concrete has performed well.
There has not been sufficient operation to evaluate the polymer impregnation performance.

The outlets at Dworshak got damaged by cavitation erosion after several years of intermittent use. Deeply eroded areas were replaced with fibrous concrete and where the damage had not progressed deeper than about 25 mm, repairs were done by polymer impregnation of dry-pack patching. Areas of the walls in one outlet where damage had not yet progressed past the surface were given added resistance to future cavitation by polymer impregnating the outer 12 mm to 20 mm of concrete. The outlets have been operational with minor surface deterioration (Sudindra et al., 1987).

e. Kinzua Dam Stilling Basin (USA)

An earth-fill and concrete gravity structure located in the Allegheny river in north-western Pennsylvania at Pittsburgh and was completed in 1967. In September 1969, the stilling basin slab which was originally 1500 mm thick and contained 150 mm nominal MSA was reported to be damaged by abrasion erosion manifested by severe loss of concrete in patterns indicating that eddy currents were being developed in the stilling basin. The eddy currents were attributed to non-symmetrical discharges from the dam, while the debris was though to be riprap and riverbed gravel from down-stream of the structure. The damage reached a depth of 1100 mm in some areas before repairs were made in 1973 and 1974 (ones half of the basin was repaired each year).

Repairs were carried out using FRC. Approximately 1,070 m$^3$ of FRC was used after filling the deeper cavities with conventional concrete of grade M20. The baffles were also reconditioned with FRC.

The performance of FRC used in conjunction with conventional concrete did not prove to be satisfactory as the damage re-appeared in the stilling basin. The design was established without the advice of personnel experienced in the use of FRC. Evaluation of the in-place material showed it to be of inferior quality and not comparable to the design mix. This is a practical illustration that FRC, as with conventional concrete, must be properly designed and controlled to attain satisfactory results.

Laboratory studies were performed at Waterways Experiment Station (WES), Vicksburg to evaluate several concrete mixtures considered for repairs of the stilling basin. These investigations showed that high-strength concrete, made with silica fume and local aggregates, would provide the greatest abrasion-erosion resistance for the structure at a cost effective price. Based on these results, silica fume concrete was used for the repairs of the structure. Inspection of the Kinzua dam stilling basin has indicated that the concrete is performing as intended (Sudindra et al., 1987).
d. Tarbela Dam (Pakistan)

Tarbela dam had stilling basin failures when full reservoir flows were passed into it under emergency conditions soon after project completion. The worst damage was about $24 \times 10^3$ mm deep. The damage was initially repaired with conventional concrete but failure occurred again after less than one day of operation. Subsequently, several modifications were made in the design including the installation of a top layer of FRC over the entire floor. The repairs comprised of post-tensioned floor slabs, air slots and 500 mm of FRC. The above repair has performed satisfactorily since then (Sudindra et al., 1987).

e. Alder and Mayfield Dams (USA)

Alder and Mayfield dams in Washington (USA) are high head structures utilizing plunge pools for energy dissipation. The concrete in the basins of both pools experienced major damage due to impact and erosion from bed loads present when they were in use. Each basin was repaired with a topping slab of FRC, some of the concrete being placed by pump and some by shotcrete. Shortly after completion of repairs, the basins at both the projects were subjected to 50-year design flood and additional heavy bed loads consisting of approximately 1500 m$^3$ of gravels and rock as large as 3/4 m$^3$ washed from rock slopes above the pools. When the plunge pools were de-watered for inspection in April 1969, it was found that Alder Dam had suffered no damage to the cast-in-place floor, but at Mayfield, the 375 mm slabs had been pulled loose. Although the FRC was in good condition, the slabs were apparently not bonded or sufficiently anchored to the base concrete. This condition allowed uplift pressure to develop under the overlay and caused failure of the anchorage system. The slabs had little visible wear but anchor bars had necked down and failed in tension. In some instances, slab-reinforcing bars had got pulled out leaving 50 mm diameter smooth holes in the slabs but the FRC was still intact.

Thus, FRC had resisted the forces of cavitation, impact and erosion well but insufficient bonding or mechanical anchorage had resulted in failure by uplift (Sudindra et al., 1987).

f. Lucky Peak Dam (USA)

The outlet flow discharges through a concrete manifold structure consisting of 6 gates to separate flip-lips into a natural punger pool. On account of cavitation, the concrete floor and side piers (which separate each of the six flip-lips) eroded badly soon after the start of operation in 1955. 20 mm thick steel plates anchored to the piers and floor areas just down-stream of the manifold gates also got eroded badly.
In 1968, the damaged plates were repaired by filling the eroded areas with stainless steel welding rod and grouting voids under the plates. Deteriorated concrete on the flip-lips was removed and additional steel plates were added in that area. Severe damage occurred and repairs were performed again. Deep areas of cavitation damage in the floor and piers were filled with concrete and some new 12.5mm thick steel plates were installed which were stiffened with steel beams welded to them at about 1500 mm centers in each direction. Peep anchor bars welded to the plates held them in place. The voids and bearing area under the plates were grouted. During the next two years, these repairs also failed. In 1974, the remaining plate material was removed. Cavities found going into the floor and through the piers from one flip-lip channel to the adjacent channel were crudely filled with fibre reinforced concrete (FRC) in a "field expedient" manner. Much of the FRC was placed in standing water with little content, and while adjacent bays were discharging. Subsequent inspections show the FRC to be performing well (Sudindra et al., 1987).

g. Oxbow Dam (USA)

The spillway at Oxbow dam in Idaho was undercut and partially destroyed by erosion resulting from wave action and unpredicted severe eddy currents. In some areas, the erosion extended through the original concrete and approximately 10,000mm into the rock foundation. Repairs were completed in the year 1980 using FRC over fill concrete at the failed spillway surface and supporting rock mass. Since the application of FRC to repair the damage caused, so far no failure has been reported (Sudindra et al., 1987).

h. Bonneville Dam, Oregon (USA)

At Bonneville Dam in Oregon (USA), where a second Powerhouse was being adopted, it was considered expedient to provide remedial measures from possible erosion action of trapped debris and rock in the apron downstream of the powerhouse. FRC overlay was applied to the apron for the purpose, which seems to have performed well (Sudindra et al., 1987).

i. Little Goose Dam (USA)

FRC was used in lieu of conventional concrete to encase and protect crane rail anchor bolts attached to prestressed beams spanning the spillway bays. The FRC has performed satisfactorily and exhibited no cracking (Sudindra et al., 1987).

j. Guri Dam (Venezuela)

Concrete in the flip bucket eroded. Repairs were made in 1979 using better quality concrete and epoxy mortar, but again failed one year later. Reconstruction of the entire area because of the raising of the
dam and incorporation of air slots prevented further cavitations erosion. The application of FRC overlays was successful to combat the cavitation erosion problem (Sudindra et al., 1987).

k. Lower Monumental Dam (USA)

In 1970, minor spalling, possibly due to cavitation was noted on the upper portion of the right wall of the right navigation lock discharge conduit immediately downstream from the filling valve liner plate. In 1975, erosion damage was noted in the left discharge culvert. The damage went from wall to wall for a length of 3000mm and 600 mm below the invert. Reinforcing steel was exposed.

Fibrous concrete held in place with hooked reinforcing bars was used for the major repairs. Epoxy mortar was used only in minor areas to be patched. The fibrous concrete has performed satisfactorily whereas the epoxy mortar repairs have performed poorly.

To eliminate nitrogen super saturation of spilled water and subsequent fish mortality, horizontal deflectors have been placed on the spillway of Lower Monumental Dam.

The deflectors which consist of conventional concrete with a top of FRC have performed satisfactorily to date (Sudindra et al., 1987).

l. Karun Dam (Iran)

The Karun Dam Project includes a chute spillway containing three 18 x 10^3 wide bays. At the normal reservoir elevation of 530 x 10^3 mm, the gross head at the flip bucket lip is about 130 x 10^3 mm. Seasonal flood releases in December, 1977 resulted in severe cavitation damage to 700 x 10^6 mm^2 of the concrete surfaces in the lower chute panels and bucket of all three bays. The cavitation damage as initiated by surface condition not conforming to specification tolerances. Concrete repairs were essentially of two types, large area and small area. The large areas were backfilled using some concrete mix as used in the original construction. Small areas included she-bolt holes, regions of shallow cavitation damage, abrasion gouges, spalled and improperly constructed joints and other abrupt offsets. These areas were saw cut and chipped to a depth of about 80 mm. An epoxy-bonding agent was applied to the exposed surfaces and the areas backfilled with a low slump (20-30 mm) high-strength fibre concrete, which was moist, cured. The fibre Concrete was similar to the FRC mix used in the repair of concrete surface at Tarbela Dam (Pakistan) anry included 47 kg/m^3 of 30 mm long hooked-end steel fibres, 10 mm nominal maximum aggregate size and a high-range water-reducing agent.
Reports received till early 1980 indicated that although some concrete failures occurred, a majority of failures were associated with epoxy mortar repairs, (e.g. thin overlays, she-bolt holes etc.). Epoxy mortar joint failures, apparently caused by thermal effects, were reported even before heavy wet season flows began. No cavitation damage was reported in the areas free of abrupt offsets and steep bevels. Thus, the failure of the repairs was attributed to the thin epoxy mortar and not FRC overlay (Sudindra et al., 1987).
Table 1.12: Table shows FRC Industrial Applications throughout the world (Source: Victor.C.U, 2002)

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<th>Application Area</th>
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<th>Property/Advantage</th>
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*Experimental.*