CHAPTER 1

INTRODUCTION

Eventhough concrete is a widely accepted building material it is not without any drawbacks. The low tensile strength and brittle nature of concrete necessitates it to be reinforced with steel rods. Placing the steel reinforcement in the tension zone of concrete will enhance the tensile strength of concrete. Later on in 1960, it was found that addition of fibers in concrete can dramatically increase the various strength properties of concrete along with the ductility of concrete. For this purpose various fibers can be used in the concrete. The various fibers that are commonly used in concrete are steel, GI, polypropylene, glass, carbon, asbestos, jute plastic etc. The addition of fibers to concrete delays the failure mechanism and induces ductility to concrete. Such product where in the fibers are introduced in concrete is called “Fiber Reinforced Concrete” (FRC).

Researchers have shown that as the percentage of fibers increase in fiber reinforced concrete, the strength properties also increase. But, the higher percentage addition of fibers, say above 4% possess many difficulties. For example, the balling effect of fibers will be conspicuous when the percentage of fibers is high. For the fiber reinforced concrete to be effective, the fibers should be dispersed uniformly in concrete. As a remedial measure to this, the researchers have found a product called “Slurry Infiltrated Fibrous Concrete” (SIFCON). In this product the fibers can be used as high as 10 – 12% by volume fraction. The
fibers are placed in the formwork and then the cement slurry is poured which infiltrates through the fibers and pack the entire formwork. Slight vibration to the formwork may be needed during the process. SIFCON shows a very high strength values as compared to fiber reinforced concrete. The ductility of SIFCON is also high as compared to FRC. SIFCON has found many applications in the field of civil engineering.

Another important invention by the concrete researchers is ferrocement, wherein the cement mortar is dashed against a cage of welded mesh and chicken mesh. Ferrocement is characterized by its thickness and crack free surface area. This has made ferrocement an ideal material for water tanks. The ferrocement has also found many applications in civil engineering field. The researchers have shown that as the percentage of steel in ferrocement increases, the strength properties also increase. But, the steel area cannot be increased beyond certain limit because of the difficulties in dashing the cement mortar to the ferrocement cage. This has lead to the concept of fibrous ferrocement where in fibrous concrete is dashed against the ferrocement cage.

4.1 FERROCEMENT

The use of fibres to reinforce brittle materials is well known, asbestos cement being a typical example in the civil engineering applications. When cement mortar is reinforced with steel fibres in the form of wire mesh, the resulting composite material is known as
ferrocement. While the mortar provides the mass, the steel fibre imparts tensile strength and deformability to the material (Abdullah and et al, 2002).

Ferrocement as a construction material has evolved from an appropriate technology applied for low cost to high performance and high durability construction material. The researchers have continuously improved the ferrocement properties and performance and also evolved its different applications (LiliaRobles-Austriaco, 2005).

The earliest known application of ferrocement was in 1848, when the French engineer Lambot constructed several boats and other items from a material which he called ‘ferciment’. His work followed by several others who built ferrocement boats of capacity up to 60 tonne, for carrying materials. But the use of ferrocement for boat building was given serious attention only during and immediately after the Second World War, due to severe shortage of traditional materials. It was the Italian engineer-architect Nervi who resurrected the use of ferrocement for the large-scale construction of boats in the 1940’s.

Nervi carried out extensive tests on ferrocement to establish its mechanical characteristics. He demonstrated that by closely spaced reinforcement in the form of small diameter wire mesh, the tensile strength and resistance to impact could be considerably enhanced. Nervi used ferrocement not only for construction of boats, but also for large-span roofs and architectural construction. Among his structures the noteworthy are the roofs for sports stadia, opera houses,
restaurants and warehouses. Nervi’s firm built the ocean-going 165 tonne motor sailor ‘Irene’ costing 40 percent less than a comparable wooden hull.

In the post war-period, the People’s Republic of China has been building several ferrocement boats and sampans. A commune in the Shanghai Province has been reported to have built more than 2000 ferrocement boats. These are powered by men, and also have a capacity of 6 to 10 tons of cargo. The above commune has also built a 60 ton capacity diesel-powered ferrocement boat.

Ferrocement has been used extensively in large-span construction in the Soviet Union and Poland. More than 10 million square meters of area have been roofed over in the U.S.S.R. alone. The roofs are generally in the form of cylindrical shells strengthened with longitudinal ribs and rings.

Industrialized system of production has been developed for the large-scale manufacture of prefabricated roofing elements, using sophisticated machinery. Besides roofing elements, ferrocement have been extensively used for water carrying troughs, wine storage tanks etc. in the Soviet Union.

Ferrocement gained wide acceptance in the 1960’s, when several boats were built in Australia, New Zealand and the United Kingdom. The 16m Yacht, ‘Awahnee’ built in New Zealand successfully circum-navigated the world in 1965. Ferrocement trawler with a length of 26 m and a displacement of 250 tons built in Hongkong in 1971 is claimed to be the world’s largest ferrocement boat. The interest of the
boat builders in ferrocement resulted in the formation of the New Zealand Ferro Cement Marine Association in 1968.

The Fisheries Department of the Food and Agricultural Organization of the United Nations showed interest in the use of ferrocement boats. It has been providing technical guidance for the design and construction of ferrocement boats in many developing countries. A seminar organized in 1972 in New Zealand resulted in the collection of up-to-date data on the design, construction methods, economics, service experience etc. relating to ferrocement fishing vessels.

A Panel set up by the National Academy of Sciences (U.S.A) presented a ‘State of the art’; report on the application of ferrocement in developing countries. The report mentioned in particular the application of ferrocement for the boat building in the People’s Republic of China, water tanks in New Zealand, U.S.S.R. and Thailand, grain shortage structures in Thailand and Ethiopia, and low-cost roofing in the U.S.S.R.

With the increasing application of ferrocement, the need for research into the properties of the materials and behaviour of structural elements had been felt. Extensive experimental studies have been carried out at institutions such as the University of Illinois (Chicago), Asian Institute of Technology (Bangkok), Structural Engineering Research Centre (Roorkee), Indian Institute of Science (Bangalore) etc. The design of ferrocement structural members is being put on a sound footing, form the data obtained from the results of these studies.
The recent trend in ferrocement has been rightly summarized by Prof. A. E Naaman “The history of ferrocement as a modern construction material is longer than that of reinforced concrete, prestressed concrete and steel. Its path for the future as a laminated cementitious composite combining advanced cement based matrices, high performance reinforcing meshes and fibres and new construction techniques, promises to be as bright.”

Ferrocement is environmentally sound technology since it is found to be ideal for rehabilitation and re-strengthening of existing structures. The ferrocement construction reduces labour cost, improves quality of the material reduces or eliminates repair and maintenance by reducing the use of raw materials (Robles-Austriaco L, 1999).

Thin reinforced concrete products or cement based composites designed for structural applications are possible either as ferrocement or as fibre reinforced mortar. The difference between them is that ferrocement uses continuous reinforcement or meshes while fibre reinforced mortar uses discontinuous reinforcement in the form of fibres.

Ferrocement and fibre reinforced mortar are the extreme boundaries of reinforced concrete products and both have historical development. Looking ahead researchers are trying to explore the area between two boundaries in the form of laminated and hybrid cementitious composites (Naaman A.E, 2005).
4.1.1 Constituent Materials

The constituent materials of ferrocement are wire mesh reinforcement, skeletal reinforcement, cement mortar and admixtures. For special applications, especially against corrosive environment it is necessary to protect the surface, using suitable coatings. While the major part of the volume is taken up by the mortar, reinforcement accounts for the major part of cost of materials.

Wire mesh reinforcement

The wire mesh reinforcement imparts to the member tensile strength and resistance to cracking. In addition, for members cast without mould, the wire mesh helps to hold the mortar together in the wet state. While it is possible to use any fibrous element to reinforce mortar, it is economically and structurally efficient to use steel wires as reinforcement, because of high modulus of elasticity compared to organic and other metal fibers. The wire mesh reinforcement is especially effective in the tension zones of the member and also close to the surface. In the later case the reinforcement is very effective in controlling the shrinkage cracks.

The wire mesh generally consists of thin wires either woven or welded into a square or rectangular grid. The main consideration in the choice of the wire mesh is the requirement to bend it into the required shape. The tensile strength of the wire mesh by itself is not the major parameter except in heavily stressed structural elements and where it is not practicable to provide additional reinforcing bars. The toughness and resistance to fracture under fatigue is especially
dependant on the amount and concentration of reinforcement. The principal types of wire mesh reinforcement used in construction are as follows:

- Hexagonal mesh
- Woven mesh
- Welded mesh
- Expanded metal
- Watson mesh

Skeletal reinforcement

Form and rigidity are imparted to ferrocement elements by the skeletal reinforcement. The skeletal reinforcement can be in the form of rods laid in the perpendicular directions or alternatively, a welded wire fabric can be used. Bars are generally suitable for curved surfaces, as the latter produces zones of weakness at junctions, when bent into a curved surface. It is generally desirable to provide skeletal reinforcement to take care of tensile forces, and provide wire mesh reinforcement to ensure crack control. In such cases the skeletal reinforcement will be sandwiched between two layers of wire mesh reinforcement.

As ferrocement elements are generally cast in thin sections of about 15 to 30mm. thick, the size of bars should not be more than say, 6 to 10mm. Welded wire fabric is suitable for thinner sections, as the wire diameter could be as low as 2.4mm.

Cement mortar
Cement mortar constitutes nearly 90 to 95 percent of the volume of ferrocement. It consists of Portland cement, sand and water, with or without admixtures. The proportion of the constituents are so adjusted that the mortar gives the required strength, workability, water-tightness and finish. The properties and specifications for the individual constituents of cement mortar are cement, aggregate and water.

Cement can be described in general as a material with adhesive and cohesive properties which make it capable binding mineral fragments into a compact mass. The most common cementitious binding material for structural applications requiring medium to high strength is Portland cement. Portland cement mixed with water reacts to form cementitious gel which in the green stage binds the sand particles to form a compact mass.

Aggregate, more specifically fine aggregate, is the inert material which occupies 60 to 75 percent of the volume of mortar. The aggregates required for the production of high quality mortar for ferrocement must, therefore, be hard, strong, non-porous and chemically inert. The I.S specifications give four different grading for fine aggregate suitable for concrete. Of these, grading II and III, with the particles greater than 2.36mm and smaller than 150 microns removed are suitable for ferrocement.

The water used for making mortar should be from impurities such as clay, loam, acids, salts, vegetable matter etc. Sea water should never be used for mixing mortar, as it contains salts which may
corrode the reinforcement. Impure water may also leave stains on the surface. Water piped from public supplies is generally satisfactory.

4.1.2 Design Approaches

Ferrocement is used most effectively in thin walled shell construction. The two way plate elements, cylindrical shells elements, segment of spherical shells, hyperbolic paraboloids, folded plate elements etc. Rigorous analysis of such structural forms is complicated, and reference to specialist literature must be made. However simplified formulae based on membrane theory are available for certain classes of shells under uniformly distributed loading. Design coefficients are available for cylindrical shells subjected to uniformly distributed loading. The determination of the internal forces can also be done by tests on scaled models. Where the structure consists of standardized ‘repeat’ elements, prototype testing may be desirable.

The process of design involves obtaining the geometrical dimensions (usually thickness) area of reinforcement etc for all the critical sections. The sections are usually designed for the most critical effects (e.g. ultimate moments) and checked for the other effects (e.g. deflection etc). In other case, analysis cross sections is required under one or the combinations of the internal forces such as bending moment, shear force, axial tension, axial compression, torsion etc.

There are broadly two approaches to the analysis and design of cross sections. In the first, the section is assumed to be made of a homogeneous material and subjected to stresses in the tension zone
not exceeding the cracking stress of the material. The analysis of section becomes very simple, based on the principles of mechanics applicable to homogeneous materials having elastic behavior. This approach is generally justified for elements subjugated to low levels of stress (e.g. small capacity bins, water tanks etc) and with the wire mesh reinforcement distributed throughout the section.

The second approach is to design the section with theories applicable to conventional reinforced concrete. The contribution of the mortar in the tension zone is ignored, assuming that the entire tensile force is resisted by the reinforcement alone. This approach gives better results for elements in which the reinforcement is concentrated towards the edges, and subjected to high levels of stresses. A typical example is the determination of the ultimate moment of the section of a plate, in which reinforcement is located close to the edges.

4.1.3 Construction Techniques

Ferrocement construction, unlike many other construction procedures do not require highly skilled labor or heavy construction equipment but it should be always remembered that proper attention on quality control and tight supervision during the actual ferrocement construction are essential otherwise desired results may not be obtained. Builders who take proper care and have patience during construction always get an end product having wonderful strength, durability and trouble free service.

The advanced / rich countries of the world have been working and using ferrocement more for academic or pleasure games. East
European countries like Poland, U.S.S.R etc use it for saving the materials, man power and money. For developing countries, ferrocement has proved to be an appropriate and problem solving construction technology which utilizes unskilled labour, traditional skills and require small quantity of building materials, most of these are locally available in these countries. The complete mechanization is suitable for developed countries and manual and semi-mechanized processes are suitable for developing countries. Local conditions like availability of equipment, skilled labour, number of units to be produced, electricity etc will decide which system of construction suit a particular job.

Construction of ferrocement structures can be carried out using various construction techniques which can be divided into three categories;

i. Skeletal steel framing with manual mortar application or the manual casting technique
ii. Semi-mechanized methods / process
iii. Complete mechanized methods / process.

4.1.4 Applications

A wide range of applications of ferrocement have been reported, from the most sophisticated, as for boats and load bearing structures, to the least sophisticated such as dustbins. The majority of the application of ferrocement has been in the field of fishing boats and barges, food storage, gas holders, water retaining structures such as tanks, pipes and conduits, industrial roofing, housing, and shutters and formwork for use in standard concrete construction. Ferrocement
has also been successfully applied in the construction of low-cost housing, long-span roofing, grain silos, water tanks, biogas plants, service-core units, kiosks, bus shelters, manhole chambers and covers, street furniture, shell roofs, and folded plates, etc.

Industrial production of ferrocement elements makes it an excellent building material both technically and economically. It improves the speed of construction as well enhance the quality. Ferrocement elements such as sump and septic tanks, pre-cast modular community toilets can be industrially produced.

Many researchers have studied the confinement of plain concrete using ferrocement casing (shell). The outcome of the study indicates the potentiality of ferrocement as a suitable material for confinement thus making ferrocement applicable for repairing old re-constructional elements like beams, and columns.

4.2 FIBER REINFORCED CONCRETE

Plain concrete possesses two major drawbacks as a structural material. They behave in 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. Micro cracks develop in the material during its manufacture due to inherent volumetric and micro structural 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 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 provides tensile strength to the concrete members, but 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 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 the occurrence of the first crack is 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).

The idea of using strong discontinuous fibers as reinforcement for concrete beams to have been a challenge to many civil engineers. Adding the reinforcement to the mixer in the form of fibers, simply like adding aggregates or admixtures, to create a homogeneous, isotropic, moldable structural material is a dream that started more than a century ago. The first patent (1874) on fiber reinforced concrete seems to be due to A. Berard from California who suggested the use of
granular waste iron in a concrete mix to create an artificial stone (Antoine E. Naaman, 1985).

The idea that concrete can be strengthened by the inclusion of fibers was also 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 fibers acting as crack arresters and established that the increase in strength is inversely proportional to the square root of fibers spacing. Since then, there has been a wave of interest in fiber reinforced concrete and several interesting experiments have been carried out all over the world using different kinds of fibers.

A French patent dated 1918 by H Alfsen describes a process to improve the tensile strength of concrete by uniformly mixing small longitudinal bodies (fibers) of iron, wood or other materials. It also suggests that the surface of these fiber elements must be rough or roughened and, if possible, their ends bent in order to provide better adherence to the concrete (Antoine E. Naaman, 1985).

Balguru and Shah (1992) reported that the modern developments of using only straight steel fibers began in the early 1960’s. Till now, wide ranges of the other type of fibers are used in cement matrices. Construction industries have led the development for different type of fibers such as steel, stainless steel glass, kelvar, carbon, polypropylene, nylon, jute, sisal, bamboo etc. 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 fibers in modern industries are discontinuous fibers. Development of concrete with modified polymer fibers systems increases the explicit effects and mechanical properties of concrete.

In the early stage of fiber development, steel and glass fibers with geometry of straight and smooth were used, as these fibers improve ductility, flexural strength and fracture toughness of concrete matrix. Steel fibers improve the shear, torsional, and fatigue strength and also the strain carrying capacity is increased making the concrete ductile (Saluja S K, and et al, 1992). The primary factors that control the composition of concrete matrix were fiber volume fraction and length/diameter or aspect ratio. The amount of fiber used ranged from 90 to 120 kg / m$^3$ of concrete. The aspect ratios were in the range of 60 to 100. With lower aspect ratio, there is increase in the compressive and tensile strength at uniform rate, and for higher aspect ratio, the compressive strength decreases with increase in tensile strength with the increase in percentage of fibers (Chandrashekar T, 2004). However, the problems faced were difficulty in mixing and workability. Balaguru and Shah (1992) reported that fibers that are long 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 concrete and strength. In the last 40 years, discovery and acceptance of reinforcement and fibers for enhancement of concrete properties has rapidly increased for use in
concrete industries. Numerous types of fibers have successfully been adapted in the different applications of concrete. Technological advances bought forward the development of fibers with different geometric shapes and properties to expand the benefits in concrete structures. The most desirable fiber characteristics are those that will induce, with the highest possible efficiency, substantial increases in the composites strength and toughness in the short and long term. (Antoine E. Naaman, 1985).

All these fibers with more complicated geometric, shape and sizes developed, mainly to modify each of their mechanical bonding with cement matrix. When fibre is added to a concrete mix, each and every individual fiber receives a coating of cement paste. The incorporation of short discrete fibers in a relatively brittle cement matrix transforms uncontrolled and unstable tensile propagation into a slow controlled growth. This gives the cement based materials a maximum ductility, overcoming its low tensile strength properties (Vijayalakshmi D and Andal T, 2004). The addition of fibers increased the strain corresponding to the peak stress. The strain capacity and the elastic deformation capability of concrete matrix in the pre-failure zone increased considerably with the inclusion of steel fibers. Increase in peak strain is maximum for the fibers having higher volume fraction and for higher aspect ratios (Nataraja M.C and et, al, 1999). The modification of fiber geometry includes hooked end fibers, deformed fibers, deformed wires, fibre mesh, wave cut fibers, large end fibers. This increases bonding without increasing in length and minimize
chemical interaction between fibers and the cement matrices. This also modifies and enhances the mechanical properties and behavior of concrete in its applications. The hooked end fibers are very effective in improving toughness for the fiber content in the range 30 to 60 kg/m$^3$ (Balaguru P, and et al, 1992).

Fiber 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 provide a significant improvement to the fiber-reinforced concrete used in the fields.

### 4.1.1 Constituent Materials

Fiber reinforced concrete is a composite material consisting of cement, aggregate, water, discrete discontinuous fibers 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 fiber-reinforced cement composite are the matrix and the fiber. The matrix generally consists of Portland cement, aggregates, water and admixtures.

Cement 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 fiber-reinforced concrete (Rafat Siddique, 2002).

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 fiber-reinforced concrete and mortar. Fiber-reinforced mortar is normally used for making thin-sheet items such as glass fiber-reinforced cement products and for fiber reinforced boards using either polymeric or natural fibers. The maximum size and size distribution of the 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 shot-creting applications and for large diameter pipes with wall thickness exceeding 25 mm.
Coarse aggregate can be normal-weight, lightweight or heavy weight in nature. Normal-weight coarse aggregate 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 22.4KN/m$^3$, whereas the structural lightweight coarse aggregate weighs in the range of 14.6-17.8 KN/m$^3$. Nonstructural weight components such as boards or noise barriers can weigh as little as 3.2 KN/m$^3$ (Rafat Siddique, 2002).

Water-reducing admixtures have become an integral part of fiber 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 fiber reinforced matrix without adding extra water. Since the addition of extra water reduces the strength, increases the shrinkage and enhances the tendency of crack, resulting in the durability problems, it is always recommended to use minimum amount of water (Rafat Siddique, 2002).

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. Use of silicafume was found to make the mix cohesive, allowing the workers to build greater thickness in single pass. Silicafume will also substantially increase the resistance to chloride penetration and also increases the electrical resistivity to such an extent that steel
corrosion will not represent any practical problem (Odd E Gjorv, 1995). The addition of silicafume results in the combination of a low-density, dispersed hydrate product of low CaO / SiO$_2$ and low Ca(OH)$_2$ content, leading to a relatively homogeneous composite (Feldman R.F and et, al, 1985). Use of mineral admixtures, especially silica fume, become more popularly after the usage of high-range water-reducing admixtures. In the case of fiber-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 silicafume has been found to improve the bond between the fibers and the matrix and the durability of the fibers that are added to the concrete.

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

Fibers

These are strong thread like filaments which when used in the concrete act as crack arresters. Continuous meshes woven fabrics and long rods do not fall within the category of discrete fiber type reinforcing elements. The main aim of introducing the fibers 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 create a low crack propagation state.

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

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

Metallic fibers are made of either carbon steel or stainless steel. The tensile strength ranges from 345 to 1380 MPa. The minimum strength specified in ASTM is 345 MPa. The modulus of elasticity for metallic fibers is about 200 GPa. The fiber cross section may be circular, square, crescent shaped or irregular. The length of the fiber is normally less than 75 mm even though the 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 fibers give good results (Balguru and Surendra.P.Shah, 1992).

Polymeric fibers

Synthetic polymeric fibers have been produced as a result of research and development in the petrochemical and textile industries. 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 are the commercially available polymeric fibers.

1.2.1.3.1 Acrylic

Fibers that contain at least 85 percent 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.

1.2.1.3.2 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 as compared with other fibers. These fibers are also available in strand form.

1.2.1.3.3 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 (fiber count) is the range of 35 million per pound (0.45 kg) for a fiber length of 19 mm.

1.2.1.3.4 Polyethylene

Polyester fibers are available both in standard lengths of 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 shotcrete fibers can also be used in cement matrix to improve ductility, impact resistance, and fatigue strength.

1.2.1.3.5 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.

1.2.1.3.6 Polypropylene

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 pulp seems to have lower strength than polyethylene pulp made with oriented molecules. Table 1.1 presents the properties of various polymeric fibers. Table 1.1 presents a summary of physical properties of various polymeric fibers.

<table>
<thead>
<tr>
<th>Fiber type</th>
<th>Eff. Dia. X 10^-3 in. (X10^-3) mm</th>
<th>Specific gravity</th>
<th>Tensile strength ksi (MPa)</th>
<th>Elastic modulus, GPa</th>
<th>Ultimate elongation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acrylic</td>
<td>(13-104)</td>
<td>1.17</td>
<td>30-145 (207-1000)</td>
<td>2000-2800 (14.6-19.6)</td>
<td>7.5 – 50.00</td>
</tr>
<tr>
<td>Aramid I</td>
<td>0.47 (12)</td>
<td>1.44</td>
<td>525 (3620)</td>
<td>17,000 (117)</td>
<td>4.4</td>
</tr>
<tr>
<td>Aramid II (high modulus)</td>
<td>1.44</td>
<td>525 (3620)</td>
<td>17,000 (117)</td>
<td>2.5</td>
<td></td>
</tr>
<tr>
<td>Nylon</td>
<td>1.16</td>
<td>140 (965)</td>
<td>750 (5.17)</td>
<td>20.0</td>
<td></td>
</tr>
<tr>
<td>Polyester</td>
<td>1.34-1.39</td>
<td>130-160 (896-1100)</td>
<td>2500 (17.5)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polyethylene</td>
<td>1.0-40.0 (25-1020)</td>
<td>0.96</td>
<td>29-35 (200-300)</td>
<td>725 (5.0)</td>
<td>3.0</td>
</tr>
<tr>
<td>Polypropylene</td>
<td>0.90-0.91</td>
<td>45-110 (310-760)</td>
<td>500-700 (3.5-4.9)</td>
<td>15.0</td>
<td></td>
</tr>
</tbody>
</table>

Naturally occurring fibers

The oldest forms of fiber-reinforced composites were made with naturally occurring fibers such as straw and horse hair. Now fibers are also extracted from various plants, such as jute and bamboo, to be used in cement composites.
Natural fibers used in Portland cement composite include akwara, bamboo, coconut, flax, jute, sisal, bagasse, wood and others.

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 fibers. Fiber

1.2.2 Shape and Geometry

Since last few decades, extensive studies are carried out and have resulted in bringing up different shapes. Shape of the fibers affects the strength of the members. The fibers 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 fiber shapes commonly used is shown in figure 1.1.

The fibers may be categorized as straight, deformed, rippled with special ends (e.g. enlarged or hooked ends) and with irregular cross sections. Round, straight steel fibers are produced by cutting into pieces thin wires having a diameter in the range of 0.25 to 1 mm. Flat straight steel fibers are produced either shearing thin sheets that are 0.16 to 0.41 mm thick or by flattening wires. These fibers have a width in the range 0.25 to 1 mm. Crimped or crimping the full length produces deformed fibers. Deformations are also made by flattening of wires to increase the bonding. Fibers with crimped (hooked) ends are also available in collated form. Collation is done by gluing the fibers together along their sides with water soluble glue. Therefore, large fiber volume fractions of fibers with higher length-diameter (aspect)
ratio can be incorporated into the concrete without balling of the fibers (Balguru and Surendra.P.Shah, 1992).

Fibers 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 fibers (Balguru and Surendra.P.Shah, 1992).

Fibers 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 fibers. These fibers have a rough and irregular surface (Balguru and surendra.P.Shah, 1992).

Figure 1.1 Various shapes of steel fibers used in fiber reinforced concrete.
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 advantages, however, of being uniformly mixed and dispersed throughout the concrete (Parameswaran 1998).

If the modulus of elasticity of the fiber is high with respect to the modulus of elasticity of the concrete or mortar binder, the fibers help to carry the load, thereby increasing the tensile strength of the material. Increase in the length: diameter ratios of the fibers usually augment the flexural and toughness of the concrete. The values of this aspect ratio are usually restricted to between 100 and 200 since fibers which are too long tend to ‘ball’ in the mix and create workability problems (Parameswaran, 1998).

Unlike the fibre composites in resin and metal matrices, in which fibers are aligned and amount to 60 to 80% of the composite volume, fibre cement/concrete composites contain much less fibers 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 fibers, 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 fiber 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 de-bonding of fibers occurs over several stages. In the post-cracking stage the resistance to full separation of the composite is provided by the fibers bridging across the cracked surfaces (Parameswaran, 1988).

The increase in strength by the use of fibers, the degree of ductility and the extent of post-cracking behavior and whether simple or multiple cracking occurs depend upon the strength characteristics of the fibers themselves, bond in the matrix-fiber interface, the ductility of the fibers, the volume of the fibre reinforcement and its spacing, the dispersion and orientation of the fibers and their shape and aspect ratio. High strength fibers, large volume of fibers, large fiber lengths, and smaller fiber diameters have been found independently to improve the strength (Parameswaran, 1988).

The fibers may be non-uniformly dispersed and randomly oriented. The orientation and dispersion effects may depend, among other things on the loading condition. As a rule, fibers are generally randomly distributed in the concrete. Unidirectional fibers uniformly distributed throughout the volume are the most efficient in uni-axial tension. While flexural strength may depend on the unidirectional alignment of the fibers 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 fibers so that the fracture strength of the fibers may be fully utilized (Parameswaran, 1988).
Thus the addition of fibers even in small quantity, considerably improves the impact resistance of concrete. Also, as the age of concrete is increased from 28 to 90 days, number of blows to first crack increases (Balasubramanian K and et al, 1996).

4.1.3 Mechanism of Fiber Reinforcement

The idea behind fiber-reinforced concrete as described by Rafat siddique (2002) is shown in figure 1.2. Without the fibers 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 fibers, the fibers effectively help in delaying the occurrence of the first crack. However if cracks are present and the breaking strains is much greater-say 10 times greater than the cracking strain of concrete, then the fibers remain in place bridging the crack. Off course, the fibers, besides having larger failure strain that the matrix must be able to withstand the load placed upon them then even if the crack in the concrete runs straight across the piece, the piece will remain unbroken because the fibers hold it together. If at this stage loading is continued, the weak concrete will break again at another and again will be held together by fibers bridging the cracks.

If FRC material is loaded in flexure, two distinct stages are generally observed in the load deflection curve as shown in figure 1.3. The curve can be considered almost linear up to point X and beyond point X, the curve is significantly non-liner and attains a maximum at point Y. The load of the stress corresponding to point X has been called “first crack
strength”, “elastic limit”, “proportionally 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 fibers, other factors include the degree of consolidation, which in turn depends on w/c ratio consolidation techniques and amount of fiber etc and also on the uniformity of fiber distribution and the surface condition of fiber.

![Figure 1.2 Flexural failure in an unreinforced beam and in beams with fibers](image)

(a) No fibers (Plain concrete)

(b) Plain concrete with short discrete fibers

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

**Figure 1.2 Flexural failure in an unreinforced beam and in beams with fibers**
4.1.4 Fiber-Matrix Bond

For a composite system such as fiber-reinforced concrete, the mechanical behavior depends not only on the properties of the fiber 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 fiber.

**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 reinforcement, although to a less extent with the alkali-resistant glasses.

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

As mentioned above, most fiber-reinforced concrete failures occur due to bond failure (fiber pull-out). It is possible to increase the bond strength substantially by deforming the fibers 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 behavior. 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 fibers is suggested by Swamy for optimizing strength absorption properties. Table 1.2 shows the pullout strength for a number of different fibers in various matrices (Parameswaran, 1988).

<table>
<thead>
<tr>
<th>Matrix</th>
<th>Fiber</th>
<th>Pull-out strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement paste</td>
<td>Asbestos</td>
<td>0.8 – 3.2</td>
</tr>
<tr>
<td></td>
<td>Glass</td>
<td>6.4 – 10.0</td>
</tr>
<tr>
<td></td>
<td>Polycrystalline Alumina</td>
<td>5.6 – 13.6</td>
</tr>
<tr>
<td></td>
<td>Steel</td>
<td>6.8 – 8.3</td>
</tr>
<tr>
<td>Mortar</td>
<td>Steel</td>
<td>5.4</td>
</tr>
<tr>
<td>Concrete</td>
<td>Steel</td>
<td>3.6 (First crack)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4.2 (Final failure)</td>
</tr>
<tr>
<td></td>
<td>Nylon</td>
<td>0.14</td>
</tr>
<tr>
<td></td>
<td>Polypropylene</td>
<td>1.0</td>
</tr>
</tbody>
</table>

**4.1.5 Shape, Geometry and Distribution of the Fibers in Cement Matrix**

The largest influences on the fiber reinforced concrete however were the shape, geometry and mechanical properties of fibers and the
dispersion of fibers in the cementitious matrix. The most common types of fibers were steel fibers and polymers fibers, due to low cost and their availability. However, other types of fibers may be used in the concrete composites depending to the needs. The properties and their respective types of fibers and properties of cement matrix are shown in Table 1.3.

Table 1.3 Properties of fiber types and cement matrix

<table>
<thead>
<tr>
<th>Fiber 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>3.5</td>
<td>2.0-4.0</td>
</tr>
<tr>
<td>Asbestos</td>
<td>3.4</td>
<td>196.0</td>
<td>2.0-3.5</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>Polyethylene</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>8.0</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 fiber</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 such problems on fiber-matrix interface associated with the fiber debonding. Furthermore, Riley (1968) stated that most fibers have surface flaws, due to handling, processing and manufacturing, as their surface defects can affect the strength properties of the composites. Such presence of flaws varies by fiber length and diameter, which acts to strength reduction of fiber reinforced concrete. Additionally the tensile strength of the fibers decreases when the fiber length increases (James, 1990).
One of the significant aspects of randomly distributed discrete fibers in cement composites is their composites in their ability to slow down the propagation of tensile cracks, thereby improving the post cracking behaviour, flexural toughness and ductility of the composite (Balasubramanian K and et al, 1996).

4.1.6 Applications

Fiber-reinforced concrete is increasingly used on account of advantages of increased static and dynamic tensile strength, energy absorbing characteristics and better fatigue strength. Fiber reinforced concrete was primarily used for pavements and industrial floors. But currently, the fiber reinforced cement composite are being used for a wide variety of applications including bridges, tunnel and canal linings, hydraulic structures, pipes, explosion-resistant structures, safety vaults, cladding and roller compacted concrete.

4.3 SLURRY INFILTRATED FIBROUS CONCRETE

Slurry infiltrated fibrous concrete (SIFCON) is a relatively new special type of high performance fiber reinforced concrete. SIFCON is made by placing short discrete fibers in the moulds to its full capacity or to the desired volume fraction, thus forming a network. The fiber network is then infiltrated by a fine liquid cement-based slurry or mortar. The fibers can be sprinkled by hand or by using fiber-dispensing units for large sections. Vibration is imposed if necessary during placing of the fibers and pouring the slurry. The steel fiber content can be as much as 30% by volume. In conventional fiber
reinforced concrete (FRC), where fibers are mixed together with other ingredients of concrete, this percentage is limited to only about 2% for practical workability reasons.

Because of its high fiber content, SIFCON has unique and superior mechanical properties in the areas of both strength and ductility. The main differences between FRC and SIFCON, in addition to the clear difference in fiber volume fraction, lie in the absence of coarse aggregates. In SIFCON which if used, will hinder the infiltration of the slurry through the dense fiber network. Furthermore, SIFCON contains relatively high cement and water contents when compared to conventional concrete.

4.1.1 Materials and Mix Proportions

The primary constituent materials of SIFCON are steel fibers and cement based slurry. The matrix can contain:

- Only cement (slurry or cement paste).
- Cement and sand (mortar).
- Cement and other additives (mainly flyash or silica fume).

In most cases, high-range water-reducing admixtures (superplasticizers) are used in order to improve the flowability of the slurry to ensure complete infiltration without increasing the water-cement ratio (W/C). The dosage of superplasticizers has the greatest effect on fluidity, cohesiveness and penetrability of cement slurries.

Fibers

A large variety of steel fibers have been investigated for use in SIFCON to develop better mechanical anchorage and bond between
the fibers and the matrix, the fibers can be modified along its length by inducing mechanical deformations or by roughening its surface. The most widely used types are hooked and crimped fibers. Surface deformed and straight fibers are used also, but they are less popular. In most cases, the cross section of steel fibers is circular. It can be also rectangular or square triangular or flat. Typical examples of steel fibers used for SIFCON are shown in Figure 1.4. In most applications in the USA and Europe, steel fibers with hooked-ends have been used. Most common steel fibers have a length from 25 to 60 mm, and a diameter ranging from 0.4 to 1mm. their aspect ratio (l/d), is generally less than 100, with a common range from 40 to 80.

Matrix

The matrix of SIFCON does not contain coarse aggregates. The matrix composite investigated include cement, cement-flyash, cement-silicafume, cement-sand, cement-sand-flyash, cement-sand-silicafume. Matrices containing filler materials were found to have better shrinkage characteristics.

Mix proportions

The primary variables are the fiber content and matrix proportion. A fiber volume fraction of about 10% seems to provide optimal strength. The recommended water-cement ratio for the matrix is 0.3.High range water –reducing admixtures may be added to improve the flowability of the slurry. Only fine sand should be used and the cement-to-sand ratio limited to 1:2.
4.1.2 Preparation

Analogous to preplaced aggregate concrete, SIFCON is preplaced fiber concrete with placement of steel fibers in a mold or form, or on a substrate as the initial construction step. Fiber placement is accomplished by hand (Figure 1.5), or through the use of commercial fiber dispersing units. As stated before, the amount of fibers that can be incorporated depends on fiber dimension, especially aspect ratio (l/d), fiber geometry, and placement technique. External vibration can be applied during the fiber placement operation. The stronger the vibration, the higher achievable $V_f$. 

**Figure 1.4 Typical profiles of steel fibers commonly used in SIFCON**
One of the important aspects in the fabrication of SIFCON is fiber orientation. As might be expected, when steel fibers are placed into a substrate or into a mold, a preferred fiber orientation occurs. The orientation is essentially two-dimensional, perpendicular to the gravity vector. The orientation effect is more exaggerated with some fibers than with the others. In general there is trend toward a three-dimensional fiber orientation that accompanies reduction in fiber diameter and aspect ratio.

The fiber orientation phenomenon must be considered when designing field installation of SIFCON or in preparing laboratory specimens. The preparation of test specimens of SIFCON requires special considerations relating mainly to the need of avoiding non-uniform fiber distribution and of avoiding unfavorable fiber orientation. The fiber density at the edges of the mold can be much less, as compared to the interior. Additionally a number of fibers may
align vertically (parallel to the long cylindrical axis) along the outer surface. Figure 1.6 depicts the edge effects in the moulds of SIFCON.

Figure 1.6 Fiber orientation “edge effects” in a molded SIFCON cylinder specimen

One way to avoid the fiber orientation and edge effect problems is to cast a slab and obtain the test specimens by coring. Here again, attention should be paid to the orientation of fibers. If fibers are aligned along the diameter of the cylinder, a much higher compressive strength can be expected compared to a cylinder in which fibers are aligned along the axis of the cylinder. Actually, it is reported that specimens with fibers perpendicular to loading axis may exhibit twice the strength of specimens with fibers placed parallel to load direction.
Cylinders shown in the figure 1.7 are cored vertically and horizontally from a slab with horizontally placed steel fibers.

Figure 1.7 Orientation of fibers in cored SIFCON specimens as influenced by the coring direction with respect to the fiber placement direction

Once the steel fibers have been placed on a substrate or in a mold, then they are infiltrated with fine-grained cement-based slurry. The slurry must be flowable and liquid enough and have sufficient fitness to infiltrate thoroughly the dense matrix in the fiber filled forms. The infiltration step is accomplished by simple gravity-induced flow or gravity flow aided by external vibration or pressure grouting from the bottom of the bed. Slurry infiltration by gravity flow aided by a vibrating table is shown in figure 1.8. The choice of infiltration technique is dictated largely by the ease with which the slurry moves through the packed fiber bed. Figure 1.9 shows an example of what happens if the slurry is not flowable enough, or if the vibration is not
intense enough. The degree of voids or honey combing extent depends on how flowable is the slurry, and how strong is the vibration.

Figure 1.8 Slurry infiltration aided with external vibration.

Figure 1.9 An example of failed preparation because of the lack of fluidity of slurry

4.1.3 Properties of SIFCON

Some of the important properties of SIFCON are discussed below,
Density

Because of high level of steel in SIFCON, its unit weight is 5% to 30% greater than that of normal Portland cement concrete. The unit weight of slurries used in SIFCON varies from 1922 to 2163 kg/m³. The unit weight of SIFCON varies from 2163 to 2403 kg/m³ for steel fiber loading around 5% volume, to 3124 to 3364 kg/m³ for steel fiber loading of 20% volume percentage. The unit weight increase is almost linearly proportional to the fiber content, as shown in Figure 1.10.

![Figure 1.10](image)

**Figure 1.10 Effect of steel fiber content on the unit weight of SIFCON**

Drying shrinkage strain

The ultimate drying shrinkage strain of the fine grained slurries used in SIFCON is quite high (0.2% to 0.3%). However, when used in SIFCON composite, the ultimate drying shrinkage obtained of SIFCON
is very similar to that of conventional PCC on the range of 0.02% to 0.05%.

Modulus of elasticity

The elastic modulus of SIFCON is different for tensile and compressive loading. The elastic modulus depends on a number of parameters which include the matrix and fiber properties, the fiber reinforcing parameter, and the properties of the interface between the fiber and the matrix. For about the same volume fraction of the fibers, the modulus of SIFCON increases with the compressive strength of the composite. However, the modulus is also quite sensitive to the length of the fibers equivalently to the bond at the fiber matrix interface.

Generally the modulus of elasticity for SIFCON is taken to range from 10.5 GPa, when latex modified slurries are used and 17.5 to 24.5 when no latex is used. The modulus of elasticity of SIFCON in tension is different from its modulus in compression and depends on the orientation of fibers (Antoine E Naaman, and et al, 1991). Since the volume fraction of fibers in SIFCON is relatively large (5 to 30%) compared to conventional FRC, and because of the elastic modulus of a cement based slurry is substantially smaller than that of a regular concrete of the same strength, the modulus of elasticity of SIFCON can be several times larger than that of slurry matrix (Antoine E Naaman, and et al, 1991). It is seen that the elastic modulus increases with an increase in volume fraction of fibers and the longer length of fibers.
Impact strength

It has been proved that SIFCON exhibits very high resistance to impact. It is clear that the SIFCON possesses high impact strength as compared to PCC.

Abrasion resistance

SIFCON possesses very high abrasion resistance when compared with plain concrete and FRC specimens. The abrasion resistance improves with the increase in percentage of fibers.

Flexural strength

The flexural strength for a constant fiber length increases with the volume content of fiber only up to a certain limit. The optimum fiber content seems to vary with fiber types. It is found to increase in fiber length. SIFCON is found to possess excellent ductility both under monotonic and high amplitude cyclic loading.

SIFCON specimen with 8% fiber content showed a five fold increase in flexural tensile strength over plain mortar specimen and two fold increase over SFRC specimen.

For conventional SFRC with fiber contents not excluding 2% volume, the flexural strength of fiber containing concrete are typically 1.2 to 2 times of the same concrete without fiber. For SIFCON 4 fold to 10 fold increase in flexural strengths are achieved. One day flexural strength values for SIFCON typically range from 14 to 42 MPa. 28 day flexural strength values typically range from 20 to 65 MPa. Ultimate flexural strength is as high as 85 MPa.
Compressive strength

The cement slurry used in making SIFCON generally develops one day strength of 25 MPa to 35 MPa and 28 days strength of 50-70 MPa. The corresponding values for SIFCON composite are 40 MPa to 80 MPa and 90 MPa to 160 MPa respectively. For every mixture the resulted compressive strength value depends on the fiber orientation, content, type and dimensions. Typical failure mode of SIFCON in compression seems to be shear failure, depending on the percentage of steel fiber incorporated in the matrix. Generally SIFCON exhibits an extremely ductile behaviour under compression. SIFCON is ideally suitable for structure subjected to cyclic loads such as in particular, same key elements of earth quake resistance structures.

4.1.4 Applications of SIFCON

While SIFCON passes many desirable properties such as high strength and durability, it is also expensive. SIFCON can be very economical material where concrete or SFRC has not performed as expected or where such unique properties as high strength and durability are required then SIFCON could be considered.

In addition, the exceptional crack resistance and durability of SIFCON would reduce future maintenance cost and extend the overall life of the structure. SIFCON when compared to the other material, it is the best suited material for application in the following areas,

- Pavement rehabilitations
- Over-lays, bridge decks and protective revetments
- Seismic and explosive-resistant structures
• Security concrete application such as safety vaults, strong rooms etc.,
• Refractory application e.g. furnace, lintels, saddle piers etc.,
• Military application such as anti-missile hangers, underground shelters etc.,
• Sea protective works
• Primary nuclear containment shielding
• Aero space launching platform.

4.4 PROPOSED RESEARCH WORK

A detailed study of the available literature shows that very less work is being done in the field of “Slurry Infiltrated Fibrous Ferrocement (SIFF)”. The following points of interest are covered in the proposed research work which is mainly experimental oriented.

1. Effect of varying percentages of fibers on the strength characteristics of Slurry Infiltrated Fibrous Ferrocement (SIFF).
2. Effect of aspect ratio of fibers on the strength characteristics of Slurry Infiltrated Fibrous Ferrocement (SIFF).
3. Effect of addition of pozzolonas on the strength characteristics of Slurry Infiltrated Fibrous Ferrocement (SIFF).
4. Effect of freezing and thawing on the strength characteristics of Slurry Infiltrated Fibrous Ferrocement (SIFF).
5. Effect of addition of combination of admixtures on the strength characteristics of Slurry Infiltrated Fibrous Ferrocement (SIFF).
6. Effect of sustained elevated temperature on the behaviour of Slurry Infiltrated Fibrous Ferrocement (SIFF).

7. Effect of alternate wetting and drying on the behaviour of Slurry Infiltrated Fibrous Ferrocement (SIFF).