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“EXPERIMENTAL STUDY OF EFFECTS OF STEEL FIBERS ON THE MECHANICLA PROPERTIES OF CONCRETE”

By

Major Shahzad Ul Hassan Amir

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DEDICATED TO MY LOVING FAMILY

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ABSTRACT

Steel Fiber reinforced concrete is constructed by adding short fibers of small cross-sectional size to the fresh concrete. Fibers reinforce the concrete in all directions, as they are randomly oriented. The mechanical properties of concrete, that are improved, include ductility, impact resistance, compressive, tensile and flexural strength and abrasion resistance. These unique properties of the fiber reinforcement can be exploited to a great advantage in concrete structural members containing both conventional bar reinforcement and steel fibers. The improvements in mechanical properties of cementitious materials resulting from steel fiber reinforcement depend on the type, geometry, volume fraction and material properties of fibers, the matrix mix proportions and the fiber matrix interfacial bond characteristics.

Effects of steel fibers on the mechanical properties of concrete are investigated through a comprehensive testing programme by varying the fiber volume fraction and the aspect ratio (L/d) of fibers. Significant improvements are observed in compressive, tensile, flexural and impact resistance of concrete accompanied by marked improvement in ductility.

Optimum fiber volume fraction and aspect ratio of steel fibers is identified. Test results are analyzed in details and relevant conclusions drawn. The research is finally concluded with future research needs.

ABBREVIATIONS & NOTATIONS

ACI	American concrete institute
PCC	Plain cement concrete
SFRC	Steel fiber reinforced concrete
FRC	Fiber reinforced concrete
SFRS	Steel fiber reinforced shot Crete
Psi	Pounds per square inch
Ksi	Kips per square inch
ASTM	American standard of testing materials
BS	British standards
Lb	Pounds
Yd	Yards
in (")	Inch / Inches
Mm	Millimeter
Fol	Following /Follows
min	Minutes
MS	Mild steel
fc´	Compressive strength of concrete
Fig	Figure
Kgs	Kilograms
%	Percent / Percentage
Dia	Diameter
Mix	Mixture

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CHAPTER - I

INTRODUCTION

1.1 GENERAL

With the advancement of technology and rapid developments in various fields of science, modern era can definitely be marked as an era of science and technology. Engineering being one of the branches has also flourished. So, the process of advancement and modernization is predominant in different fields of engineering. Civil engineering is one of the main branches of engineering, which has its almost complete application for the ease and comfort of people. Although we are still in the process of switching over from ordinary construction procedures and thumb rules to modern complex construction procedures, nevertheless, civil engineering has a vast scope in Pakistan.

Civil Engineering and concrete has the same monolithic relationship as that of body and soul. Without concrete, civil engineering seems to be meaningless. For normal construction, concrete of 3000 - 4000 Psi is being used throughout the world. This is for ordinary construction but if there is some special construction such as pre-cast and pre-stressed concrete structures, nuclear reactors, blast resistance structures etc, then concrete with superior mechanical properties is required. Therefore for special projects we need to modify PCC to induce enhanced mechanical properties fulfilling the requirements of the structure. For ordinary construction, no doubt, PCC is the most suitable in all respects, but when there is some special construction then it is required to modify PCC. There have been a number of methods developed to enhance the strength properties of concrete and one of the current and still under developed methods is fiber reinforced concrete.

Fibers are materials of varying length, shape and diameter; mixed randomly or by some arrangement, to achieve different strengths and to control cracks. Fibers have their own material properties, advantages and disadvantages. One good thing about fibers is that if suitable mix proportions alongwith correct fiber length and volume fractions are used, then any desired mechanical property can be obtained and crack formation can be effectively controlled.

1.2 FIBER REINFORCED CONCRETE

Concrete, the most widely used structural material in the world is prone to cracking for a variety of reasons. These cracks may be attributed to structural, environmental or even economical factors but most of the cracks are formed due to the inherent weakness of the material to resist tensile forces. Also, when concrete shrinks and it is restrained, it will crack. Steel fiber reinforcement offers a solution to the problem of cracking by making concrete tougher and more ductile.

Fiber reinforced concrete is constructed by adding short fibers of small cross-sectional size to the fresh concrete mix to reinforce the concrete. Fibers reinforce the concrete in all directions, as they are randomly oriented. The mechanical properties of concrete, that are improved, include ductility, impact resistance, compressive, tensile and flexural strength and abrasion resistance. The improvements in mechanical properties of cementitious materials resulting from fiber reinforcement depend on the type, geometry, volume fraction and material properties of fibers, the matrix mix proportions and the fiber matrix interfacial bond characteristics.

Extensive research on steel fiber reinforced concrete has shown that the most significant influence of incorporation of steel fibers in concrete is to delay and control the tensile cracking of the composite material. Steel fiber reinforcement, thus, transforms inherently unstable tensile crack propagation in concrete in to a slow controlled growth. This crack controlling property of the fiber reinforcement, in turn delays the onset of flexural and shear cracking, imparts extensive post- cracking behavior and significantly enhances the ductility and energy absorption capability of the composite. These unique properties of the fiber reinforcement can be exploited to a great advantage in concrete structural members containing both conventional bar reinforcement and steel fibers.

1.3 HISTORY

Fibers have been used to reinforce brittle building materials since ancient times. Straw was used to reinforce sun-baked bricks, horsehair to reinforce plaster and more recently asbestos fibers were used to reinforce Portland cement. In western history, the oldest recorded account of the use of fiber reinforcement is in the Old Testament of the Bible as “And Pharaoh commanded the same day, the task master of the people and their officers, saying, He shall no more give the people, straw to make bricks, as heretofore; let them go and gather straw for themselves”.

A chronological review of the earliest patents that have been taken out on fiber reinforced cement and concrete is given by Naaman (1985). This includes a 1918 French patent by Alfsen in which is described the use of fibers (Iron & Wood etc) to increase the tensile strength of concrete and it is suggested that the performance might be improved if the surface of the fibers was roughened or the ends of the fibers bent. In 1926, a Patent was lodged by Martin who described the use of plain or crimped steel wires to strengthen concrete. In 1943, constantinescu filed a Paten in which he described the use of various kinds of steel fibers for increasing the toughness of the concrete. He suggested applications for this concrete including air raid shelters, Army tanks and machine foundations. The fibers he described are similar to the ones currently in use.

It was only after 1960 that the use of fibers in cement and concrete became widespread and the range of materials used to make the fibers increased. During the early 1960s in the US, the first major investigation was made to evaluate the potential of steel fibers as reinforcement for concrete. With NATO pact development of hanger protection, the military research in fiber reinforced concrete begins. Falling concrete pieces damaged planes, after bomb strikes on hangers and there was a need to find a way to minimize the distance between the reinforcing elements to avoid this. FRC had the properties to improve the situation and the planes were less damaged after FRC application. The civilian industry of NATO countries then overtook the military experience and developed methods for shotcrete industry floors and later on for concrete elements.

Since then, a substantial amount of research, development, experimentation and industrial application of steel fiber reinforced concrete has occurred all over the world.

1.4 APPLICATIONS OF SFRC

The applications of steel fiber reinforced concrete will depend on the ingenuity of the designer and builder in taking advantage of the enhanced mechanical properties of the SFRC. Present day applications of SFRC with and without conventional reinforcement have been in a variety of structures, which include: -

- **Overlays:** Roads, Airfields, Runways, Container, Movement and Storage Yards and Industrial Floors.
- **Advantages of using SFRC:**
  - Fatigue and impact resistance increased

- Wear and tear resistance increased
- Joint spacing increased
- Thinner pavements possible due to higher flexural strength of SSF

❖ **Pre-Cast Concrete Products:** Manhole covers and Frames, Pipes, Break-Water Units, Building Floors Components, Acoustic Barriers, Kerbs, Impact Barriers, Blast Resistant Panels, Vaults, Coffins etc.

➢ **Advantages of using SFRC:**

- Fatigue and Impact resistance increased
- Thinner sections possible with SFRC reducing handling and transportation
- Reduced consumption and savings in cost of materials make pre competitive in price with cast iron or reinforced concrete products
- Products possess increased ductility and resistance to chipping as SFRC products suffer less damage and loss during handling and overall improvement in all structural properties
- Many different sizes and shapes of pre-cast units possible with SFRC.

❖ **Hydraulic and Marine Structures:** Dams, Spillways, Aprons, Boats and Barges, Sea Protection structures

➢ **Advantages of using SFRC:**

- Outperforms conventional materials by exhibiting resistance to cavitations and impact damage of hydraulic heads and swirling water currents.
- Ideally suitable for repair of hydraulic and marine structures

❖ **Defense and Military Structures:** Aircraft Hangers, Missile and Weaponry Storage Structures, Blast resistant structures, Ammunition Production and Storage Depots, Underground Shelters etc.

➢ **Advantages of using SFRC:**

- Exhibits high ductile and toughness resulting in superior resistance to impact and falling loads and missiles.
- Fragmentation effect very less compared to other materials due to confining effects of fibers on concrete.
- Far superior resistance to fire and corrosion
- High resistance to penetration by drills and hammers.

- A highly versatile material with longer service life.

❖ **Shotcreting Applications:** Tunnel Linings, Domes, Mine Linings, Rock-Slope Stabilization, Repair of Distressed Concrete Structures etc.

➢ **Advantages of using SFRC:**

- Highly efficient, convenient and economical compared to mesh reinforcement used in conventional shot Crete.
- One stage operation for irregular profiles.
- High resistance to abrasion and Impact loads.
- Improvement in ductility.
- Construction of energy-efficient domes and shell structures possible.

❖ **Special Structures:** Machine Foundations, Strong Rooms, , Column-Beam Joints in Seismic Resistant Structures, End Zones of Pre-stressed Concrete, High Volume Steel Fiber Reinforced Concrete Structures made out of SIFCON and CRC (Slurry Infiltrate and Compact Reinforced Concrete)

➢ **Advantages of using SFRC:**

- Improved performances under action of any kind of loading
- High seismic-resistance in buildings due to ductile behaviors of joints & connections.

1.5 DEVELOPMENT AND SCOPE IN PAKISTAN

During the 1970,s and 1980,s extensive research and development work, together with a wide range of practical applications, have transferred fiber concrete materials from a laboratory curiosity into a reliable construction material all over the developed countries and to some extent in developing countries. Today hundreds of projects, incorporating fiber reinforced concrete are existing around the world. But unfortunately, the engineering community in Pakistan is lacking far behind. Only one example of use of Steel fibers exists in Pakistan and that is in Terbela Dam. In 1970,s Steel fiber reinforced concrete was used in Terbela Dam and it is still in excellent condition.

A country like India has executed many projects using FRC and they are producing fibers locally to make the concrete cast effective. Whereas we in Pakistan, even hesitate to conduct laboratory work in FRC. There is a great scope of FRC usage in a variety of applications in Pakistan like Dams, tunnels, overlays, industrial floors and above all Military structures like aircraft hangers, missiles and weaponry storage structures, underground and blast resistant bunkers. So it is the utmost duty of our engineering community to carryout extensive laboratory work on SFRC and to educate the people about the huge benefits offered by FRC if incorporated in structural members.

1.6 <u>OBJECTIVE</u>

The objective of this research is, “*To study the effects of steel fibers on the mechanical properties of concrete*.”

CHAPTER – II

LITERATURE REVIEW

2.1 Fiber Reinforced Concrete

Fiber Reinforced Concrete (FRC) is concrete made primarily of hydraulic cements, aggregates, and discrete reinforcing fibers. Fibers suitable for reinforced concrete have been produced from steel, glass, and organic polymers (synthetic fiber). The role of the randomly oriented, discrete, discontinuous fibers, which are added to produce FRC is to bridge across the cracks that develop in concrete either as it is loaded or as it is subjected to environmental changes. If the fibers are strong enough, are appropriately bonded to the matrix and are there in sufficient quantity, they will help to keep the crack widths small and permit the FRC to carry significant stresses over a relatively large strain capacity in the post-cracking stage. They provide some post-cracking “pseudo-ductility” to the composite material, often expressed in terms of toughness.

It must be noted that, for the fiber volumes now being used commercially (generally less than 1% by volume), the fibers will not improve the strength of the concrete in any significant way. Moreover, the fibers can not compensate for deficiencies in concrete mix design or in curing procedures. Indeed, since fibers are relatively expensive, one should seriously consider whether the same amount of money might be better spent on additional conventional reinforcement, on a better matrix, or on better curing practices, before fiber reinforcement is considered.

The fibers can act most effectively if they are aligned in the direction of the largest tensile stresses. This principle is applied in reinforced and pre stressed concrete. However, only in a few cases, the direction of maximum tensile stresses is known in advance, and production of aligned short fiber reinforcement is difficult.

Fibers are most beneficial when large strains occur in the cement matrix. Since the tensile strain capacity of the matrix is small, fibers will be activated. The aim of the addition of fibers should be to keep the crack widths as small as possible and to resist the tensile forces which are no longer taken by the cement matrix in its softening stage. The fibers should act during both the early and mature age of the matrix.

2.2 FRC VS Conventional Reinforced Concrete

Over the past four decades, a great deal of research has been carried out on the combination of FRC and the conventional steel reinforcement, using a variety of fiber types. Fibers cannot, in general, be used to simply replace the conventional steel reinforcement. Steel bars are placed at specific locations in the structural members, to withstand the designed tensile, shear or compressive loads. Fibers are not very effective in this regard, since they are randomly oriented throughout the matrix. The prime function of the fibers is to control matrix cracking and to enhance the bond between the FRC and the conventional steel reinforcement, if used together. Therefore, fibers and steel reinforcement should be seen as "*COMPLEMENTARY*" rather than "*COMPETING*" materials.

2.3 The Fibers. Different types of fibers are as follows:-

2.3.1 Naturally Occurring Fibers.

The oldest form of fiber reinforced composites was made with naturally occurring fibers such as straw and horse hair. 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. Natural fibers used in Portland cement composites are as follows:-

- Akwara Fibers
- Bamboo Fibers
- Coconut Fibers
- Flax and Vegetable Fibers
- Jute Fibers
- Sisal Fibers
- Sugarcane Bagasse Fibers
- Wood Fibers (Cellulose Fibers)

2.3.2 Artificial Fibers. Different artificial fibers being used all over the world are as fol: -

- **Glass Fibers**. Glass fiber reinforced concrete is economical, light weight, versatile and almost unrivalled in terms of potential interior and exterior applications. Common applications of glass fibers include architectural cladding, roofing shingles and fire doors, marina walkways, municipal shelters and furniture and water tanks. The common properties of glass fiber are :-

- Commonly used glass fibers are round and straight.
- Strength of glass fibers is comparable to steel fibers but their density is lower.
- Modulus of elasticity of glass fiber is equal to one third of the modulus of elasticity of steel fiber.
- Highly vulnerable to alkaline environment, which seriously damages the long term properties of glass fiber reinforced concrete.
- Glass fibers are relatively high priced (roughly three times the price of steel fibers for same volumes).

➢ **<u>Plastic Fibers</u>**

The strength properties of plastic materials are reasonably good in civil engineering terms but their stiffness, when measured by their modulus of elasticity, is low. For structural applications in which both the strength and stiffness of material are critical, it is therefore necessary to combine plastics with other materials into composites whose properties transcend those of the constituents. The most commonly employed component is in a particulate or a fibrous form. In the particulate composites, particles of a specific material or materials are embedded in. In fibrous composites, fiber with high strength and high modulus are embedded in and bonded together by the low modulus continuous matrix. The fibrous reinforcements may be oriented in such a way so as to provide the greatest strength and stiffness in the direction in which it is needed, and the most efficient structural forms may be selected by the mouldability of the material. To increase the stiffness of the composite still further, the structural units which make up the complete structure may be folded so that the structure is derived from its shape as well as from the material.

➢ **<u>Polymer Fibers</u>**

Polymer fibers are generally low modulus and high elongation fibers and thus do not improve strength of concrete but give toughness and resistance to impact and explosive loading. Polypropylene is a current example of polymer fiber. It is one of the cheapest fibers among the family of synthetic fibers. The Polypropylene fiber is able to form proper bond with cement, hence it may increase the strength.

➢ **<u>Carbon Fibers</u>**

Low cast carbon fibers are made from petroleum pitches in large volumes. They have extremely small diameters as compared to other fibers and they can also be used in short lengths. They can be separated in the form of threads. Warps and Wefts are separated and then they can be used in short pieces. Another form of using carbon fibers is to use it in sheet form without separating it into warps and wefts. Special care must be taken for using carbon fibers. They must be placed at right angles to applied loads so that they can be utilized properly. If carbon threads are to be used randomly then it need not to be designed. Carbon fibers can be manufactured with density 1/5th that of steel fibers but strength of both is same. Carbon fibers possess high stiffness and desirable long-term mechanical properties. The main problem in using carbon fibers is their extremely high price and special care at site, which is not so much required in case of other fibers.

➢ **Steel Fibers**

Short steel wire is currently the most common fiber type. Basic characteristics of steel fibers are presented in Table 2.1, alongwith those of other fibers. Steel fibers might be round or rectangular in cross section and they are produced in the forms of straight smooth, straight deformed, crimped, crimped end, hooked end, irregularly shaped and paddled Steel fibers. They have relatively large strength and modulus of elasticity. Different shapes of steel fibers are shown in figure 2.1.

Steel fibers are inert in the alkaline environment of the cementitious matrix and their bond to the matrix can be enhanced by mechanical anchorage. Long term loading does not adversely influence the mechanical properties of steel fibers, and their price is also comparable with those of the other fibers. They are, however, prone to corrosion if not protected by the matrix and relatively heavy. They cannot also be impregnated in the cement-based matrices in high volume fractions.

➢ **Manufacturing Processes for Steel Fibers**

There are some principle techniques for making steel fibers, according to the forms of the materials used in the manufacturing process. In the sheet shearing process, steel fibers are produced by shearing, high hardness cold rolled carbon steel to the fiber width. Burr, torsion and buckling deformations are seen in fibers produced by this process, but these are effective for increasing the bond strength with concrete. Also for the purpose of improving bonding, the fibers are made uneven by a sheet-feeding roller or corrugated by appropriate technique. In the melt extracting process, a disk with a threaded edge rotates, lightly touching the surface of the melt steel, which instantly solidifies. The solidified bits of steel are extracted and thrown off out of the disk by centrifugal force. It is possible to make fibers of specified lengths by notching the disk edge and to produce dog-bone-shaped fibers (wider at both ends) by making the notches wider. These fibers have an irregular surface, and crescent shaped cross-section. Some fibers have been collected into bundles to facilitate handling and mixing.

Wires are cut in specified lengths by a continuously rotating cutter. Fibers produced by this process are characterized by high tensile capacity. In the wire cutting process, dozens of rolled and drawn steel wires are produced but the bond strength is low. To improve the bond strength, the surfaces of the steel fibers are made irregular, or they are hooked at both ends. In the mill cutting process, a thick plate or slab is cut by a rotating flat mill cutter. The tensile strength of the fibers produced by this process is twice as high as that of the original materials, as a result of plastic deformation and quenching hardening. The bond strength is also considerably improved by the torsional effect of cutting, the skin lamination and the hook at both ends.

2.4 Fundamental Concepts of Fibers in Concrete

2.4.1 Interaction Between Fibers and the Matrix

The interaction between the fiber and matrix is the fundamental property that affects the performance of a cement based fiber composite material. An understanding of this interaction is needed for estimating the fiber contribution and for predicting the composite's behavior. A large number of investigators have studied the various aspects of this interaction. A variety of factors are involved; the following are the major parameters affecting the fiber interaction with the matrix.

- Condition of the matrix: un-cracked or cracked
- Matrix composition
- Geometry of the fiber
- Type of fiber: for example, steel, polymeric, mineral, or naturally occurring fibers
- Surface characteristics of the fiber
- Stiffness of the fiber in comparison with matrix stiffness
- Orientation of the fibers: aligned versus random distribution
- Volume fraction of fiber
- Rate of loading
- Durability of the fiber in the composite and the long-term effects.

2.4.2 Fiber Interaction with Homogeneous Uncracked Matrix

This type of interaction occurs in almost all composites during the initial stages of loading. In certain cases, such as highly reinforced thin sheets, the composite may remain uncracked during the service life. However, in most cases, the matrix will crack during the service life. The fiber interaction with the uncracked matrix has therefore limited importance in practical applications. Study of this interaction does yield useful information for understanding the overall behavior of the composite. In addition, even when cracks develop in the composite, the uncracked portions of the structure affect the overall behavior of the structural system.

A simple fiber matrix system containing a single fiber is shown in Figure 2.2 In the unloaded stage, the stresses in both the matrix and the fiber are assumed to be zero. Applying tensile or compressive load to the composite or subjecting the composite to temperature change results in the development of stresses and deformations that must remain compatible. In the case of a cement matrix, the hydration of cement alone may induce stresses both in the matrix and in the fiber. When the load is applied to the matrix, part of the load is transferred to the fiber along its surface. Because of the difference in stiffness between the fiber and the matrix, shear stress develops along the surface of the fiber. This shear stress helps to transfer some of the applied load to the fiber. If the fiber is stiffer than the matrix, the deformations at and around the fiber will be smaller. This type of situation arises with steel and mineral fibers. If the fiber modulus is less than the matrix modulus, then the deformation around the fiber will be higher. This occurs in composites with polymeric and some naturally occurring fibers. Elastic stress transfer exists in an uncracked composite as long as the matrix and the fiber are within elastic stress range. Based on the composite behavior, it is established that fibers contribute to both composite strength and stiffness. The amount and nature of contribution depend on fiber type, fiber volume fraction and matrix properties.

2.4.3 Fiber Interaction in Cracked Matrix

When the composite containing the fibers is loaded in tension, at a certain stage the matrix cracks (fig 2.3). Once the matrix cracks, the fiber carries the load across the crack, transmitting load from one side of the matrix to the other. In practice, several fibers will bridge the crack, transferring the load across the crack. If the fibers can transmit sufficient load across the crack, more cracks will form along the length of the specimen. This stage of loading is called the multiple cracking stage. In most practical applications, this multiple cracking stage occurs under service load conditions. The fiber interaction characteristics also determine the peak load carrying capacity of the composite and the post-peak load deformation behavior.

The critical issues to be addressed in fiber interaction are:-

- Load-slip variation
- Geometry and orientation effect
- How to quantify the pull-out resistance (load) of a single fiber and Interaction of randomly distributed fibers so as to evaluate the behavior of multiple fiber pull out.

2.4.4 Strong Fibers in Brittle Matrix

The primary reason for using strong fibers in a relatively weak (in tension) brittle matrix is to improve the ductility of the matrix. The fibers contribute to the increase in strength as well. However, in many applications involving this type of combination, the fiber volume fractions are kept relatively low (<1%), resulting in an insignificant increase in strength. In these composites, since the ultimate strain capacity of the matrix is lower than the strain capacity of the fibers, the matrix fails before the full potential capacity of the fiber is achieved. The fibers that bridge the cracks formed in the matrix contribute to the energy dissipation through the processes of de-bonding and pull out. In applications where higher volume fractions of fibers (>5%) are used, there is a significant increase in tensile strength.

The relative stress-strain curves in tension for a strong fiber and a weak brittle matrix are shown in Figure 2.4. In this case, the matrix will fracture (crack) long before the fiber reaches its tensile strength since the fracture strain for the matrix is very low compared to the fracture strain of fiber. Once the matrix cracks, further behavior of the composite could be one of the following:-

- The composite will fracture immediately after the fracture of the matrix. Figure 2.5 shows this type of behavior. Very low fiber volume fraction could lead to this type of failure.
- After the matrix cracks, the load carrying capacity could drop, but still the composite could continue to resist loads that are lower than the peak load (fig 2.5). When the matrix cracks, the load is transferred from the composite (matrix plus fibers) to the fibers at the crack interface. Hence, further load carrying capacity comes from the fibers transferring the load across the crack. As the deformation increases, fibers pull out of the matrix, resulting in lower and lower load carrying capacity. This type of composite does not provide an increase in strength (over the matrix strength) but provides ductile behavior.

The area under the stress strain curve is an indication of the ductility or toughness of the composite.

- If the volume fraction of fibers is large enough, after the matrix cracks, the fibers will start carrying the increased loads. If there are sufficient fibers across the crack, then they will continue to resist higher loads than the cracking load (fig 2.5). The stiffness of the stress strain curve will drop because of the loss of matrix contribution. The slope of the post cracking response would depend on the volume fraction of fibers and their bonding capacity to the matrix. As the load increases, more cracks will form along the length of the specimen. Eventually, when fibers start to pull out from the matrix, the slope of the stress - strain curve will reach zero and the load carrying capacity will start to drop. This type of failure provides for optimum use of the fiber and matrix properties.

2.5 Properties of SFRC

2.5.1 Mixing Sequence

It is very important that the fibers be dispersed uniformly through out the mixture. This must be done during batching and mixing phase. 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.

- Add the clump-free fibers directly to the mixer once the other ingredients have been uniformly mixed. The recommended rate of addition is 100 1bs (45 Kg) per minute. The fibers can be added manually, by emptying the containers into the truck hopper, or via a conveyor belt or a blower either at the batch plant or at the job site. The mixer should be rotating at full speed as the fibers are being added. After the fiber addition is complete, the contents should be mixed for at least another 50 revolutions at normal recommended mixing speed.
- Or add fibers to the aggregates before charging into the mixer. The common procedure is to add the fibers 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. Fibers should be spread out as much as possible to avoid heavy concentrations.
- Or place the fibers on top of the aggregates, weighed and ready to be charged into the mixer. The flow of aggregates from the weight batchers to the mixer will distribute the fiber within the aggregate. Fibers can be added manually or using a conveyor belt

- Or mix the fibers in by feeding them simultaneously with aggregates, cement, admixtures, and about 90 percent of water. This procedure is achieved by slowing down the aggregate feed and adding the other ingredients.
- It is essential that the method chosen for the addition of fibers be tested in the filed using the actual working crewmembers. The mixed concrete should be inspected to ensure uniform distribution of clump free fibers

2.5.2 <u>Transporting Placing and Finishing SFRC.</u>

- Transporting and placing of FRC with steel fibers can be done with conventional equipment. Trucks carrying concrete with higher fiber contents should be loaded to less than heir full capacity. The maximum should be limited to about 85 percent. Typically, fiber concrete is more cohesive than unreinforced concrete, and more power is needed to rotate the drum. Hence, the decreased load will help not only to reduce the total weight but also to maintain proper rotation of the drum.
- A well-proportioned FRC mix barely slides down the chute when discharged from the mixer. Slope of the chute should be increased slightly for easy discharge. If the mix is stiff, the concrete may have to be pulled down manually.
- If concrete buckets are used, they should have steep hopper slopes and large gate openings. If fibers bridge the opening, FRC may not fall freely when the buckets are opened. The solution is to attach 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 just dumped on the hopper. Fiber bridging may totally block the pipe. Vibrating the concrete in the hopper with an immersion vibrator will make the concrete fluid enough to facilitate flow.
- A properly proportioned FRC mix can be pumped without problems. Even though the mix may look harsh, it flows through smoothly. In general it is advisable to
  - Use pumps with a slightly larger capacity than needed for plain concrete.
  - Use larger-diameter lines, (>6 in).
  - Minimize the use of flexible hoses.
  - Provide screens to avoid fiber clumps entering the pump.
  - Avoid mixtures with excessive slump. Pumping of mixture with excessive slump results in the separation of fibers from the paste, leading to formation of plugs.

- Only minor adjustments are needed in finishing FRC compared with plain concrete. Open slab surfaces should be struck off with a vibrating screed, preferably a metal screed, with slightly rounded edges.
- Magnesium floats can be used to close up tears or open areas caused by the screeds. Wood floats normally leave rough surfaces with some fibers on the surface. For certain applications such a pavements further finishing may be necessary. If a texture is required for skid resistance, a broom or roller can be used before initial set. Burlap drags are not recommended because they can get caught on the fibers. Even though they are more difficult to use, larger floats provide flatter and better finish. Floats should not be moved on edges when finishing as they will pick up and move the fibers.
- Loose fibers on the finished surface should be removed because they are a potential hazard, especially on airport runways. The fibers may become airborne missiles that result in injuries. In some airport pavement applications, "roller bugs" are used to press down fibers near the surface.
- Experience has shown that with careful workmanship, FRC can be finished to any desired smoothness and flatness.

2.5.3 Behavior Under Compression

The increase in strength provided by steel fibers very rarely exceeds 35%. With increased use of deformed fibers, the fiber quantity is often limited to 1001b/yd3, or less than 0.75%. At this volume fraction the strength increase can be considered negligible for all design purposes. In special cases where the fiber content is more than 200Ib/yd3, an increase in strength though not significant in high-strength concrete, may be expected.

Adding any fiber to a cementitious matrix produces a substantial change in its compressive stress – strain response. This change is generally characterized by a noticeable increase in strain at peak stress and a significant increase in ductility as described by the descending portion of the stress – strain curve (Fig.2.6). The improvement in ductility obtained by fiber reinforcement is comparable to that achieved by confining concrete with conventional transverse reinforcement.

The toughness of concrete in compression, however, generally increases with the volume fraction of fiber. The fiber type, volume fraction and aspect ratio seem to play an important role in improving the peak strain and toughness of the composite. The effects of the specimen dimensions and the casting direction versus the loading direction also seem to be significant.

In regard to the fiber type effect on compressive behavior, the available test data indicates that steel fibers lead to toughness higher than glass or polypropylene fibers. The toughness of fibrous concrete in compression is observed to increase with increasing steel fiber volume fractions up to 3%. Because of the mixing difficulties at higher than 3% fibers content, which lead to a harsh mix and increased air entrapment, deterioration in the stress-strain response in often observed.

An increase in the aspect ratio of steel fibers at a constant volume fraction is observed to significantly improve the post peak performance and toughness of fiber reinforced concrete in compression. Matrix properties also influence the effectiveness of fibers in improving the compressive behavior of concrete. Everything else being equal, improvements due to fiber addition are relatively more significant at lower matrix compressive strengths. Addition of silica fume to fibrous concrete is also observed to increase the compressive strength and toughness of steel fiber reinforced concrete through improvement of the fiber-matrix interfacial bond. Compressive strength seems to govern the brittleness of both plain and fiber-reinforced concrete. Higher compressive strength always results in brittle mode of failure.

2.5.4 Behavior Under Tension

There are two types of tension tests used for concrete: direct tension and splitting tension. In the former, specimens such as dog-bone shapes are subjected to axial tension. Such tests are rarely used in practice for concrete containing coarse aggregates. In the splitting tension test, which is more popular, a cylindrical specimen is subjected to a splitting tension along its axis. Cubes can also be used for this test.

Incorporation of randomly distributed short fibers into concrete increase the tensile strength of concrete by restraining the internal flaws, and it improves the post-peak resistance and toughness through the pull-out resistance of fibers. The closer the fibers are spaced and the higher their resistance against pullout, the more effective they will be in improving the behavior of concrete under direct tension.

Uniaxial tension test results can provide direct information on the constitutive behavior of the material and the crack arresting properties of fibers. The difficulty of proper performance of this experiment has, however, discouraged the generation of sufficient direct tension test data in the past. The reported results of direct tension test have indicated that the post cracking response of fibrous cement-based composites to uniaxial tension is generally dominated by a single major crack at the weakest cross-section of the specimen. This weakest section has either a small number of crossing fibers or an exceedingly large number of fibers that damage the fiber–matrix interaction as shown in fig2.7.

2.5.5 Behavior Under Flexure

Behavior under flexure is the most important aspect for FRC because in most practical applications the composite is subjected to some kind of bending load. Moreover, the addition of fibers improves the flexural toughness of plain concrete. The increase in flexural toughness provides the primary motive for using fibers in concrete

When fiber reinforced concrete specimens are loaded in flexure, two stages of behavior have been generally observed in the load deformation curve. The behavior is more or less linear up to the “first crack strength”, beyond which the curve is significantly nonlinear and reaches its peak at the “ultimate strength”.

Two factors with significant influence on the flexural performance of fiber reinforced concrete are fiber type and volume fraction. Steel, glass and carbon fibers are observed to increase the first crack and ultimate flexural strength of concrete. A significant contribution of fiber is to increase the ductility and toughness of the material. Steel fiber, with its desirable pull-out performance, is especially effective at large deformations and crack widths. Its effect on the ultimate flexural strength is also significant.

Flexural performance of fiber reinforced concrete tends to improve with the increase in fiber volume fraction. This tendency, however, will reverse at a certain fiber volume fraction after which the relatively large amount of fibers can hardly be dispersed uniformly.

For a constant fiber volume fraction, test results have indicated that the flexural behavior of fiber reinforced concrete improves with increasing the fiber length to diameter ratio (usually referred to as aspect ration). At increased aspect ratios, however, fibers become more difficult to disperse. Hence, there is a maximum aspect ratio for each fiber type, above which the practical manufacturing problems stop the improvement in flexural performance with increasing aspect ratio.

With fiber volume fraction and aspect ratio being the two principal variables influencing the flexural performance of fiber reinforced concrete, some investigators have suggested that the fiber reinforcement effects can be represented conveniently in terms of a combination of following two variables i.e. critical volume fraction and the flexural toughness of steel fiber reinforced concrete and motor.

The flexural behavior of fiber reinforced concrete at the ultimate condition is marked by major nonlinearities of the tensile and compressive stress distributions at the highly stressed cross-sections. As a result, the conventional elastic equations for calculation of the flexural stresses can not be applied to fiber reinforced concrete (fig2.8 & 2.9).

2.5.6 <u>Behavior Under Impact And Fatigue Loading</u>

The impact resistance of a material is represented by the number of times a standard size mass must be dropped from a standard distance before cracking the specimen and causing it to separate into pieces. By definition, ultimate failure occurs when sufficient impact energy has been supplied to crack the material and cause its failure. The impact resistance of a material is related to its toughness and strain capacity.

Plain concrete, due to its brittle nature, has especially low impact resistance. A major contribution of fiber reinforcement is to significantly improve the impact resistance of the concrete matrix.

Fiber reinforcement results in a significant increase in the fatigue strength of concrete. Fatigue strengths of about 90% and 70% of the static flexural strength at 2 million cycles of non-reversal and complete reversal of loading have been observed for concrete incorporating 3% volume fraction of steel fiber. The crack width under fatigue loading also decreases with fiber reinforcement and the deflections caused by fatigue tends to decrease. In some cases, the post fatigue static flexural strength is observed to be greater than the pre-fatigue strength, possibly due to the reduction in residual shrinkage stresses (through the acceleration of creep under fatigue loading).

2.5.7 <u>Behavior of SRFC Under Shear, Torsion And Bending</u>

- One of the very promising applications of fiber-reinforced concrete is in the area of shear reinforcement. The random distribution of fibers provides a close spacing of reinforcement in three dimensions that cannot be duplicated with bar reinforcement. The fibers intercept and bridge cracks in all directions. This process not only increases shear capacity but also provides substantial post- peak resistance and ductility. When used in conjunction with stirrups, spacing is reduced. The behavior of fiber – reinforced concrete beams under pure torsion has been investigated and it was found that, when fibers are added to plain concrete, both torsional strength and energy – absorbing capacity increases.

- The addition of steel fibers in reinforced concrete provides a substantial improvement in ductility. The load-deflection curve of fiber reinforced beams has longer plateau at the peak load, and the descending part of the curve is less steep compared to normal reinforced concrete beams. This increase in energy absorption capacity is even more notable under cyclic and impact loads. There is notable improvement in cracking characteristics. The cracks are more uniformly distributed, with substantial reduction in maximum crack width. First – crack strengths are also higher. The fibers also provide increase in moment capacity and flexural stiffness. The increase in stiffness reduces both deflection and total crack width, alongwith also provides substantial post -peak resistance and ductility. When used in conjunction with stirrups, fibers make it possible to increase the spacing of stirrups, thereby reducing reinforcement congestion in high-shear areas, which is the tension face of the beam at service loads.
- Very rarely are structural elements subjected to pure bending, shear, or torsion. In most cases bending and shear forces occur together. In some instances the structural element will also be subjected to torsion in addition to bending and shear. In the case of torsion, the members could be subjected to either equilibrium or compatibility torsion.
- When fibers are added to members subjected to compatibility torsion, they were found to reduce stiffness degradation. The cracks were finer and more uniformly distributed, thus reducing sudden drops in stiffness at wider cracks. The members with fibers could also sustain more rotation without loosing their load carrying capacity.

2.5.8 Freeze – Thaw Durability of SFRC

When SFRC is used in extremely cold regions, the concrete will be exposed to freeze-thaw cycles. Fol points must be kept in mind for durability of concrete;

- Air content is the most significant parameter for freeze-thaw durability of fiber-reinforced concrete. The addition of entrained air improves freeze-thaw durability.
- Under freeze-thaw cycling, the behavior of fiber-reinforced concrete is similar to that of plain concrete. For the same air content, the durability of fiber concrete and plain concrete are similar.
- For a water-cement ratio of more than 0.4 and a cement content of less than 700 Ib/yd3, a minimum of 6% air, preferably 8% should be used to avoid deterioration under freeze-thaw cycling.

- The toughness index, which is an important property of fiber – reinforced concrete, does not change appreciably as a result of freezing and thawing if the mixture has been designed to prevent deterioration by entraining sufficient air into the mixture.

2.5.9 <u>Unit Weight, Abrasion Resistance, Friction and Skid Resistance, Thermal and Electrical Conductivity of steel fiber reinforced concrete:</u>

- The unit weight of hardened SFRC is about the same as plain concrete. The unit weight tends to increase for steel fiber-reinforced concrete at volume fractions higher than 3%.
- Standard abrasion tests conducted using ASTM C779Procedure show that steel fibers have almost no effect on the abrasion resistance of concrete. Field observations of pavements and floor slabs under wheel loads also indicate that steel fibers do not affect abrasion resistance. Steel fibers were found to provide significant improvement in resistance to disintegration when abrasion is caused by particulate debries under high velocity. These conditions typically occur at the downstream side of dams.
- A simulated skid test was conducted to compare steel fiber-reinforced concrete with identical plain concrete for static friction, skid, and rolling resistance. The static friction of SFRC and plain concrete was found to be same if there was no surface deterioration. If the surface has been subjected to erosion, than SFRC had better skid and rolling resistance. The improvement was about 15 percent under dry, wet or frozen conditions.
- Thermal conductivity of concrete increases with the addition of steel fibers. A fiber volume fraction of about 1% is needed to see a notable increase in thermal conductivity. The effect of fibers on electrical conductivity has not been well established.

2.5.10 <u>Shrinkage and Shrinkage Cracking of SFRC</u>

- Strength properties form only one aspect of structural design. Other engineering benefits of incorporating fibers in concrete need to be considered if the use of fiber reinforcement is to be encouraged. Drying shrinkage is an inherent property of all concrete materials; associated with this phenomenon is the development of internal stresses due to differential moisture gradients and the resulting incidence of cracking. Cracking behavior is also often further aggravated by the restraints, internal or external, imposed on free shrinkage.
- The addition of steel fibers to concrete imparts several beneficial effects to counteract the effects of movements arising from volume changes taking place in concrete, particularly in the early stages of its life. Fibers exercise an additional restraint to drying shrinkage. In fiber concrete, the fiber volume is very low compared to the aggregate volume, and the

matrix tends to be slightly thicker than that in comparable normal concrete. Nevertheless. Fibers have a distinct beneficial influence in reducing shrinkage strains, and also tend to stabilize these movements earlier. If fibers are used largely to restrain movements alone, then these benefits can be further enhanced by using shorter fibers, because of the larger number of fibers available in a given volume.

- Reduction of drying shrinkage strains is only one aspect of the role of fibers in concrete. Fibers also control shrinkage cracking: they delay the formation of the first crack, enable the concrete to accommodate more than one crack, reduce the crack widths substantially and continue to sustain the shrinkage stresses for up 12 months.
- When one considers the overall durability of bridge decks, control of shrinkage cracking is a significant contribution to their preservation of durability. Shrinkage cracking is only one aspect of the spectrum of cracking behavior; but it does occur in the early life of a structure and together with load and temperature induced cracking, can lead to steel corrosion. The presence of fibers can, thus, be a significant beneficial factor to add to the serviceability life of bridge structures. The following observations can be made regarding the shrinkage behavior of steel fiber reinforced composites.
- The fiber addition decreases the shrinkage strain. An increase in fiber content can be expected to produce a consistent decrease in shrinkage.
- The shrinkage reduction provided by fibers is the maximum for cement paste, followed by mortar, rich mixtures containing more cement, and lean mixtures containing less cement.
- The differences among fiber types tested are not significant. The types tested include crimped, surface-deformed, hooked-end, paddle, and melt-extracted fibers.
- The contribution of fibers becomes more pronounced at later ages of drying shrinkage. The shrinkage process also stabilizes faster for fiber composites compared to plain matrices.
- Age (time of initial measurement), size (surface-volume ratio), and curing conditions have the same effect on both plain and fiber reinforced composites.

2.5.11 Effects of Fiber Type and Volume Fraction on Toughness

- For a given fiber type, a higher volume fraction provides more energy absorbing capacity or toughness as long as the fibers can be properly mixed and the composite can be cast and compacted properly. This result should be expected because more fibers provide more resistance, especially in the tension zone.

- For a given fiber geometry, longer fibers typically provide greater toughness. The effect is predominant in the case of straight smooth fibers. For deformed fibers, the mechanical deformations provide more anchorage and therefore the length/diameter ratio is less influential compared with straight fibers. For a given fiber volume and length, deformed fibers provide better toughness. Fibers with end anchorage provide the best performance.

2.5.12 <u>Corrosion of Steel Fibers.</u>

- When using steel fibers in concrete, attention has to be given to the question of corrosion of the fibers. As the steel volume locally is very small when fibers are used, only limited expansion forces develop due to the corrosion and normally no spalling occurs. Steel fibers in the immediate surface layer rapidly corrode to the depth of surface carbonation, which might however give aesthetical defects in the form of rust coloured surfaces. The loss of contribution to the strength of a corroded fiber has also to be considered.
- In most applications, low carbon, plain steel fibers are used. Steel fibers are less susceptible to corrosion as they are electrically discontinuous.
- Steel fibers are protected from corrosion by the alkaline Portland cement environment and are apparently not subjected to galvanic cell corrosion effects due to the fact that they are present as discrete non-continuous fibers. Corrosion of steel fibers even in the severe exposure of marine tidal zones appears to be limited to those fibers exposed at or within 1 mm of the surface. However, in the post cracking state, when corrosive environments can penetrate cracks, corrosion may occur on exposed fibers. Thus fibers bridging cracks under post ultimate strain conditions must be expected to exhibit reduced service life.
- Carbonation also appears to adversely affect corrosion resistance of steel fibers and surface staining is the by-product result. However the near surface corrosion is not accompanied by matrix disruption from expansive pressures caused by the products of corrosion.
- In crack-free concrete, the corrosion of fibers is limited to surface skin of the concrete. In situations where carbonation occurs, the corrosion was found to occur up to the depth of carbonation. The performance of uncracked FRC beams was studied by placing 4x4x84 in beams in a tidal zone. The bottoms of the specimens were immersed in seawater and the tops exposed to air at all times. The middle part was subjected to wetting and drying by tidal waves. The concrete had a cement content of 983 Ib/yd^3 and a water-cement

ratio of 0.51. The fiber content was 270 Ib/yd^3. After the exposure period of 2.5, 5.0 and 10.0 years, the beams were cut into six sections and evaluated for carbonation, chloride penetration, fiber corrosion, and flexural strength variation.

- The average flexural strengths were 1700, 1800, and 1700 psi after 2.5, 5.0, and 10.0 years of exposure, indicating no loss of flexural strength.
- The carbonation depth was about 0.04 in after 5 years of exposure. After 10 years of exposure, the carbonation depth was 0.04 in at the immersed sections, 0.06 to 0.08 in at the tidal zone sections, and up to 0.12 in at the sections exposed to air. In all instances, the corrosion of fibers was limited to the carbonation depth.
- Chloride ion penetration does not affect the fiber corrosion. Even in section with high chloride ion concentration, fibers were not corroded. This is explainable because the chloride ion concentration gradient, rather than the amount of ions, was found to cause corrosion in metals. Within the fiber length, there may not be sufficient ion gradient to cause corrosion.
- Surface staining was found to occur in the first month. Staining was found to be independent of the cover (provided by the concrete) or amount of fibers nears the surface.
- The fibers were found to be corrosion – resistant even in mixes with a relatively high water-cement ratio. Tests of FRC beams made using 725/Ib/yd^3 cement and a water cement ratio of 0.58 after 2000 cycles of marine water spray indicated that fibers are fully effective. The load – deflection curves of flexural specimens indicated that both strength and ductility (toughness) characteristics are fully retained. The fibers used in this case were either stainless steel melt extract fibers or corrosion-resistant fibers at a volume fraction of 3% and 2.2% respectively
- The corrosion of fibers could be more intense if the concrete is cracked. Studies have been conducted by exposing cracked FRC beams to a chloride environment. An earlier study indicated that fibers bridging the crack do not corrode if crack widths are less than 0.004 in. A more recent investigation shows that the permissible crack widths could be as high as 0.006 in and 0.008 in for low carbon steel fibers and melt extract fibers respectively. This conclusion was based on the strength and toughness test results of FRC beams exposed to wetting-and- drying marine cycles. Corrosion process is shown in fig 2.10.

2.6 Incorporation of Fly Ash and Silica Fume in SFRC

Fly ash and silica fume are the two pozzolanic materials which have been established in the recent years as commonly used mineral admixtures. They are capable of providing plain and fiber reinforced concrete with distinct performance advantages. Fly ash and silica fume also have their differences. Silica fume is distinguished from fly ash by its fineness, high pozzolanic reactivity and high silica content. The effects of the two pozzolanic materials on fresh mix workability are also different, while fly ash tends to improve workability; the reverse is only true in the case of silica fume. Let’s discuss fly ash and silica fume one by one:-

- **Fly Ash**
    - Substitution of cement with fly ash in steel fiber reinforced concrete mixes has positive effects on the workability of fresh mix.
    - The 28-day flexural strength and energy absorption capacity of steel fiber reinforced concrete tends to increase with increasing fly ash-binder ratio up to about30%. The increase in fly ash–binder ratio from 30 to 40%, however, adversely influences the flexural performance of steel fiber reinforced concrete.
    - Substitution of up to 20% of cement with fly ash in steel fiber reinforced concrete mixes results in improved 28-day compressive strength and energy absorption capacity of the material. Higher fly ash contents, however, start to have adverse effects on compressive characteristics.
    - The increase in fly ash content leads to some reductions in the air content of steel fiber reinforced concrete mixture.
    - Substitution of more than 20% of cement with fly ash tends to reduce the rate of compressive strength development in steel fiber reinforced concrete.
- **Silica Fume**
    - The compact ability of steel fiber reinforced concrete is not much influenced by the increase in silica fume-binder ratio up to a value of about 10%. Higher silica fume contents, however, adversely influence the workability of fresh mix.
    - The flexural strength and energy absorption capacity of steel fiber reinforced concrete tend to increase with increasing silica fume binder ratio up to a value of about 10%, beyond which the effects of silica fume on these aspects of the hardened material behavior tend to be reversed.

- The compressive strength and energy absorption capacity of steel fiber reinforced concrete tends to increase with increasing silica fume-binder ratio of 10%. Further increase in silica fume content has relatively small effects on the compressive behavior of steel fiber reinforced concrete.
- For the steel fiber reinforced concrete mixes, substitution of 10% of cement with silica fume gives the best results as far as the workability of fresh mix and the strength and energy absorption capacity of the hardened material under the action of flexural and compressive loads are concerned.

2.7 Steel Fiber Reinforced Shot Crete (SFRS)

SFRS is probably the major application for steel fibers throughout the world. Shot Crete has become a widely used material for rock support in history. In the beginning it was used without any reinforcement at good rock conditions. Later on it was also used in combination with mesh reinforcement at more deficient rock conditions. Now it is possible to replace the mesh reinforcement with steel fibers. This joins the shotcreting and the reinforcing work because it takes place in the same operation and at the same time.

The placing of steel wire mesh on uneven rock surfaces is difficult, costly and in some cases connected with great risks. Also in repair, the installation of normal reinforcement is troublesome and often results in undesired thick repair layers. It was in the early 1970s that first experimental work was undertaken with SFRS and a few years later, it rapidly gained interest, initially for slope stabilization, mining and in not too demanding repair situations.

Most of the early research on steel fiber reinforced shot Crete was conducted using relatively high fiber loading and using steel fibers of relatively small diameter and relatively high aspect ratios. Later research showed that by using hooked fibers with a high equivalent aspect ratio, considerably smaller fiber quantities can be used to achieve the same strength characteristics.

Since then SFRS has been extensively and successfully used in tunnel linings, slope stabilization works, culverts, sewers, dams, canals, swimming pools and reservoirs. Other major uses of fibrous Shot Crete are in repair and rehabilitation of marine, highway, railway and other structures. In spite of its widespread use, only a limited research activity has so far taken place to develop a fundamental understanding of fiber reinforced shot Crete.

Mixing

Shot Crete properties allow it to be blown or shot on surfaces (thus, the name 'shot' crete). It is generally applied drier than concrete since it needs to remain where it is applied. Shot Crete may be divided into two broad categories: dry-mix and wet-mix. Fortunately, no special changes need to be made to conventional shot Crete mix designs in order to use steel fibers.

In the dry-mix process, the ingredients (cement, aggregates and admixtures) are pumped through a conveyer tube in the dry state and water is added at the nozzle just before shooting on a formerly prepared surface. In the wet-mix process all ingredients including water are premixed before shooting. Wet shot Crete is preferred but dry Shot Crete is still used for small scale remedial work in the mining industry for example and a number of pre-bagged steel fiber reinforced mixed have been developed. One of the big advantages of wet-process shotcreting is the low rebound that is experienced between 5 and 10 percent by weight, while in the dry process rebound can be as high as 50 percent.

Higher cement content, more fines in the mixture, smaller maximum size aggregate, proper moisture content of the aggregate, a finer gradation, and inclusion of fly ash or silica fume are reducing factors for rebound. The difficult part with the wet process is to get a pump able mix with a consistence, which without accelerator can be Shot Creted on an overhead or vertical surface to an acceptable thickness and with high capacity.

SFRS in Tunnel Linings

Design considerations for shot Crete linings include: thickness, strength, reinforcement, ductility, time and locations of SFRS applications, and use of other support elements. It was found that the adhesion between rock and the shot Crete plays a determining role for the strength of the lining, unless other support is arranged, e.g. systematic rock bolting.SFRS is a practical and interesting technique for protecting, repairing or strengthening existing tunnels. A homogeneous and equally thick SFRS layer, with a limited thickness, can be applied on the cleaned existing tunnel surface.

2.8 Factors Inhibiting the Widespread Use of SFRC

Two factors have tended to inhibit the widespread use of steel fibers in reinforced and pre- stressed concrete structures. One is the inherent difficulties of mixing, placing and compacting satisfactorily, concrete containing short discrete fibers in forms which may be congested with conventional steel reinforcement. The second is the inevitable fear of steel corrosion, which in time could deprive the structural member of its enhanced structural properties assumed in design. Fortunately both these problems have been satisfactorily solved. It is now possible to produce steel fibre concrete with adequate flow characteristics or pumping qualities, and there is evidence that fiber corrosion does not in fact occur in practice. Further stainless steel fibers and copper coated steel fibers which are totally immune to corrosion, are also now available which would have negligible economic impact to the cost of the structure as a whole.

Therefore, now it is possible to design and construct concrete structures incorporating steel fibers without fear of loss of serviceability life or of their major structural characteristics and also overcoming the difficulties of mixing, placing and compacting.

2.9 Performance Study of a Few SFRC Pavements Around the World

Fiber – reinforced concrete has been used to produce both overlays and full-depth slabs for airport pavements. The overlay application is more popular than the full-depth slab applications. Let's discuss a few SFRC pavements around the world

The performance of two experimental sections of fibrous – concrete pavement was studied by the Waterways Experiment Station June 1970 – March 1971. The slabs were intended to carry heavy, wheeled loads such as a Boeing 747.

Two SFRC slabs were cast on a concrete base of 9-in. thickness. A 6 in. thick, 35 x 46 ft slab was placed as paving apron and a 6 in. thick, 5x22 ft slab was cast for use as a taxiway. Steel fibers that were used were 0.010 x 0.022 x 1-in. Polyethylene sheet placed on the base, thus producing an un bonded 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.

An 8 in. thick, 20 x 30 ft steel fiber – reinforced concrete slab was cast near the gate area used by Boeing 747 aircraft. The SFRC slab was cast adjacent to a 12 in. 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.

One of the first uses of SFRC for a bridge deck overlay was on a precast bridge in Winona. The 2.5 to 4.0 in. overlay was placed on a severely deteriorated precast deck after removing the surface scale to a depth of 1.5 in. The fiber content was 200 Ib/yd^3 .The overlay was reported to be in good condition in spite of deicing salts and studded tires.

SFRC was used to replace asphalt overlays on a steel truss bridge that was 155 ft long and 40 ft wide. The overlay, which was 2 to 5 in thick, consisted of concrete containing 200 Ib/yd3 straight steel fibers. The fibers were 1 in long and 0.01 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 1994 in spite of the heavy traffic involving about 13,700 vehicles per day.

2.10 Economical Benefits of Using SFRC

Steel fiber reinforced concrete (SFRC) has been used in a diverse range of applications since its commercial debut in 1970. The addition of this discontinuous steel fiber reinforcement to concrete enhances many of the properties in the hardened composite. The most significant property is to make concrete, a very brittle material, ductile. This ductility is exemplified by fracture toughness, dynamic and thermal shock control, and crack and spall resistance. It is in applications, which exploit many of the above properties while simultaneously taking advantage of materials and labour saving.

There are many parameters that enter the economic consideration for fiber reinforced concrete products. Since we are talking about fiber reinforcement, let’s first consider the fiber itself. The cost of this addition is of the utmost importance. In fiber economics we must consider the following parameters:-

- Type of fiber
- The source of manufacturing and
- The performance offered

The design concept must take into account the desired results. When the concrete must be designed for a machine base, two factors must be considered, impact resistance and fatigue life. These two factors are provided by SFRC and it can easily be the most cost effective.

The slab thickness is reduced to half by addition of fibers. Two major strengthening factors allow us to consider such a drastic reduction in slab thickness. One is the primary increase in flexural strengths of the concrete. This flexural strength is easily increased by factor of 1.5 to 2. The other major factor is the endurance limit of the concrete. The increased endurance limit of the fiber reinforced concrete is as high as 90% of the first crack strength while the endurance limit of a normally reinforced concrete is considered only 50% of the initial cracking strength. Flexural strengths allow the reduction of the slab on grade to one-half the thickness. Therefore, with simple arithmetic, if steel fibers cost less than one cubic yard of concrete there will be a cost savings in the materials used. Besides the cost savings of materials, we would then realize also cost savings in placing standard reinforcements.

One design consideration is whether to go for new construction or an overlay. The first major production overlay was an overlay of a parking ramp at Las Vegas International Airport. The overlay ramp was 45 x 600 feet. The design performed by the Corps of Engineers called for 15" of concrete. The controlling economic factor at this point was substantial thickness of pavement required. Since other overlays had previously been made in this parking ramp, the terminal building was now 6" below grade, and 15"additional to be added, would be 21" below grade. By selecting a steel fiber reinforced concrete overlay at only 6" thickness, the rate of grade change of the terminal was substantially slowed. The same consideration will face many more airport engineers in the future. With many of the national airport primary runways and taxiways deteriorating rapidly under the heavy loadings of the new jets, overlays are going to be required. Talking with airport engineers, they feel that an overlay of normal concrete would require as much as 12". Again the primary economic consideration is the change in grade. It is the opinion of most of these engineers that a 12" grade change will require a change in drainage systems and lighting systems. While if steel fibrous concrete is used and a change in grade of only 4"-6" might occur there would be no requirement for changing drainage and lighting systems. With the present cost of concrete the fiber concrete overlay can be cheaper than conventional overlays.

In 1979, Las Vegas placed 18 acres of new airport paving construction for a parking ramp for the international arrivals building. Originally designed for 15" thick concrete over a 2 in asphalt leveling layer over 12" crushed stone base, the design was revised to 7" SFRC over the 2" leveling layer and 12" gravel base. The Nevada officials estimated the cost of the fibrous concrete at $22 per square yard. (This construction cost included surface finishing, saw cutting, and joint fitting).

The cost of the fibrous concrete per cubic yard was $113 ($148.68 per cubic meter) compared to $60 per cubic yard ($78.95 per cubic meter) for conventional concrete. However, less than one-half as much fibrous concrete was required as would have been needed using conventional concrete. Therefore, the cost of using the superior fibrous concrete was approximately the same as would have been the cost of using conventional concrete.

By using fibrous concrete, additional cost savings are achieved during construction operations by being able to lay thinner concrete sections over variations which occur in the grade of any surface and by eliminating the need for forms to shape the edges of the concrete.

The largest cost advantage will be realized at McCarran Airport through the minimum maintenance which will be needed for the fibrous concrete ramp surface as compared to the costs which would have been incurred for maintaining a conventional concrete ramp.

The gunning of concrete has always been an economical placement method for various types of construction. However, it has even become more economical with the advent of steel fiber reinforcement. In 1985, 30% of the 5,000 tons of steel fibers used in Japan went to Shot Crete applications. Not only can concrete be sprayed into place, but in this case the reinforcement can be sprayed along with it, substantially reinforcing materials. An application showing the greatest economical advantage has been slope stabilization. The past technique has been to drive pins into the slope and tie wire mesh to these pins and then spray concrete on the mesh to thickness a minimum of 6” and a maximum of 9” to ensure coverage of the mesh. On an irregular surface, where the mesh cannot get down into the low spots, the thickness of the concrete may even run to greater depths.

2.11 Codes

The various national Building Codes and Codes of Practice do not as yet recognize the benefits that fibers can bring to concrete and concrete structures, even though these benefits are well known at least within the research community. In reality, until the Building Codes accept, at least in part, the principles of fracture mechanics (in which failure prediction is based on the concept of fracture energy), fibers are unlikely to be used as effectively as they should be in concrete structures.

Table 2.1: Properties of Artificial Fibers

Fiber	Sp. Gravity	Tensile Str. (Ksi)	Youngs Modulus (1000 Ksi)	Elongation At Failure.	Volume Fraction	Common Dia (In)	Common Length (In)
STEEL	7.86	50-300	30	30	1-3	0.0005-0.04	0.5-2.5
GLASS	2.7	Upto 180	11	3.5	2-8	0.004-0.03	0.5-1.5
PLASTIC	1.6	Upto 100	0.14-1.2	25	1-3	Upto 0.1	0.5-1.5
CARBON	1.6	Upto 100	Upto 7.2	1.4	1-5	0.0004 -0.0008	0.02-0.5

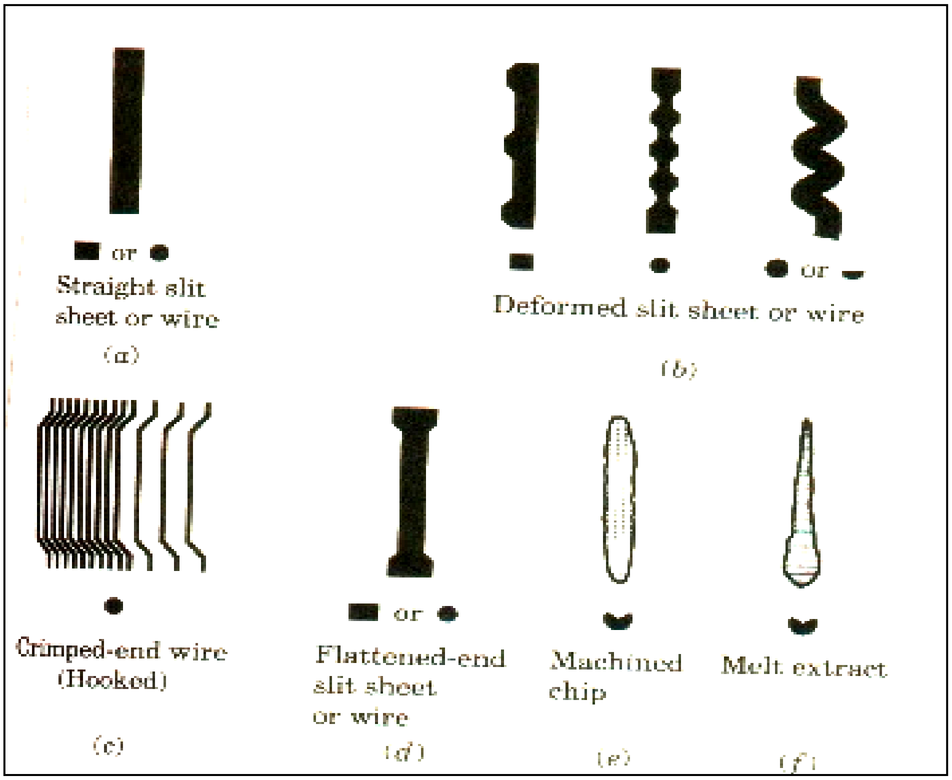

Fig 2.1: Different Shapes of Steel Fibers

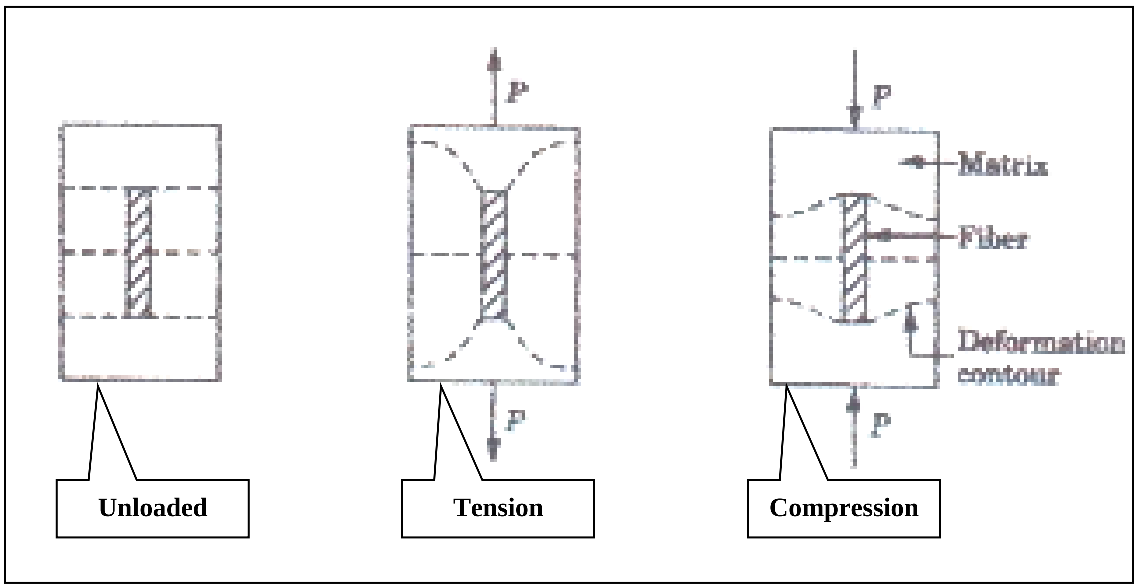

Fig 2.2: Fiber- Uncracked Matrix Interaction

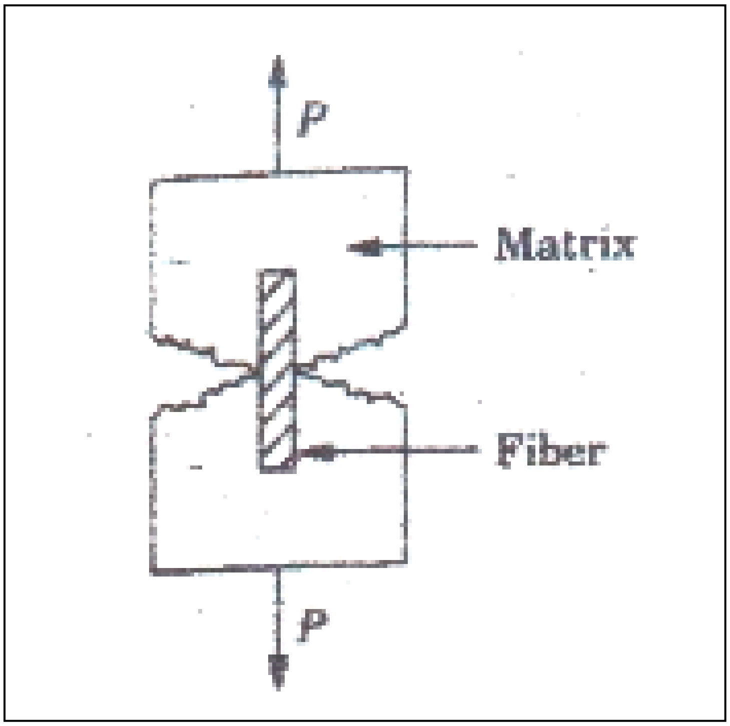

Fig 2.3: Fiber – Cracked Matrix Interaction

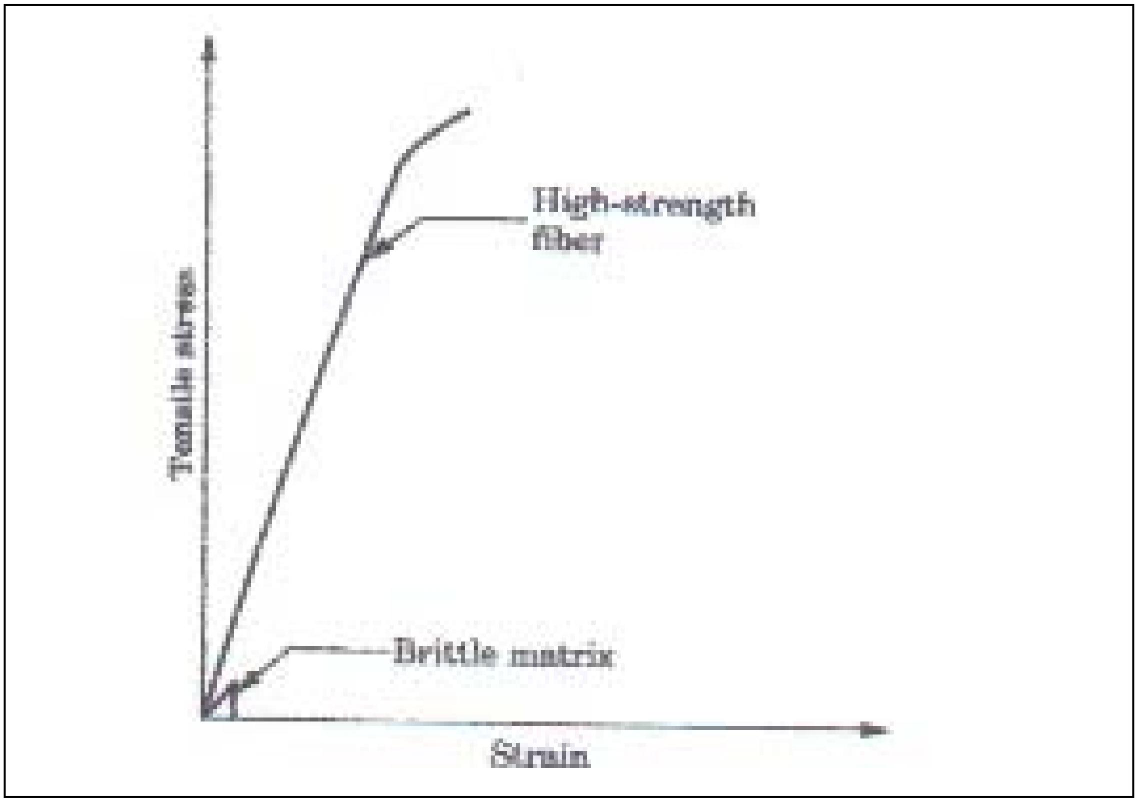

Fig 2.4: Tensile Stress-Strain Curve for Fibers with a Brittle Matrix

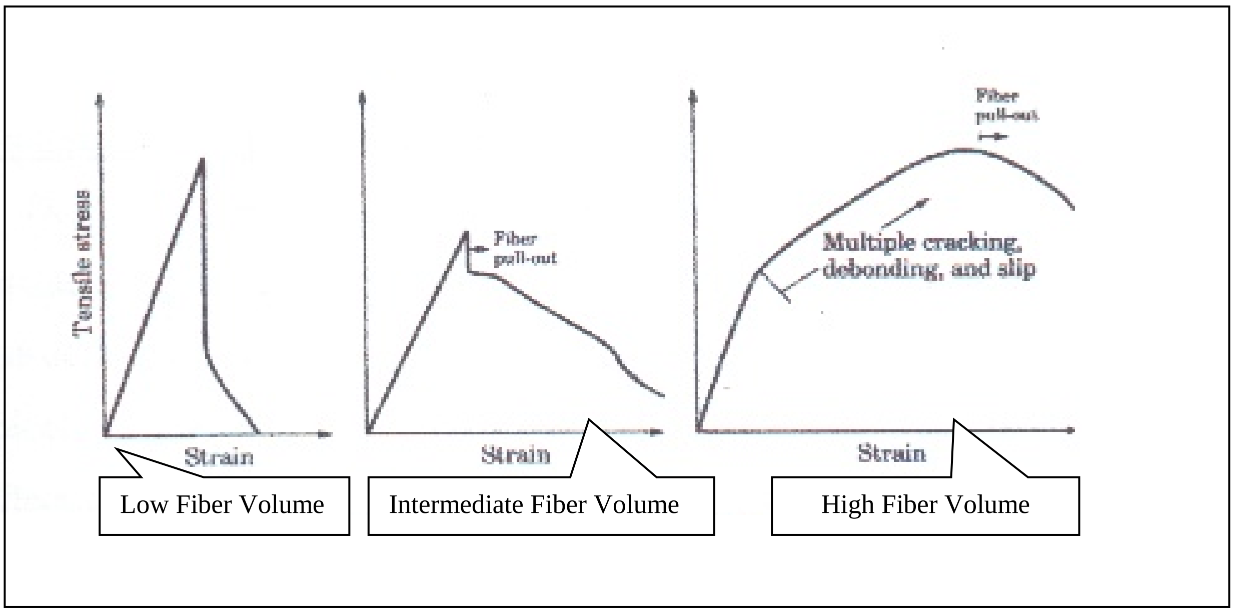

Fig 2.5: Composite Stress-Strain Curve for Fiber Reinforced Brittle Matrix

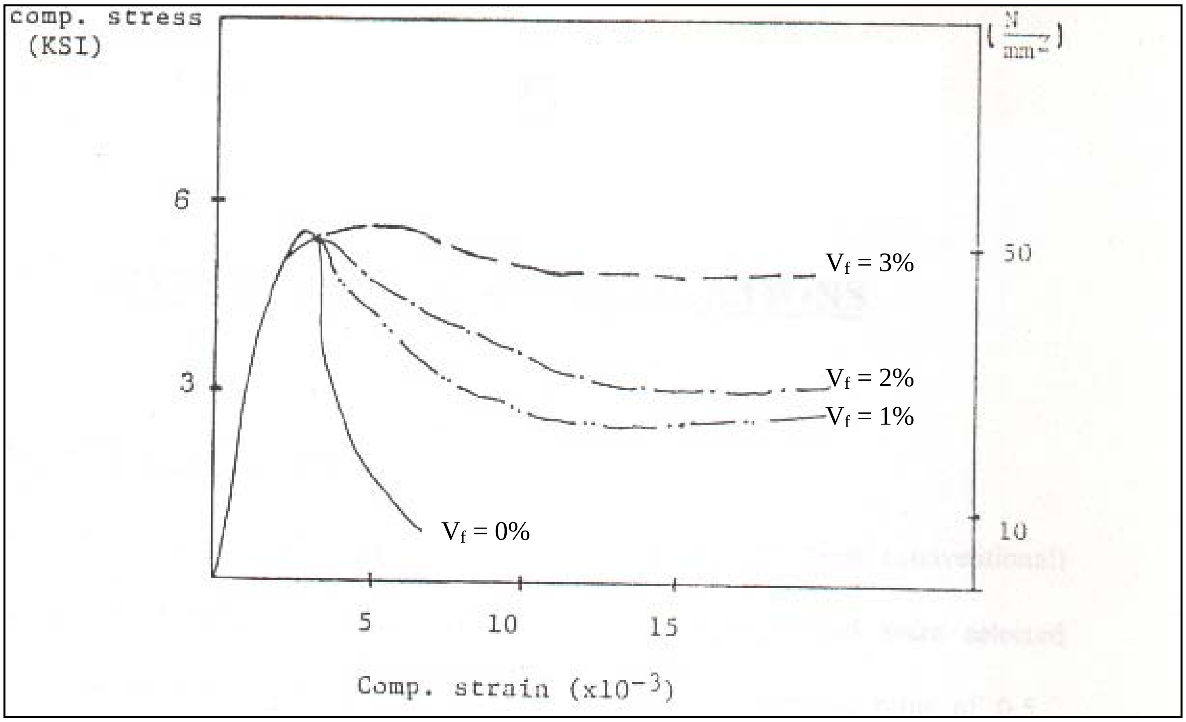

Fig 2.6: Compressive Stress-Strain Relationship

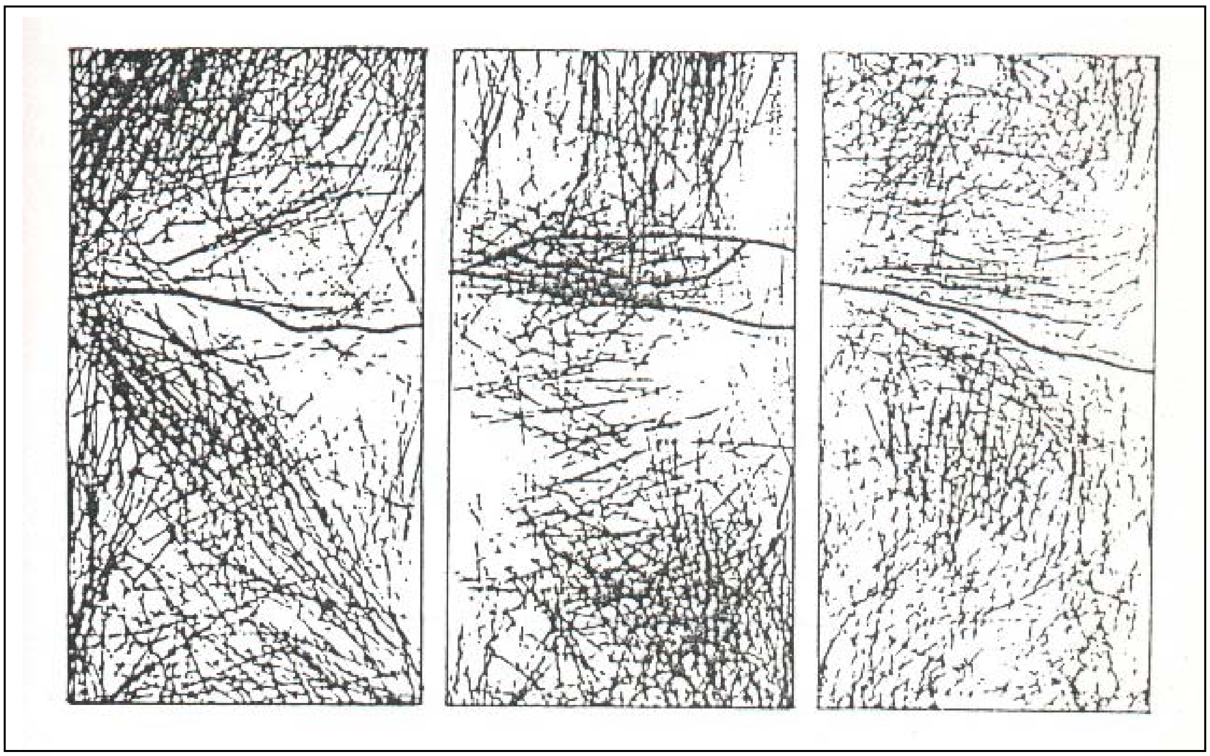

Fig 2.7: Cracking at the Weakest Section in Uniaxial Tension

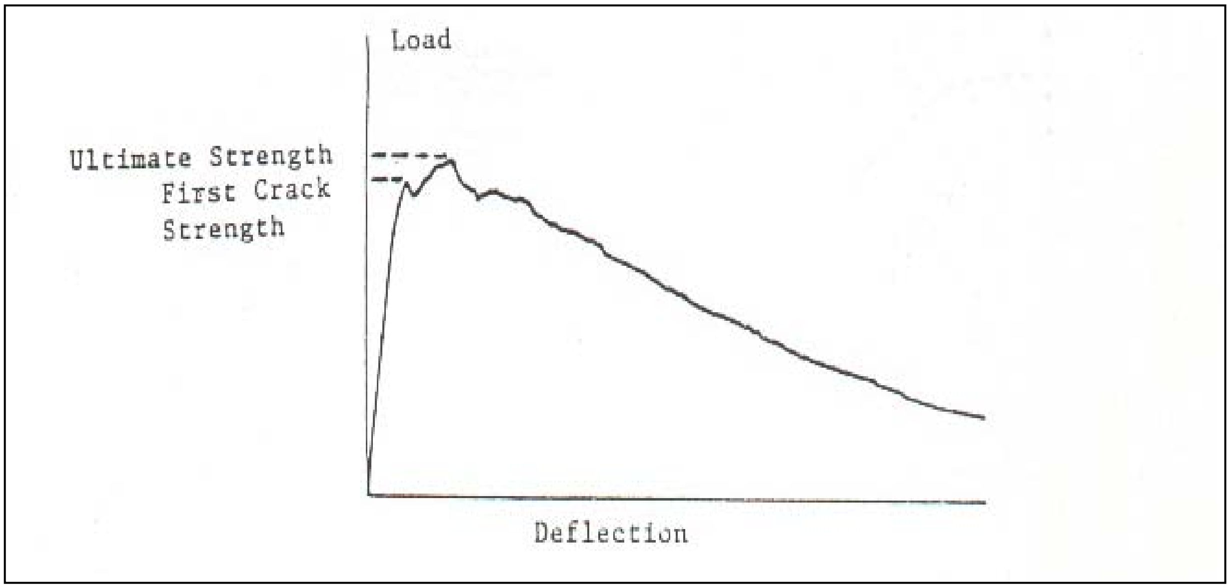

Fig 2.8: Flexural Load – Deflection Diagram

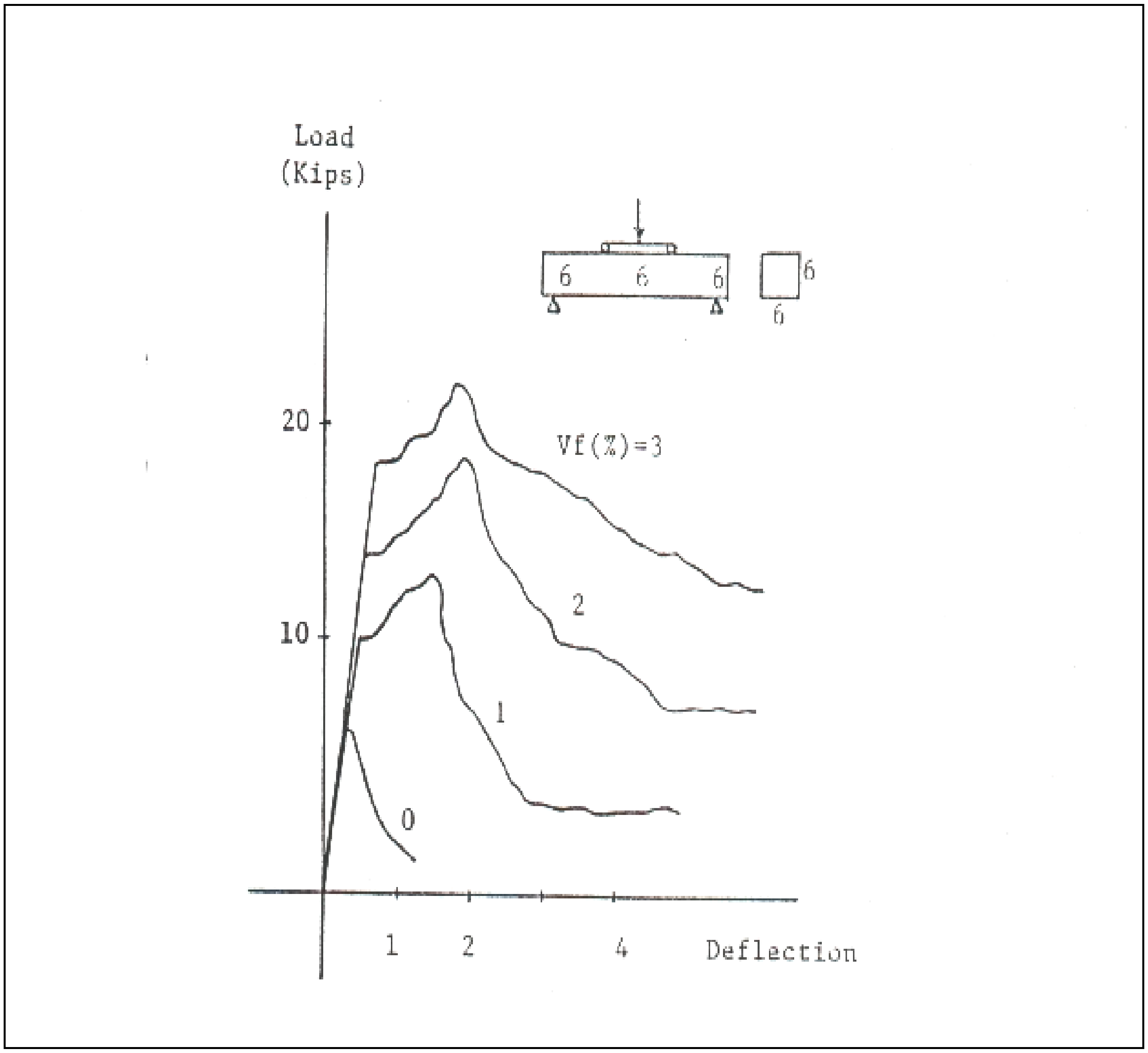

Fig 2.9: Load Deflection Curve at Different Volume Fractions of Steel Fibers

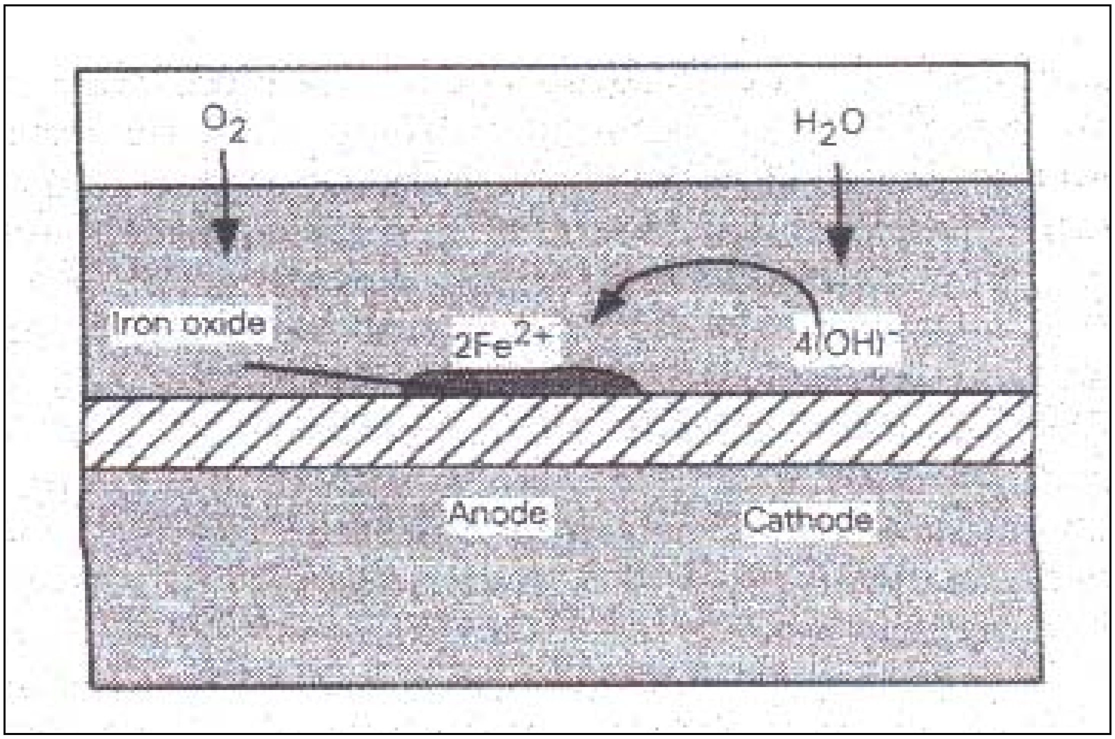

Fig 2.10: Corrosion Process of Steel Fibers

CHAPTER-III

EXPERIMENTATION DETAILS & TEST PROCEDURES

3.1 General

Two major components of fiber-reinforced concrete are the matrix and the fiber. The matrix generally consists of port land comment, fine aggregate (Sand) and coarse aggregate (Crush) and the fibers used in this investigations are metallic. The properties of concrete will primarily depend on the properties of its constituent materials. Therefore it is important to perform specified acceptance tests on the constituent materials to determine their properties in the laboratory. Each constituent material along with the tests performed is discussed in the succeeding paragraphs: -

3.1.1 **Cement**. The most commonly used cement is the normal Portland cement designated as Type-1 by ASTM. Other cement types commercially available include high early strength cement, low heat of hydration cement and sulphate resistant cement. All these cements can be used to produce fiber reinforced concrete. The type of structure, rate of strength development needed and exposure conditions dictate the type of cement to be selected. Normal Portland cement (Type-I) from cherat cement factory has been selected for incorporation in this research work.

➢ **Testing of Cement**. Following tests were performed on cement: -

- **Setting Time**. Setting time tests are performed to determine if the cement paste remains plastic long enough to permit normal placing of concrete without hampering finishing operations. According to ASTM C-191, 92, the range of initial and final setting time is from 45 to 600 minutes. Setting time of cement was determined by using Vicat apparatus. Initial setting time was found to be 230 minutes and the final setting time was 550 minutes, which are well with in the specified limits.
- **Fineness**. Fineness of cement affects the rate of hydration. Higher cement fineness increases the rate at which cement hydrates and thus accelerates the rate of strength development. The cement sample was sieved through No 200 sieve and the weight retained was found to be 0.6 % of the weight of cement sample. It is less than 10% as specified by ASTM C 184-76.

- **Soundness.** Soundness of a hardened cement paste is its ability to retain its volume after setting. Soundness test on cement sample was carried out by Le-chatlier apparatus for finding the expansion of the cement in accordance with BS - 4550: Part 3: Section 3.7. The expansion was found to be 2.9 mm which is less than the maximum specified limit of `10 mm.
- **Specific Gravity**. The specific gravity of cement is not an indication of its quality. Its principle use is only in mix design calculations. To determine the specific gravity of cement sample, procedure as laid down in ASTM C 188 was followed, according to which, the range of specific gravity of type-1 cements is 3.1 to 3.15. Lechattlier flask and kerosene oil free from moisture was used and specific gravity of cement was found to be 3.12, which is within the specified limits.
- **Compressive Strength**. Compressive strength test is the final check on the quality of cement. This test is performed to determine whether the cement conforms to standard specifications or not. The compressive strength is measured by determing the compressive strength of cement mortar, of 1 part of cement to 3 parts of sand, confirming to British Standards.Compressive strength of cement was determined according to BS - 4550: Part 3: section 3.4 and the results obtained meet the specified requirements of the relevant standards. Test results of cement are summarized in Table 3.1

3.1.2 **Fine Aggregate**. Lawrncepur sand was selected for use in this research work. The sand possesses no plasticity or cohesion and is siliceous in composition having round and angular particles.

- **Testing of Fine aggregate.** Following tests were performed on fine aggregate: -

- **Sieve Analysis**. Sieve analysis is carried out to determine the grain size distribution, hence the Fineness Modulus. Fineness Modulus indicates relative fineness of aggregate. It is an empirical number used to classify the aggregate and normally used for fine aggregate only. Values vary from 2.3 to 3.1.Coarser the sand, higher the number. Sieve analysis of sand was carried out according to BS 882: 1973. The fineness modulus of sand was 2.69, thereby indicating coarser sand. The results of sieve analysis are shown in table 3.4 and the grading curve is shown in fig 3.1.
- **Specific Gravity and Absorption**. The bulk specific gravity (oven dry) was determined according to ASTM C 128-79 and was found to be 2.41. The absorption after 24 hours

immersion in water was 1.2%. Results of various tests conducted on fine aggregate are given in table 3.2.

3.1.3 Coarse Aggregate

Aggregates suitable for plain concrete are suitable for SFRC. Coarse aggregates can be normal weight, lightweight or heavy weight in nature. The coarse aggregate selected for this research was Margalla Crush, being a major supply in this region. Source is located in Margalla hills near Islamabad. Parent rock can be classified as Lime stone, it is sedimentary rock comprising of 50% carbonate, of which silicate is the main contributent. The aggregate is durable and sufficiently strong to enable the full strength of cement matrix to be developed. Surface texture of aggregate was mainly rough. Maximum size of coarse aggregate used was ½".

- **Testing of Coarse Aggregate**. Following tests were carried out on coarse aggregate to ascertain its suitability.
- **Grading.** Grading or particle size distribution of aggregates is determined by sieve analysis. Sieve analysis of the course aggregate was carried out as per the procedure laid down in BS and the results are shown in table 3.5. Grading curve for the coarse aggregate is shown in figure 3.2. The grading of coarse aggregate selected is well within the specified boundaries.
- **Specific Gravity and Absorption**. All the aggregates are porous with a varying degree and accordingly differ in specific gravity and absorption. Weaker stones have lower specific gravity and high absorption. These two parameters are the basic indicators of the quality of aggregate and form the basis for acceptance or rejection. Normal range of specific gravity for coarse aggregate is between 2.4 to 2.9. Water absorption is a measure of porosity. Porosity of coarse aggregate effects very important properties of concrete such as permeability, absorption, resistance to freeze – thaw, resistance to abrasion and chemical stability. More porous aggregate will absorb more water in specified time (24 hours). Range of absorption values can vary from 0 to 8%. Good aggregates normally have a value less than 1%. The specific gravity and absorption of course aggregate was found by the method given in ASTM C 127-81.Specific gravity was found to be 2.63 and absorption as 0.85%, which are within the specified range.

- **Crushing Value**. Crushing value was determined according to BS 812-1967 and was found to be 22.3, which is a good indicative of coarse aggregate. Results of various tests conducted on coarse aggregate are presented in table 3.3.

3.1.4 **Water.** Fresh potable water from Nowshera was used in this research work. Water was clean and free from injurious amounts of oil, acids, salts, organic materials or other substances deleterious to concrete.

3.1.5 **Fibers.** Extensive efforts were made to procure steel fibers. Initially the local markets at Peshawar, Rawalpindi, Lahore and Karachi were explored but all in vein. A no of importing agencies and individuals were contacted for the purpose. To name a few, Sika at Rawalpindi, an importer at Karachi and three parties involved in export/import, stationed at Dubai were contacted many a times. Sika showed its inability to provide the material. However, two Parties at Dubai agreed to provide the steel fibers but two factors hindered the process to be fulfilled.

- Shipping of material was to take about 4 to 6 months.
- Cost of fibers was in the range of $7.5 to 10 / Ib. Total requirement of the steel fiber was approximately 170 lbs. Transportation by air was further expensive.

In view of the above situation, it was decided to look for alternatives in local markets. After some investigations, MS wire available in rolls was selected for detailed investigations.

- **Converting Rolls into Fibers**. The difficult part of this research was how to convert steel rolls into the fibers of varying lengths and the provision of end conditions. The wire was cut with the help of a mechanical cutter and then manually converted into three different end conditions as shown in figure 3.3. A colossal effort was required. "Z" type end conditions provided better result in laboratory testing.

  Properties of Steel Fiber are:-

  Dia 0.62 mm

  Tensile Strength 65 Ksi

  Carbon Content 0.09 %

3.2 **Trial Mix Proportions.** Five trial mixes, varying the basic constituents of matrix but keeping the fiber content as constant, were prepared as shown in table 3.6. Water to cementitious material ratio was kept as 0.55 for all mixes. Samples were casted and tested for compression and flexure at 7 days. As shown in table 3.6, Mix no.4, having more fines gave the best results and was selected for detailed investigation.

3.3 **Aspect Ratio (L/d)**. Aspect ratio is simply a numerical number achieved by dividing the length of the fibers by the diameter of the same fiber. This is an indicative of the surface area of the fibers available in the matrix for bond. Aspect ratio plays a very significant rule when straight smooth fibers are used as increased aspect ratio (L/d) provides additional anchorage to fibers and a restraint against fiber pull out. Role of aspect ratio (L/d) in case of deformed and hooked fibers is not very pronounced.

3.4 **Concrete Testing**. Concrete mix selected from trial mix proportions was investigated in details, varying the fiber contents as well as the aspect ratio (L/d). A variable dosage of 60 to 100 lb/yds^3 was used in fabrication of steel fiber reinforced concrete. Six mixtures were prepared, details of which are shown in table 3.7.

After the mix no.4 was selected, it was investigated for fibers end conditions and "Z" shape gave the best results. Different fiber shapes experimented in the laboratory are shown in fig 3.3. So mix no.4 with "Z" shaped fibers was investigated in details.

3.4.1 **Test Specimens**. For the purpose of testing, following test specimens were casted:-

- Compression 6″ x 12″ Cylinders
- Split Cylinder 6″ x 12″ Cylinders
- Modulus of rupture 4″ x 4″ x 15″ Prisms
- Stress - Strain 6″ x 12″ Cylinders
- Impact resistance 6″ x 12″ Cylinders

3.4.2 **Batching Quantities**. The capacity of Pan Mixer available in the Concrete Laboratory was 1.6 ft3 of concrete. In one batch, concrete for six specimens of Cylinders was cast. To weigh fibers, a self-indicating balance of 100 gm capacity, capable of reading up to 1 gm was used.

3.4.3 **Mixing of fibers in Concrete**. The concrete ingredients were mixed in Pan Type Mixer. Coarse aggregate was first added, then Cement followed by sand. Dry constituent materials were thoroughly mixed for 1 min. The calculated quantity of water was then added to the Plain (Conventional) Concrete and mixed for about 1 min so as to produce homogenous concrete. The steel fibers were then added slowly and gradually to have uniform dispersion and to prevent balling. During the course of mixing of constituent materials, it was found that fiber quantity beyond 100 lbs/yd3 is not practicable as the fibers would not mix uniformly and balling was observed. Increased aspect ratio also had negative effects on even distribution of fibers in concrete. So it can be said that fibers with a volume fraction of 100 lbs/yd^3 with an aspect ratio of 75 is optimum.

3.4.4 **Casting and Curing**. The specimens were casted in steel moulds satisfying the dimensions as per ASTM standards. Used oil was used on the contact surface of the moulds to prevent adhesion of concrete with the contact surface. Specimens were placed on the vibratory table and concrete was poured in these specimens in three approximately equal layers. The time of vibration was kept between one to two minutes. Compaction by the use of tamping rod was not done, as tamping rod may displace the location of fibers which may result in to uneven distribution of fibers in concrete samples. The top surface of the mould was finished by means of a trowel. The moulded specimens were kept in the laboratory for twenty-four hours, after which the specimens were demoulded, marked and placed in the curing tank.

3.4.5 **Capping.** At the time of casting of specimens, all efforts were made to smooth the top surface of the cylinders with the help of trowel, but true plane surface was difficult to achieve. The uneven top surface results in non-uniform stress distribution, thus resulting in premature failure of specimens. In order to over come the problem of uneven top, capping procedure of ASTM C 617-87 was followed.

3.5 **Test Procdures**.

3.5.1 **Workability**. Workability of concrete is defined as the ease with which the concrete can be placed, compacted and finished. Steel fibers tend to reduce the workability of concrete mix, thus resulting in a harsh mix. Slump test is the standard method for determining the workability of concrete. Results of slump tests conducted on different mixes are given in chapter IV, table 4.3.

3.5.2 **Compressive Strength.** For determining the compression strength of specimens, ASTM standard lays down procedures which are internationally acceptable for quality control of concrete proportioning, mixing, placing operations; determination of compliance with specifications; control for evaluating effectiveness of admixtures and similar uses. This test method consists of applying a compressive axial load to mould cylinders or cores at a rate, which is with in a prescribed range until failure occurs. The compressive strength of the specimen is calculated by dividing the maximum load attained during the test by cross-section area of the specimen. Relevant ASTM specifications for making and testing of specimen are given below:-

- ASTM C 192 – 90. Practice for making and curing test samples in the laboratory.
- ASTM C 39-86. Compressive strength testing of cylindrical concrete specimens.
- ASTM C 617-87. Practice for capping cylindrical concrete specimens.
- ASTM C 470-87. Moulds for casting concrete test cylinders vertically.

3.5.3 **Testing of Specimen in Compression.** After moist curing for 7, 14 and 28 days, specimens were taken out of the curing tank and placed in the laboratory at normal conditions of temperature and moisture until their surface became dry. Then these specimens were put through following test.

- **Apparatus.** 200 Ton Compressive Testing Machine, 6" x 12" cylinders, Sulphur for capping.
- **Test Procedure.** For compressive strength, Cylinders were chosen instead of cubes because of their reliability. 6" x 12" size cylinders were tested for compressive strength in 200 Ton testing machine as per ASTM Standards C 39-86 and BS 1881: Part 4: 1970. The top surface obtained was not as finished as was required for testing, For remedial measures of this problem, Sulphur as Capping material was used. The thickness of capping material was kept in the range of 1.5-3 mm (1/16 to 1/8 in) as specified. Sulphur was applied in molten state and then allowed to harden. With the specimen in machine, load was applied at the rate of 1500 Psi/min without shock till failure of the specimen. An average of three specimens for each test was tested. Results are presented in chapter IV, table 4.4, 4.5.

3.5.4 **Tensile Strength**. There are two types of tension tests used for concrete, direct tension and splitting tension. In the former, specimens such as dog-bone shapes are subjected to axial tension. Such tests are rarely used in practice for concrete containing coarse aggregates. In the splitting tension test, which is more popular, a cylindrical specimen is subjected to a splitting tension along its axis. Cubes can also be used for this test.

- **Apparatus.** 200 Ton Testing Machine, Metallic & Wooden Strips.
- **Test Procedure.** Out of different Tension tests, Splitting test was adopted because it is not only simple to perform but also gives more uniform results. Strength obtained by splitting test is believed to be closer to the true tensile strength of concrete. Cylinders of 6" x 12" in size were tested for tensile strength as per ASTM C 496 – 86, in a 200 Ton testing machine. Cylinders were placed with the axis horizontal between the plates of testing machine. Firstly Plywood Strips and over them metallic strips were placed on concrete specimen. These were used as contact material between the cylinders and Platens to

overcome the effects of unevenness of cylinder surface. Load was applied continuously and without shock at a constant rate of 125 Psi/min. The load indicated by testing machine at the failure was recorded. During test, plates of testing machine were not allowed to rotate in a plane vertical to the axis of cylinder, but a slight movement in a vertical plane containing the axis was permitted in order to accommodate a possible non-parallelism of the generations of the cylinder. The splitting tensile strength is calculated as follow:-

fsp = 2P/(3.14 LD)

fsp = Splitting tensile strength

P = Maximum load applied

L = Length of specimen

D = Diameter of specimen

Results of split cylinder tests are presented in chapter IV, table 4.6, 4.7.

3.5.5 **Modulus of Rupture.**

Behavior under flexure is the most important aspect for FRC because in most practical applications the composite is subjected to some kind of bending load. Moreover, the addition of fibers improves the flexural toughness of plain concrete. The increase in flexural toughness provides the primary motive for using fibers in concrete.

Modulus of rupture, also known, as flexural tension is the theoretical maximum tensile stress reached in the bottom fiber of the test beam. ASTM Methods C - 192 and C - 31 describes the procedures for making flexural specimens and also cylinders for the modulus of rupture test in the laboratory and in the filed. ASTM Method C - 31 stipulates that the length of the beam should be 2” longer than three times its depth and that its width should not be more than one and half times its depth. The minimum depth or width should be at least three times the maximum size of coarse aggregate. A typical specimen used would be 4”x4”x15” and is tested using third-point loading. For calculation of modulus of rupture the requirement of ASTM Standard C 78-84 are similar to those of BS 1881: Part 4: 1970. If the fracture occurs within the central one third of the beam, the modulus of rupture is calculated on the basis of ordinary elastic theory and is therefore given as below: -

Fr = PL/(bd2), where

P = The maximum load on the beam

L = Span of the beam

b = Width of the beam

d = Depth of the beam

If the fracture occurs outside the load points, i.e. say at a distance “a’ from the near support, “a” being measured along the center line of the tension surface of the beam, then the modulus of rupture is measured in a different way.

During the testing of samples, all samples failed with a fracture in the middle one third of the bean. An average of three test specimens was tested for each type of concrete. Load was applied gradually without shock at a constant rate of 2 tons per min till failure of the specimen. Results of flexure tests are shown in chapter IV, table 4.8, 4.9.

3.5.6 **Compressive Stress - Strain Test.** Adding any fibers to a cementitious matrix produces a substantial change in its stress - strain response. A noticeable increase in strain at the peak stress and a significant increase in ductility generally characterize this change. The improvement in ductility obtained by fiber addition is comparable to that achieved by confining concrete with conventional transverse reinforcement.

- **Apparatus.** Strain Gauges, 200-Ton Compression Machine, 6" x 12" cylinders, sulphur for capping.
- **Test Procedure.** Strain tests were applied by first fitting the cylinder in the respective testing equipment, which includes a very delicate strain gauge. After fitting the cylinder in the gauges, it was put in the compression machine. Slowly and steadily the load on the specimen was increased, thus increasing the stress till the specimen failed. In the mean time the strain gauges were also noted down simultaneously. Load was applied even after the samples failed and strain noted corresponding to the load at that particular load.

  Results of stress – stain tests are shown in chapter IV, table 4.10, 4.11, 4.12, 4.13, 4.14 & 4.15.

3.5.7 **Impact Resistance Test**

The impact resistance of a material is represented by the number of times a standard size mass must be dropped a standard distance before cracking the specimen and causing it to separate into pieces. By definition, ultimate failure occurs when sufficient impact energy has been supplied to crack the material and cause its failure. The impact resistance of a material is related to its toughness and strain capacity.

Plain concrete, due to its brittle nature, has especially low impact resistance. A major contribution of fiber reinforcement is to significantly improve the impact resistance of the concrete matrix. Impact resistance of SFRC can be measured by using a number of different test methods. These methods can be broadly grouped into the following categories.

- Weighted pendulum Charpy type impact test
- Drop-weight test (single or repeated impact)
- Constant strain rate test
- Projectile impact test
- Split Hopkinson bar test
- Explosive test
- Instrumented pendulum impact test

The results from these tests should be interpreted very carefully because they depend on a number of factors including specimen geometry, loading configuration, loading rate and test system compliance.

- **Test Method: Drop- Weight Test**

  This is the simplest test for evaluating impact resistance. The test method cannot be used to determine basic properties of the composites. Rather, the method is designed to obtain the relative performance of plain and fiber-reinforced concretes containing different types and volume fractions of fibers.

  A 6 in. diameter, 4 in thick concrete disc is subjected to repeated impact loads (blows) by dropping a 32 Ib hammer from a height of 16 in. The load is transferred from the hammer to the specimen through a 2.0 in steel ball placed at the center of the disc. The test sample was cut from a standard 6" x 12" cylinder. The specimen is placed between four guide pieces (lugs). A frame (positioning bracket) is then used in order to target the steel. The disc was coated at the bottom with a thin layer of grease to reduce friction between the specimen and the base plate.

  The bottom part of the hammer unit was placed with its base upon the steel ball and the load was applied by dropping the 32 Ib. weight. The number of blows that caused the first visible crack was recorded as the first crack strength. The loading continued until the sample failed. The number of blows that caused this condition is recorded as the failure strength.

  The rate of loading was kept constant for all specimens and was 10 blows per min. A total of six specimens were tested for each type of test. This is a very time consuming test and took about two days. Test results are summarized in chapter IV.

Table 3.1: Results of Various Tests Conducted on Cherat Cement

S/No	TEST	RESULTS	STANDARDS
1.	Standard Consistency	32.5	Not less than 25
2.	Initial Setting Time	230 mins	Not less than 45 mins
3.	Final Setting Time	550 mins	Not more than 600 mins
4.	Compressive Strength (3 days) 1:3	2730 Psi	Not less than 1800 Psi

Table 3.2: Results of Various Tests Conducted on Fine Aggregates

S/No	TEST	RESULTS	STANDARDS
1.	Specific Gravity	2.41	2.25 to 2.9
2.	Water Absorption	1. 2	Less than 2
3.	Fineness Value	2.69	2.3 to 3.1
4.	Grading	Coarse Sand	

Table 3.3: Results of Various Tests Conducted on Coarse Aggregate

S/NO	TEST	RESULTS	STANDARDS
1.	Specific Gravity	2.63	2.5 to 3
2.	Water Absorption	0.85	Less than 1
3.	Crushing Value	23.5	Not more than 30
4.	Aggregate Impact Value	16.25	-
5.	Abrasion	20.05	-

Table 3.4: Grading of Fine Aggregates

Sieve Size	**%Passing**
#4	100
#8	82
#16	64.5
#30	46.5
#50	34
#100	15
#200	2

Table 3.5: Grading of Coarse Aggregate

Sieve Size	**%Passing**
3/4"	100
1/2”	92
3/8”	62
#4	28
#8	9
#16	4

Table 3.6: Trial Mix Proportions

Mix No	Mix Proportions	7x days strength results		Remarks
		Compressive Strength	Flexural Strength	
1	1: 2: 4	2550	591	W/C = 0.55 Fiber Content = 80 lbs/yds^3 L/d = 75
2.	1: 1.75: 3.5	2500	632	
3.	1: 1.5: 3	2600	600	
4.	**1: 2: 3**	**2914**	**713**	
5.	1: 1.9: 3	2783	672	

Table 3.7: Mix Proportion

Mix No	Mix Proportions	Fiber Content	Aspect Ratio	Remarks
1	1:2:3	0	0	A fiber content of 120 lbs/Yd3 was also tried but balling occurred and non-uniform mix was obtained, being non-workable, so discarded.
2.	1:2:3	60 lbs/Yd3	75	
3.	1:2:3	80 lbs/Yd3	75	
4.	1:2:3	100 lbs/Yd3	75	
5.	1:2:3	80 lbs/Yd3	100	
6.	1:2:3	80 lbs/Yd3	120	

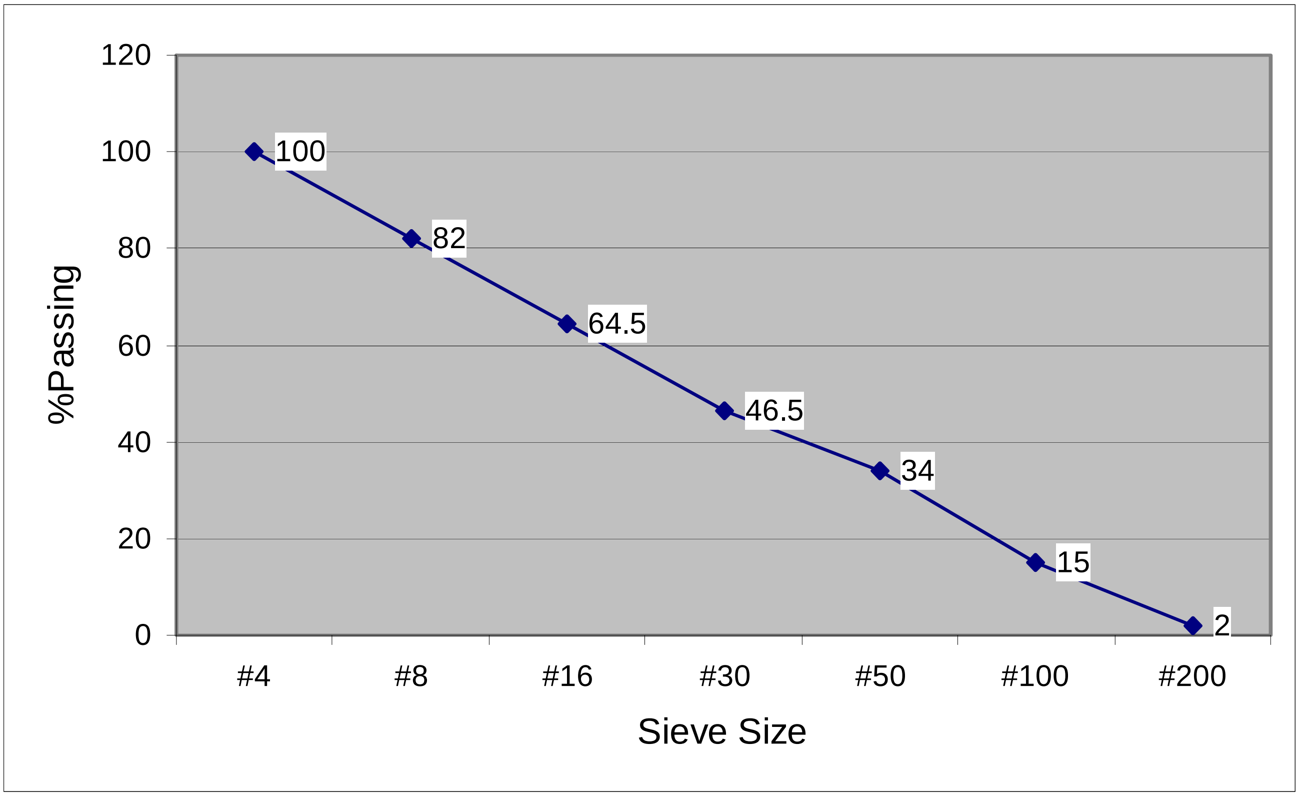

Fig: 3.1: Grading Curve of Fine Aggregate

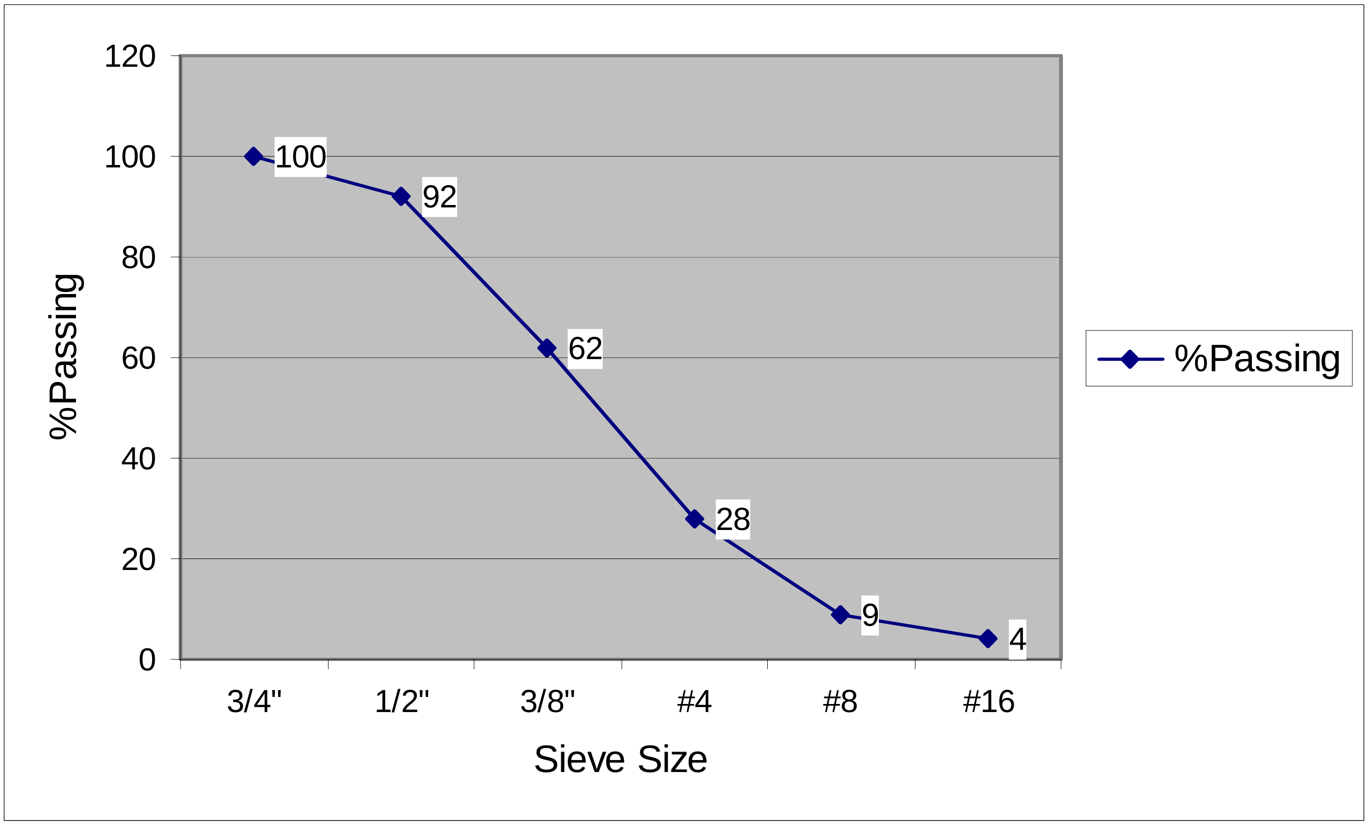

Fig 3.2: Grading Curve of Coarse Aggregate

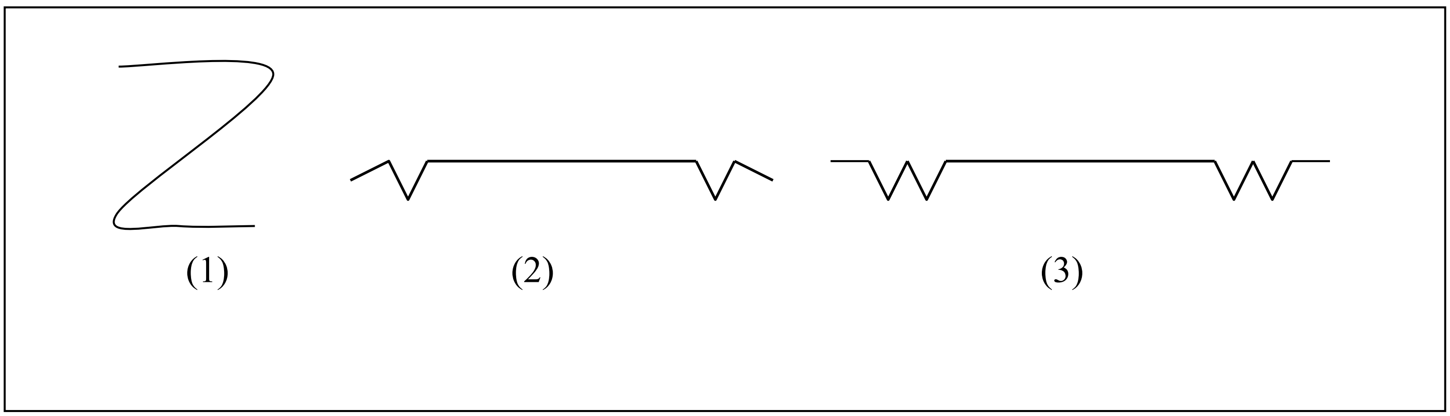

Fig 3.3: Different Fibers Shapes

CHAPTER –IV

RESULTS AND DISCUSSIONS

4.1 General

In this research work, studies were conducted on two aspects of steel fiber reinforced concrete. Steel fibers were used in concrete, varying the volume fractions as well as the aspect ratio (L/d) to determine their influence on the mechanical properties of concrete. Cylinders and prisms were casted for compression, tension, impact resistance, compressive stress – strain and flexural tests. Details of test samples are shown in table 4.1 & 4.2. For all specimens, the mix design was unchanged. The results of these test specimens were analyzed and compared with the P.C.C.

4.2 Workability

The workability of various mixes for different volume fractions and aspect ratios (L/d) of steel fibers, maintaining a constant water cement ratio was measured by slump test. Test results are shown in table 4.3 and graphically represented in fig 4.1. During the course of testing, following observations were made:-

- As evident from the results, there was a gradual decrease in the workability of concrete with an increase in Steel Fiber volume fraction.
- Increase in the aspect ratio also decreased the workability of concrete.

4.3 Compression Tests

- Test results of compression test are presented in table 4.4 & 4.5 and graphically represented in fig 4.2 and 4.3. From the critical analysis of test results, following inferences can be drawn:-
- The maximum increase in compressive strength with the addition of fibers in concrete is 36%, which is reasonable, as the role of fibers towards the compressive strength is limited.
- Rate of gain of compressive strength in SFRC is rapid during the early stage ie up to 14 days and is slow in the later stage. This is because of the development of bond between fibers and the matrix at early age.
- Overall increase in compressive strength is proportional to the volume fraction of steel fibers. It followed the simple rule of, “More the fibers, more the increase in compressive strength”.
- Aspect ratio has no influence on the ultimate strength of concrete. When aspect ratio (L/d) was increased from 75 to 120, there was an increase of 30 psi in the compressive strength

of concrete which is negligible. So one can conveniently conclude that aspect ratio (L/d) plays no major role in compressive strength improvement.

- Failure mechanism of the test samples changed completely. In case of PCC samples, after the appearance of first crack, the samples failed suddenly whereas, in case of SFRC samples, the failure was gradual. PCC samples failed with a single major crack, whereas the SFRC samples developed many cracks before failure in a ductile manner. The fluctuating dial gauge of the testing machine in case of SFRC samples also provided sufficient evidence of this behavior. So addition of steel fibers in concrete makes it ductile as compared to PCC, which is highly brittle in nature.
- Analysis of distracted samples showed an even distribution of Steel Fibers in case of L/d as 75 and it was slightly uneven as the aspect ratio was increased. It was observed during mixing stage that as the aspect ratio (L/d) was increased, balling of fibers started occurring, resulting into an uneven distribution of fibers. Same was observed in the analysis of distracted samples.

4.4 **Tensile Test**

Test results of split cylinder test are presented in table 4.6 & 4.7 and graphically represented in fig 4.4 and 4.5. During the course of testing and analysis of the test results, it was found that: -.

- SFRC samples exhibited more elastic behavior than P.C.C. This was more pronounced as the volume fraction of fibers was increased. Increased aspect ratios had positive contribution until 100, beyond which a retrograde effect was observed.
- Splitting tensile strength of SFRC is higher as the volume fraction of steel fibers is increased.
- The rate of gain of tensile strength is rapid in the early age of SFRC and it slows down with time, as the bond between the fibers and the matrix developed rapidly in early stage.
- Improvement in tensile strength of SFRC is more pronounced as compared to compressive strength.
- Analysis of distracted samples showed an even distribution of steel fibers in samples and a retrograde trend was observed as L/d was increased. It was observed during mixing stage that as the aspect ratio (L/d) was increased, balling of fibers started occurring, resulting into an uneven distribution of fibers. Same was observed in the analysis of distracted samples.

- As per the recommendations of ACI Committee-363, the splitting tensile strength of conventional concrete is given by

  $fct = 7.5 \sqrt{f'c}\ \ psi$

- Based on these experimental results, the empirical equation can be established between tensile and compressive strength as under:-

  $fct = 9.75 \sqrt{f'c}\ \ psi$

This equation is based on a limited data and more tests are required to verify the degree of accuracy. Also this equation holds good for steel fiber reinforced concrete with fiber volume fraction of 100 lbs/yd^3 and aspect ratio (L/d) as 75.

4.5 **Flexural Strength**

Test results of flexural test are presented in table 4.8 & 4.9 and graphically represented in fig 4.6 & 4.7. Observations during the course of testing and analysis of test results and distracted samples lead to following conclusions:-

- There was an appreciable increase in the flexural strength of SFRC samples as compared to its plain concrete counterpart.
- Before failure of SFRC sample, there were numerous cracking observed in the sample where as PCC sample just failed suddenly with a major crack developed. Therefore, mode of failure of SFRC being ductile, a quality most wanted in concrete.
- Rate of development of flexural strength is more in the early age as compared to in the later age, due to the rapid development of bond between fibers and the matrix at early age.
- Analysis of distracted samples showed that failure of sample was partially due to pull out and partially by yielding of fibers. Distribution of SF was reasonably uniform.
- Aspect ratio has reasonably contributed to the flexural strength of specimens because of the increased anchorage provided by the longer fibers.
- The empirical equation to predict the modulus of rupture for conventional concrete in terms of compressive strength is given as:-

  $fr = k [f'c]^{2/3}$ (psi) ,where, K ranges between 7.5 to 12.

- Based on experimental results, the proposed equation is as under:-

  $fr = K [f'c]^{2/3}$ (psi),where, K ranges between 17.5 to 19.

  This equation holds good for steel fiber volume fraction of 80 to 100 lbs/yd^3 and aspect ratio (L/d) of 75 to 100. This equation is based on a limited data and more tests are required to verify the degree of accuracy.

4.6 **Stress - Stain Relation Tests**

Test results of stress-strain are presented in table 4.10, 4.11, 4.12, 4.13, 4.14 and 4.15 and graphically represented in fig 4.8. During the course of testing and analyzing the test results, it is concluded that:-

- SFRC samples continued resisting load even after failure of samples whereas PCC samples could not resists any load after failure.
- There is a gradual increase in the strain after peak stress is attained because of the ductility induced as a result of the addition of steel fibers.
- The modulus of elasticity of concrete is strongly influenced by the concrete materials and the fiber volume fraction.
- Values of strain increase as the fiber volume is increased.
- No empirical relationship has been established between compressive strength of SFRC and the stress-strain values.
- From these results, it is evident that there is no increase in strain in case of SFRC till it reaches its ultimate strength and the strain starts increasing only after the sample has attained its ultimate strength. This behaviour is vary useful and will provide warning time before the final collapse of any structure, in which steel fibers has been used. PCC and SFRC have the same relationship as that of a tight and a spiral column.

4.7 **Impact resistance test**

Test results of impact resistance test are tabulated in table 4.16 and graphically represented in fig 4.9. Observations made during the course of testing of samples and analysis of test results leads to following conclusions:-

- Impact resistance of SFRC samples gave extraordinary high values as compared to P.C.C.
- After appearance of first crack, PCC samples failed immediately taking only 5-8 additional blows of drop weight. In case of SFRC, the first crack strength was recorded to be approximately 90 to 100% of the ultimate impact resistance strength.
- Failure of PCC samples was preceded by major cracks; where as failure of SFRC was preceded by initiation of small cracks all over the surface of sample, showing purely a ductile behavior.
- Impact resistance is proportional to the volume fraction of fibers.
- Aspect ratio has no contribution on the impact resistance of concrete.

Table: 4.1: Detail of Samples for Series –1
(Varying Fiber Content but Keeping Aspect Ratio Constant)

Ser	Test	Fiber Content (Aspect ratio = 75)							
		0Ib/yd3		60 Ib/yd3		80 Ib/yd3		100 Ib/yd3	
		Cyl	Prism	Cyl	Prism	Cyl	Prism	Cyl	Prism
1.	Compressive Strength	9	-	9	-	9	-	9	-
2.	Tensile Strength	9	-	9	-	9	-	9	-
3.	Modulus of Rupture	-	9	-	9	-	9	-	9
4.	Compressive Stress-Strain	3	-	3	-	3	-	3	-
5.	Impact Resistance	6	-	6	-	6	-	6	-
	Total	**27**	**9**	**27**	**9**	**27**	**9**	**27**	**9**

Table: 4.2: Detail of Samples for Series – II
(Varying Aspect Ratio but Keeping Fiber Content Constant)

Ser	Test	Aspect Ratio (Fiber Content = 80 Ib/yd3)			
		L/D = 100		L/D = 120	
		Cyl	Prism	Cyl	Prism
1.	Compressive Strength	9	-	9	
2.	Tensile Strength	9	-	9	-
3.	Modulus of Rupture	-	9	-	9
4.	Compressive Stress-Strain	3	-	3	-
5.	Impact Resistance	6	-	6	-
Total		**27**	**9**	**27**	**9**

Total No of Samples = 216

Table: 4.3: Workability of Concrete

S/No	Type of Concrete	Slump (mm)
1.	PCC	72
2.	SFRC 60 Ibs (L/D = 75)	60
3.	SFRC 80 Ibs (L/D = 75)	54
4.	SFRC 100 Ibs (L/D = 75)	45
5.	SFRC 80 Ibs (L/D = 100)	45
6.	SFRC 80 Ibs (L/D = 120)	41

Table: 4.4: Test Results – Compression Series-I

S/No	Type of Concrete	Compressive Strength (Psi) (Average of 3 specimen each)			
		7 days	14 days	28 days	% Increase
1.	P.C.C	2531	2849	4135	-
2.	SFRC (60 Ibs/Yd3)	3412	4044	4900	18.5
3.	SFRC (80 Ibs/Yd 3)	3574	4694	5270	27.4
4.	SFRC (100 Ibs/Yd 3)	4361	4768	5645	36.5

Table: 4.5: Test Results – Compression Series-II

S/No	Type of Concrete	Compressive Strength (Psi) (Average of 3 specimen each)			
		7 days	14 days	28 days	% Increase
1.	P.C.C	2531	2845	4135	-
2.	SFRC (80 Ibs/Yd3) L/d = 75	3574	4694	5270	27.4
3.	SFRC (80 Ibs/Yd 3) L/d = 100	3844	4184	5340	29.1
4.	SFRC (80 Ibs/Yd 3) L/d= 120	3774	4303	5300	28.2

Table: 4.6: Test Results – Tensile (Split Cylinder)
Series-I

S/No	Type of Concrete	Tensile Strength (Psi) (Average of 3 specimen each)			
		7 days	14 days	28 days	% Increase
1.	P.C.C	231	309	412	-
2.	SFRC (60 Ibs/Yd3)	454	506	635	54
3.	SFRC (80 Ibs/Yd 3)	525	605	710	72.3
4.	SFRC (100 Ibs/Yd 3)	520	640	784	90.3

Table: 4.7: Test Results – Tensile Test (Split Cylinder)
Series-II

S/No	Type of Concrete	Tensile Strength (Psi) (Average of 3 specimen each)			
		7 days	14 days	28 days	% Increase
1.	P.C.C	231	309	412	-
2.	SFRC (80 Ibs/Yd3) L/d = 75	525	605	710	72.3
3.	SFRC (80 Ibs/Yd 3) L/d = 100	532	589	740	79.6
4.	SFRC (80 Ibs/Yd 3) L/d= 120	520	618	722	75.2

Table: 4.8: Test Results – Flexural Test
Series-I

S/No	Type of Concrete	Flexural Strength (Psi) (Average of 3 specimen each)			
		7 days	14 days	28 days	% Increase
1.	P.C.C	510	594	775	-
2.	SFRC (60 Ibs/Yd3)	892	1053	1230	58.7
3.	SFRC (80 Ibs/Yd 3)	990	1135	1377	77.6
4.	SFRC (100 Ibs/Yd 3)	974	1070	1451	87.2

Table: 4.9: Test Results – Flexural Test
Series-II

S/No	Type of Concrete	Flexural Strength (Psi)			
		7 days	14 days	28 days	% Increase
1.	P.C.C	510	594	775	-
2.	SFRC (80 Ibs/Yd3) L/d = 75	990	1135	1377	77.6
3.	SFRC (80 Ibs/Yd 3) L/d = 100	985	1203	1540	98.7
4.	SFRC (80 Ibs/Yd 3) L/d= 120	1087	1219	1610	107

Table 4.10: Compressive Stress – Strain Relation PCC

Load (Tons)	Stress (Psi)	Strain
5	396	0.00025
10	792	0.00137
15	1188	0.00262
20	1584	0.00425
25	1981	0.0059
30	2377	0.00785
35	2773	0.0080
40	3170	0.0084
45	3565	0.0088
50	3962	0.0093
55	4358	0.0098
34	2694	0.01

Table 4.11: Compressive Stress – Strain Relation SFRC (60 lb/yd^3,L/d as 75)

Load (Tons)	Stress (Psi)	Strain
5	396	0.00011
10	792	0.00019
15	1188	0.00028
20	1584	0.00039
25	1981	0.00043
30	2377	0.0007
35	2773	0.00083
40	3170	0.00091
45	3565	0.00093
50	3962	0.0019
55	4358	0.0032
60	4754	0.0035
51	4041	0.0062
42	3327	0.008
39	3090	0.0093
33	2614	0.0098
30	2377	0.019
25	1981	0.027
21	1663	0.039

Table 4.12: Compressive Stress – Strain Relation SFRC (80 lb/yd^3, L/d as 75)

Load (Tons)	Stress (Psi)	Strain
5	396	0.00011
10	792	0.0014
15	1188	0.002
20	1584	0.0034
25	1981	0.004
30	2377	0.006
35	2773	0.0063
40	3170	0.0075
45	3565	0.0077
50	3962	0.0086
55	4358	0.009
60	4754	0.0091
65	5150	0.011
59	4674	0.015
50	3962	0.017
39	3090	0.022
31	2456	0.028
29	2197	0.037

Table 4.13: Compressive Stress – Strain Relation SFRC (100 lb/yd^3, L/d as 75)

Load (Tons)	Stress (Psi)	Strain
5	396	0.0004
10	792	0.00059
15	1188	0.0013
20	1584	0.0023
25	1981	0.0039
30	2377	0.0051
35	2773	0.0060
40	3170	0.0072
45	3565	0.0074
50	3962	0.0081
55	4358	0.0093
60	4754	0.01
65	5150	0.013
70	5546	0.017
75	5942	0.02
59	4674	0.021
51	4041	0.029
43	3407	0.031
35	2773	0.033
30	2377	0.037
26	2060	0.041
21	1663	0.044

Table 4.14: Compressive Stress – Strain Relation SFRC (80 lb/yd^3, L/d as 100)

Load (Tons)	Stress (Psi)	Strain
5	396	0.0000
10	792	0.001
15	1188	0.0025
20	1584	0.0029
25	1981	0.0035
30	2377	0.0039
35	2773	0.0041
40	3170	0.0049
45	3565	0.0054
50	3962	0.0060
55	4358	0.0065
60	4754	0.0083
65	5150	0.0099
57	4516	0.011
52	4120	0.011
45	3565	0.013
40	3170	0.021
36	2852	0.028
30	2377	0.031
24	1901	0.040

Table 4.15: Compressive Stress – Strain Relation SFRC (80 lb/yd^3, L/d as 120)

Load (Tons)	Stress (Psi)	Strain
5	396	0.0000
10	792	0.0012
15	1188	0.0015
20	1584	0.0020
25	1981	0.0023
30	2377	0.0031
35	2773	0.0035
40	3170	0.0043
45	3565	0.0047
50	3962	0.0052
55	4358	0.0061
60	4754	0.0088
65	5150	0.0091
54	4278	0.093
47	3724	0.010
40	3170	0.014
38	3010	0.019
34	2694	0.025
30	2377	0.030
26	2060	0.032

Table 4.16: Test Results – Impact Resistance Test

S/No	Type of Concrete	No of Blows to (Average of six specimen each)		Increase (Times)
		First Crack	Failure	
1.	PCC	23	28	-
2.	SFRC (60 Ibs/Yd3) L/d = 75	113	215	7.6
3.	SFRC (80 Ibs/Yd3) L/d = 75	137	257	9
4.	SFRC (100 Ibs/Yd3) L/d= 75	167	310	10
5.	SFRC (80 Ibs/Yd3) L/d= 100	123	224	8
6.	SFRC (80 Ibs/Yd3) L/d= 120	110	206	7.3

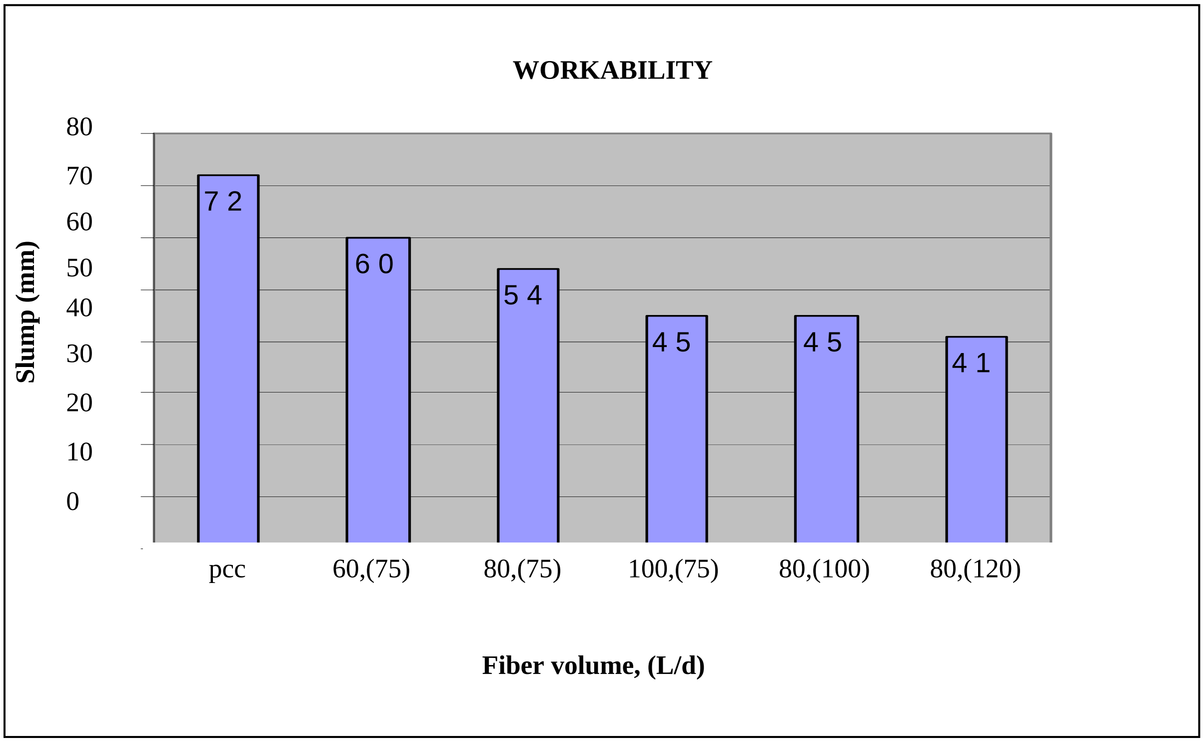

Fig- 4.1: Workability of Concrete

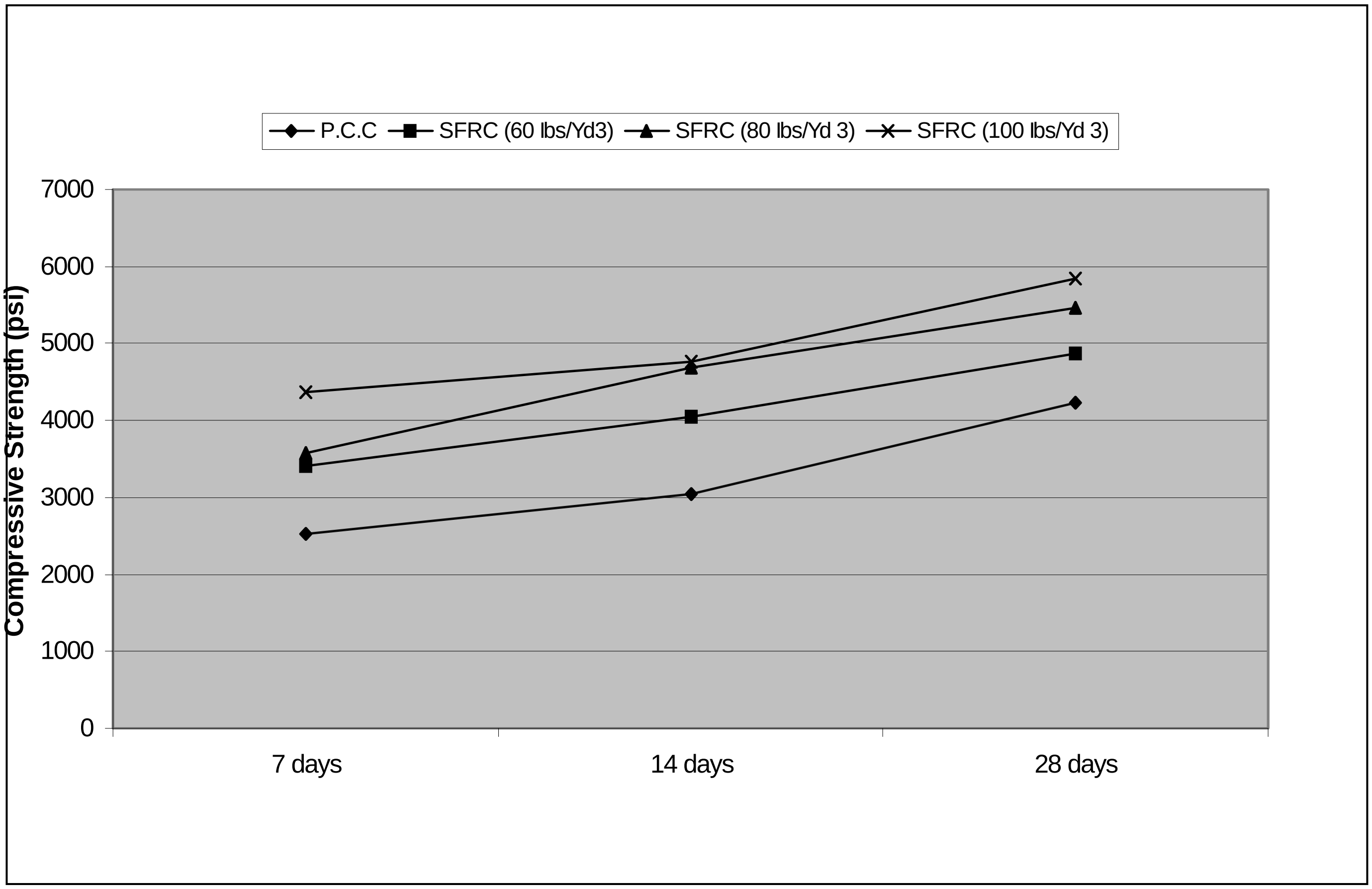

Fig: 4.2: Test Results – Compression Series-I

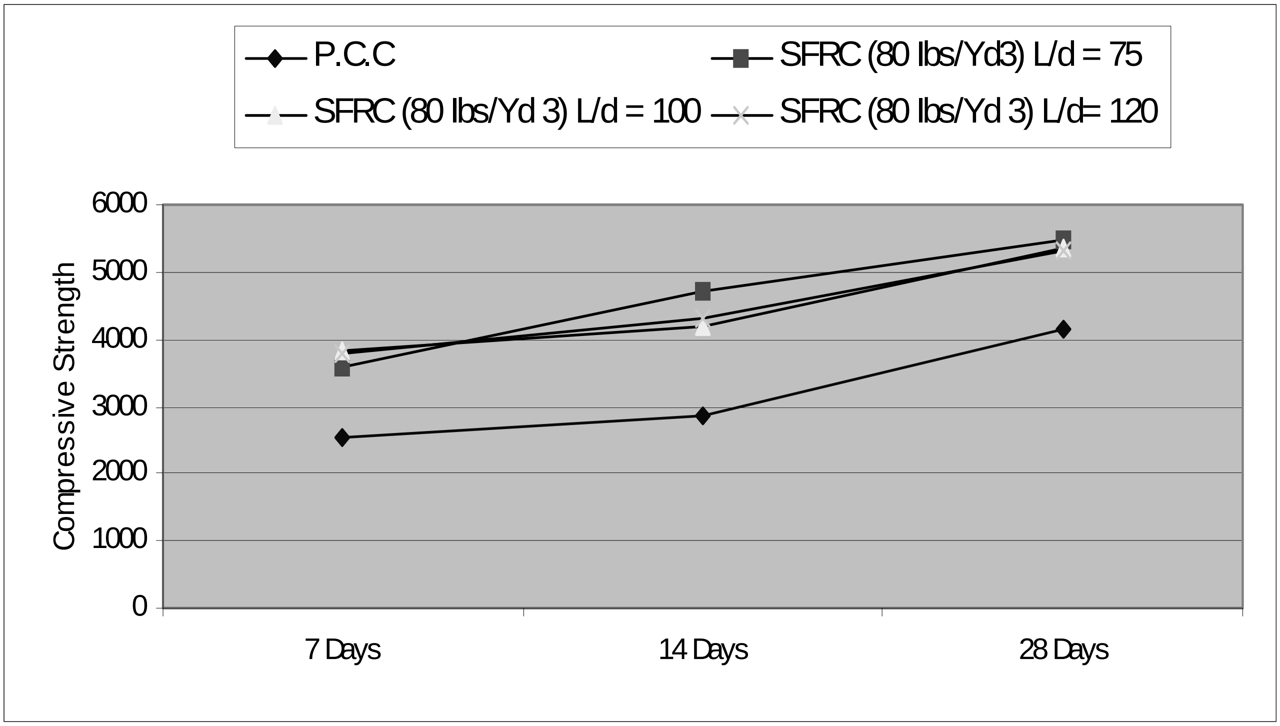

Fig: 4.3: Test Results – Compression Series-II

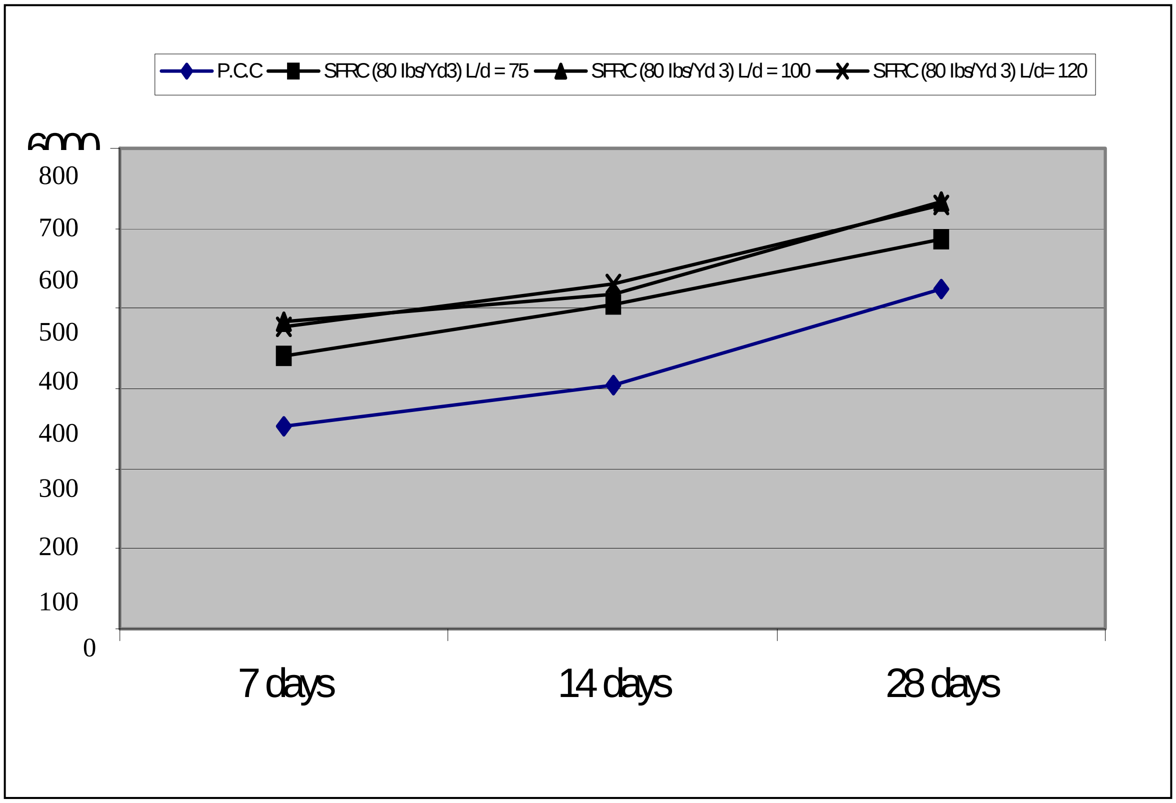

Fig: 4.4: Test Results – Tensile (Split Cylinder) Series-I

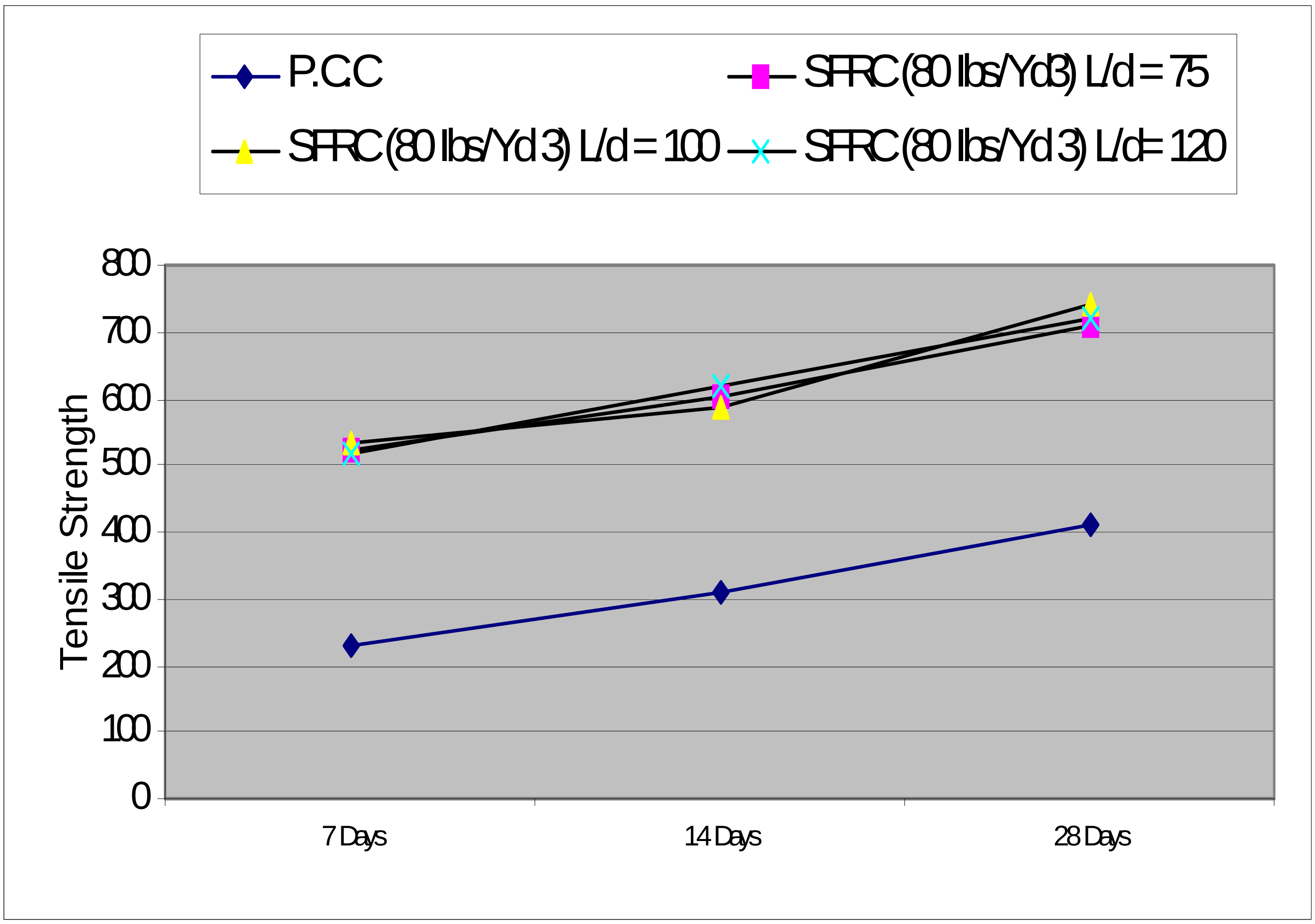

Fig: 4.5: Test Results – Tensile (Split Cylinder) Series-II

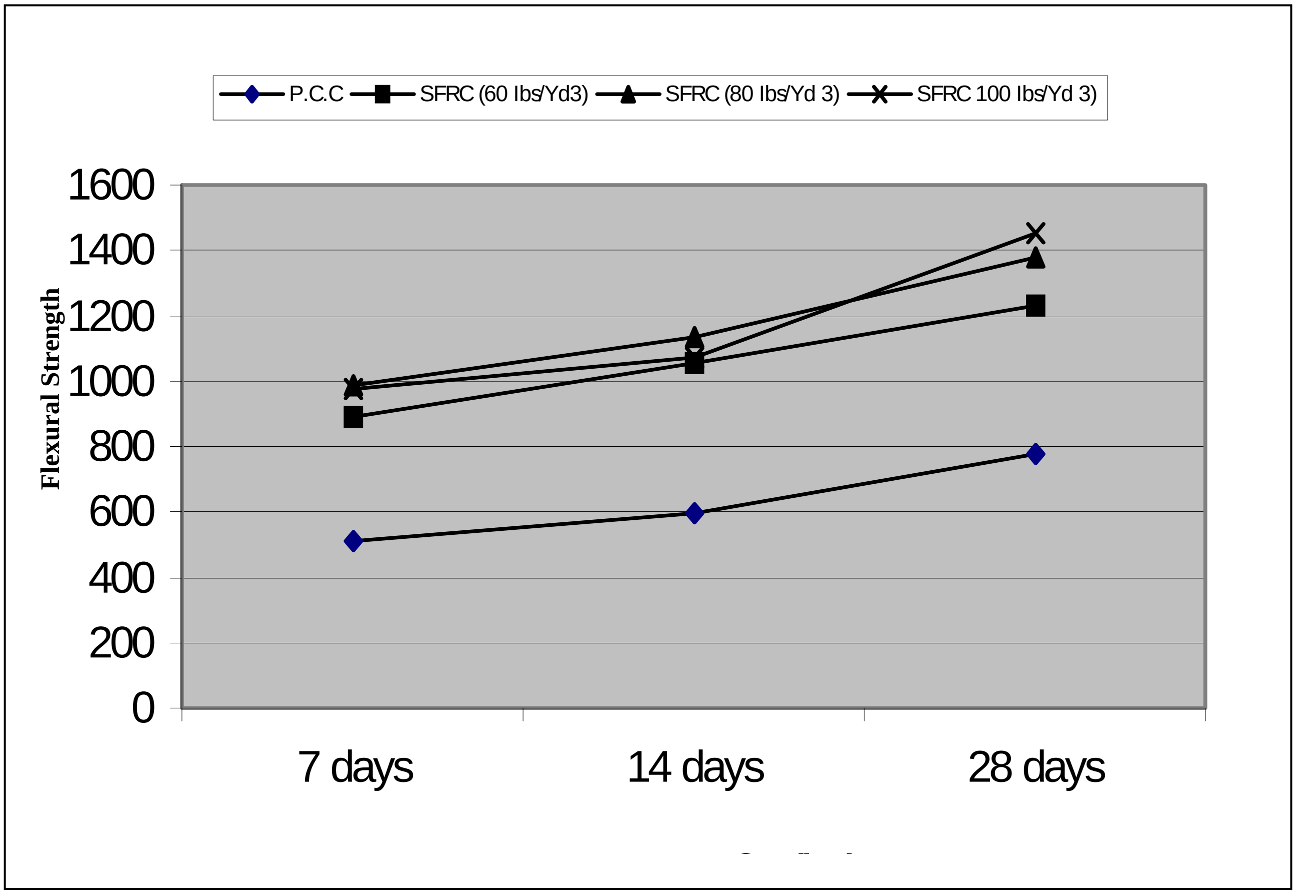

Fig: 4.6: Test Results – Flexural Test Series-I

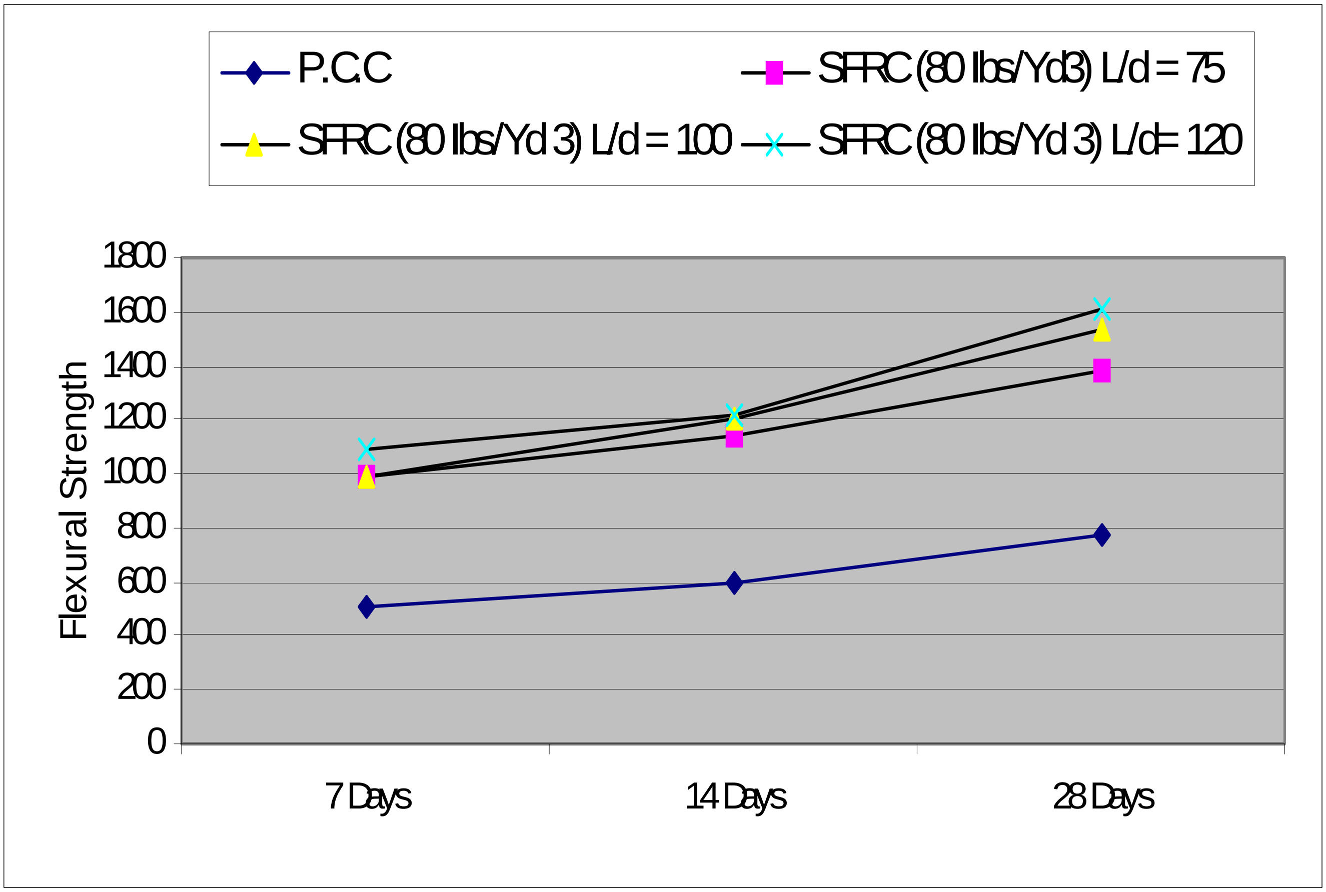

Fig: 4.7: Test Results – Flexural Test Series-II

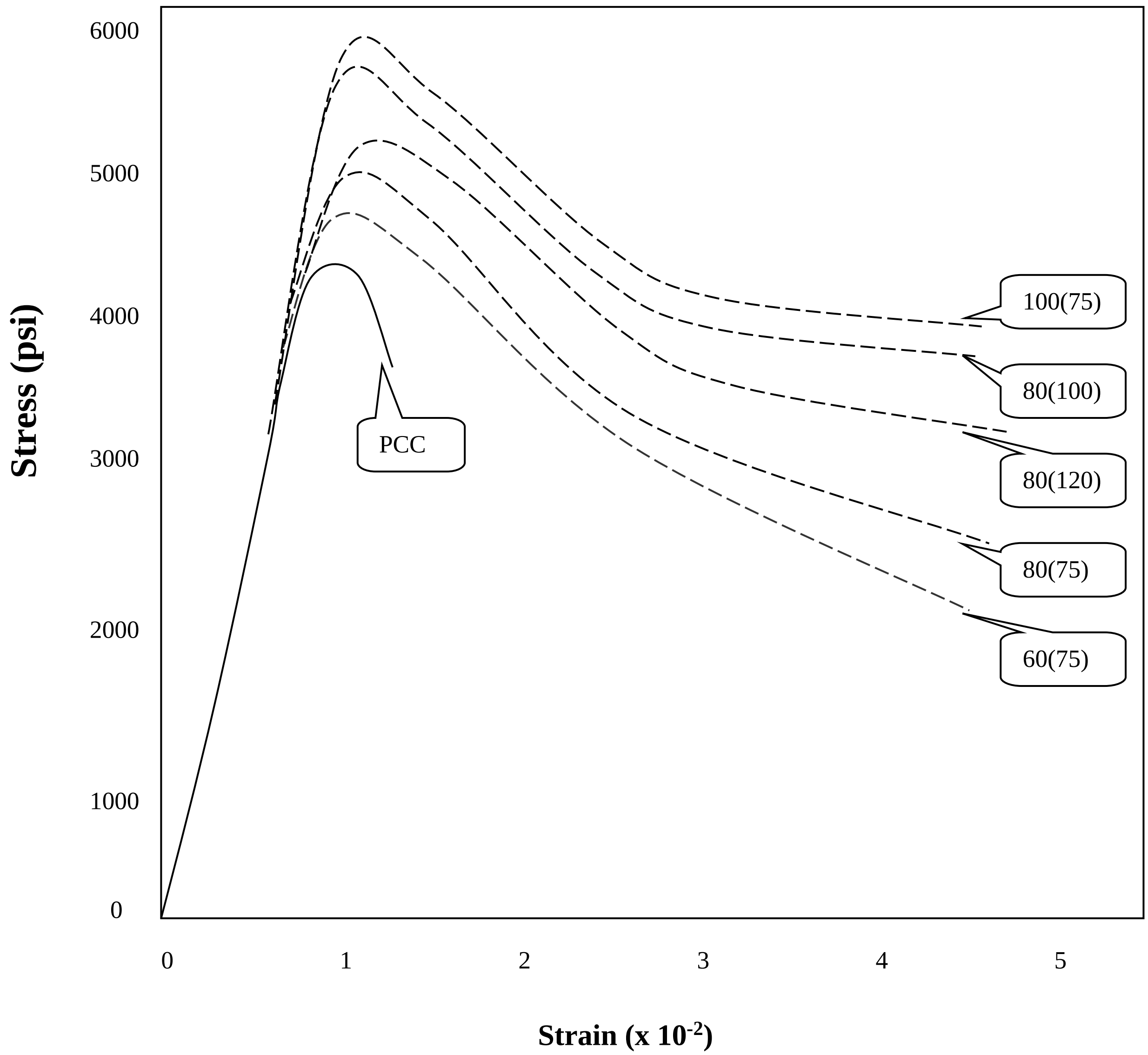

Fig: 4.8 : Compressive Stress Strain Relationship

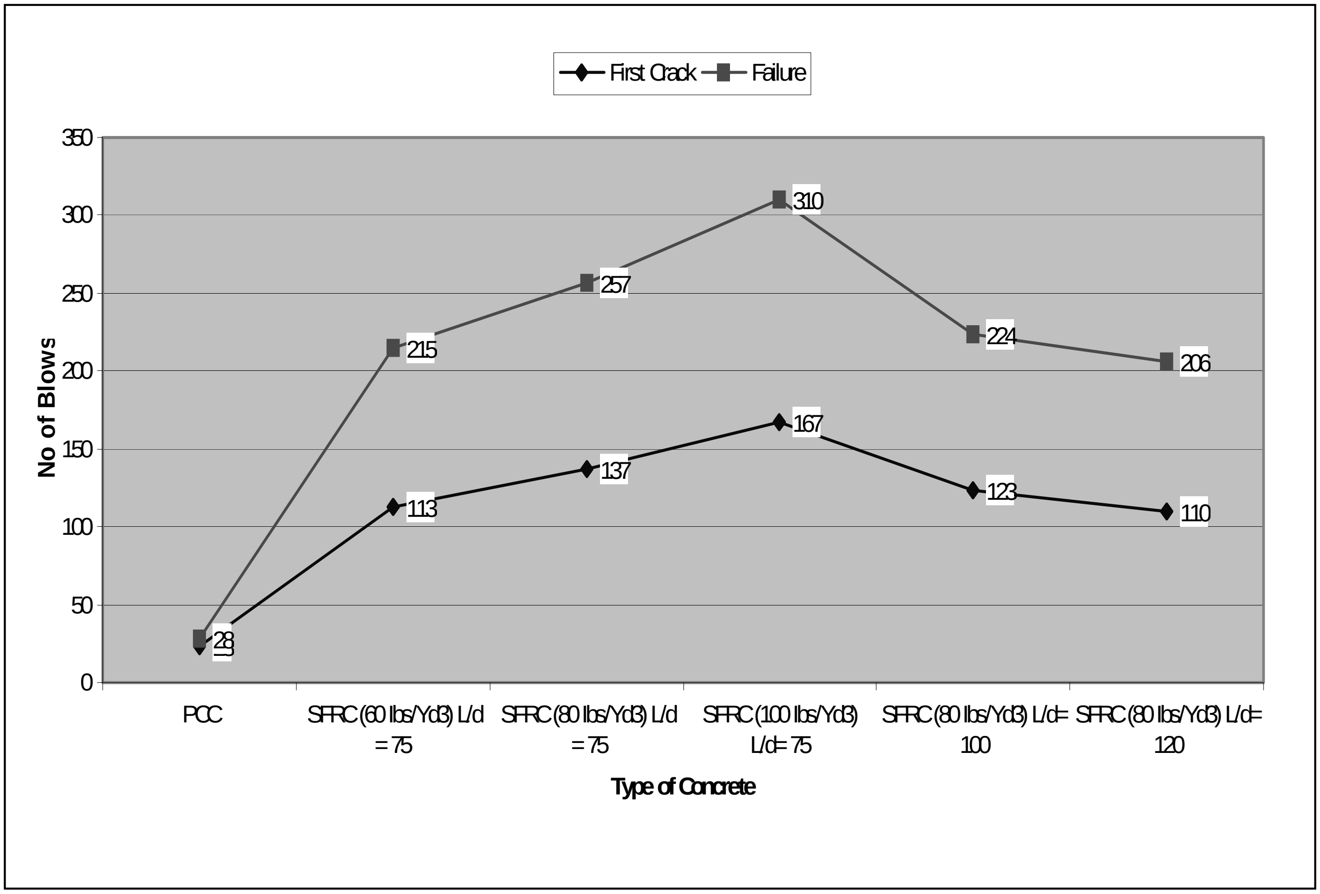

Fig: 4.9 : Test Results – Impact Resistance

CHAPTER – V
CONCLUSIONS & RECOMMENDATIONS

5.1 CONCLUSIONS

The construction of ever long span bridges, tall buildings, deep off-shore structures, defense related infrastructure, roads, runways and other numerous mega structures are calling for construction materials with increasingly improved properties such as strength, stiffness, toughness, ductility and durability. In some cases, simultaneous improvements in a combination of properties are required. Addition of steel fibers to concrete provides satisfactory results in response to the above mentioned properties.

SFRC has already established itself around the world and is not a passing fad. It is going to stay around and the future belongs to SFRC. Hundreds of projects incorporating steel fibers already exist in the world. Pakistan construction industry is yet to recognize and reap the benefits offered by SFRC. Once SFRC is recognized in Pakistan its uses will become much more widely accepted. The increased use and profitability of SFRC will lead to better production facilities, design methods and mixing procedures, all of which will benefit humanity as whole. The increased ductility and strength properties of SFRC will lead to its uses in areas once never imagined for conventional concrete. During the research work a no of key properties have been investigated and very encouraging results found. Based on the results of investigation and their analysis following conclusions are drawn:-

- Rate of strength development was higher up to 14 days as compare to 28 days.
- The increase in compressive strength was found to be 36% at a volume fraction of 100Ibs/yd^3 and aspect ratio as 75.
- Addition of 100Ibs/yd^3 of fibers almost doubled the flexural strength.

- There is a considerable increase in the tensile strength of concrete with the addition of fibers.
- It is observed that there is a considerable increase in the post peak compressive strain of SFRC as compare to its plain concrete counterpart.
- The comparison between the impact resistance of PCC and SFRC demonstrates that the key role of addition of fibers is the extraordinary increase in impact resistance of SFRC. The increase is about 10 times over PCC.
- The ultimate impact resistance of SFRC is almost double the first crack strength.
- Incorporation of steel fibers to concrete changed the mode of failure from brittle to ductile.
- SFRC specimens developed multiple cracking before failure and could resist loads even after failure. This was confirmed by the fluctuating dial gauge of testing machine.
- An appreciable decrease in workability of concrete was noticed with addition of steel fibers. The decrease is proportional to the increase in the volume fraction and the aspect ratio of steel fibers.
- It was observed that steel fibers in excess of 100Ibs/yd^3 created balling and mixing difficulties, especially with the aspect ratio beyond 100.
- Results of split cylinder tests do not match with the existing relationship in terms of compressive strength. Based on experimental results, though based on limited tests, the established relationship is a under:-

  $$f_{ct} = 9.75 \times [f'_c]^{0.5} \text{ (psi)}$$

- Results of flexural strength test also do not follow the already existing, empirically derived relationship in term of compressive strength. The relationship established, though based on limited tests is as under:-

$$f_r = K \times [f'_c]^{2/3} \text{ (psi)}$$ Where, K ranges b/w 17.5 to 19.

These equations may be used only if the fiber type, fiber volume fractions and the aspect ratios are similar to the one used in this research.

- Corrosion of steel fibers exposed to atmosphere was observed.

5.2 RECOMMENDATIONS

During the course of investigation it was felt that certain other aspects of fibers be under-taken for further studies. Following topics are recommended for detailed investigation for future research:-

- High strength concrete is a highly brittle material. Incorporation of steel fibers in high strength concrete be investigated for improvement in the ductility of high strength concrete.
- Presently steel fibers have been investigated. Other types of artificial fibers like carbon, glass and polymer fibers be investigated for their use in concrete. Also steel fibers with higher tensile strength be investigated for their use in concrete.
- Corrosion of the exposed steel fibers in cementitious matrix due to the environmental affects has revealed that methods be developed to reduce / eliminate corrosion to enhance the serviceability of the structure.

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