STRENGTH AND FLEXURAL TOUGHNESS OF STEEL FIBRE REINFORCED CONCRETE

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CERTIFICATE

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"One can pay back the loan of gold, but one dies forever in debt to those who are kind."

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ABSTRACT

It is known that concrete is relatively a brittle material and has serious short-coming of poor toughness. Addition of randomly distributed fibres improves concrete structural characteristics viz. static flexural strength, ductility and flexural toughness etc., which depend upon fibre type, size, aspect ratio and volume fractions of the fibres used. Fibres are added to concrete to improve energy absorption and apparent ductility. Flexural toughness, derived from the load-deflection response, is often used to describe these improvements. There are however, a number of uncertainties regarding how fibre reinforced concrete flexural toughness should be measured interpreted or used.

In the present investigation mechanical properties such as compressive strength, splitting tensile strength and flexural strength were compared for concrete containing different combinations of rectangular corrugated and both end hooked steel fibres at a fibre volume fraction of 1.0% and 1.5%. Flexural toughness results of all mix combinations as measured by toughness indices using ASTM C1018 method are also presented. The results indicate that concrete containing a fibre combination of 50% corrugated steel fibres + 50% both end hooked steel fibres at 1.5% volume fraction can be adjudged as the most appropriate combination to be employed in steel fibre reinforced concrete for compressive strength, flexural strength and flexural toughness.

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CHAPTER-1 INTRODUCTION

1.1 GENERAL

Concrete is a composite material containing hydraulic cement, water, coarse aggregate and fine aggregate. The resulting material is a stone like structure which is formed by the chemical reaction of the cement and water. This stone like material is a brittle material which is strong in compression but very weak in tension. This weakness in the concrete makes it to crack under small loads, at the tensile end. These cracks gradually propagate to the compression end of the member and finally, the member breaks. The formation of cracks in the concrete may also occur due to the drying shrinkage. These cracks are basically micro cracks. These cracks increase in size and magnitude as the time elapses and the finally makes the concrete to fail.

The formation of cracks is the main reason for the failure of the concrete. To increase the tensile strength of concrete many attempts have been made. One of the successful and most commonly used methods is providing steel reinforcement. Steel bars, however, reinforce concrete against local tension only. Cracks in reinforced concrete members extend freely until encountering are bar. Thus need for multidirectional and closely spaced steel reinforcement arises. That cannot be practically possible. Fibre reinforcement gives the solution for this problem.

So to increase the tensile strength of concrete a technique of introduction of fibres in concrete is being used. These fibres act as crack arrestors and prevent the propagation of the cracks. These fibres are uniformly distributed and randomly arranged. This concrete is named as fibre reinforced concrete.

The main reasons for adding fibres to concrete matrix is to improve the post-cracking response of the concrete, i.e., to improve its energy absorption capacity and apparent ductility, and to provide crack resistance and crack control. Also, it helps to maintain structural integrity and cohesiveness in the material. The initial researches combined with the large volume of follow up research have led to the development of a wide variety of material formulations that fit the definition of Fibre Reinforced Concrete.

1.2 FIBRE REINFORCED CONCRETE

Fibre Reinforced Concrete (FRC) is concrete containing fibrous material which increases its structural integrity. So we can define fibre reinforced concrete as a composite material of cement concrete or mortar and discontinuous discrete and uniformly dispersed fibre.

Fibre is discrete material having some characteristic properties. The fibre material can be anything, but not all will be effective and economical. Some fibres that are most commonly used are:

- Steel fibres
- Glass fibres
- Carbon fibres
- Natural fibres

Steel fibre is one of the most commonly used fibres. Generally round fibres are used. The diameter may vary from 0.25 to 0.75mm.The steel fibre sometimes gets rusted and lose its strength. But investigations have proved that fibres get rusted only at surfaces. It has high modulus of elasticity. Use of steel fibres makes significant improvements in flexure, impact and fatigue strength of concrete. It has been used in various types of structures.

Glass fibre is a recently introduced fibre in making fibre concrete. It has very high tensile strength of 1020 to 4080MPa. Glass fibre concretes are mainly used in exterior building facade panels and as architectural precast concrete. This material is very good in making shapes on the front of any building and it is less dense than steel.

Use of carbon fibre is not a developed process. But it has considerable strength and young’s modulus. Also investigations have shown that use of carbon makes the concrete very durable. The study on the carbon fibres is limited. These are mainly used for cladding purpose.

Natural fibres are available at low cost and are abundant. They are nonhazardous and renewable. Some of the natural fibres are bamboo, jute, coconut husk, elephant grass. They can be used in place of asbestos. It increases toughness and flexural strength. It also induces good durability in concrete.

Studies conducted so far, proved that the short and discrete small fibres can improve the flexural load carrying capacities and impact resistance for non ferrous fibres.

1.3 HISTORY

The use of fibres is to increase the structural properties of construction material is not a new process. From ancient times fibres were being used in construction. In BC, horse hair was used to reinforce mortar. Egyptians used straw in mud bricks to provide additional strength. Asbestos was used in the concrete in the early 19th

century, to protect it from formation of cracks. But in the late 19th century, due to increased structural importance, introduction of steel reinforcement in concrete was made, by which the concept of fibre reinforced concrete was over looked for 5-6 decades. Later in 1939 the introduction of steel replacing asbestos was made for the first time. But at that period it was not successful. From 1960, there was a tremendous development in the FRC, mainly by the introduction of steel fibres. Since then use of different types of fibres in concrete was made. In 1970's principles were developed on the working of the fibre reinforced concrete. Later in 1980's certified process was developed for the use of FRC. In the last decades, codes regarding the FRC are being developed.

1.4 PROPERTIES OF FIBRE REINFORCED CONCRETE

Properties of Fibre Reinforced Concrete is affected by many factors like properties of cement, fine aggregate, coarse aggregate. Other than this, the fibre reinforced concrete is affected by following factors:

- Type of fibre
- Aspect ratio
- Quantity of fibre
- Orientation of fibre

1.4.1 Types of fibres

A good fibre is the one which possess the following qualities:

- Good adhesion within the matrix.
- Adaptable elasticity modulus (sometimes higher than that of the matrix).
- Compatibility with the binder, which should not be attacked or destroyed in the long term.
- An accessible price, taking into account the proportion within the mix.
- Being sufficiently short, fine and flexible to permit mixing, transporting and placing.
- Being sufficiently strong, yet adequately robust to withstand the mixing process.

1.4.2 Aspect ratio

Aspect ratio is defined as the ratio of length to width of the fibre. The value of aspect ratio varies from 30 to 150. Generally the increase in aspect ratio increases the strength and toughness till the aspect ratio of 100. Above that the strength of concrete decreases, in view of decreased workability and reduced compaction. From investigations it can be found out that good results are obtained at an aspect ratio around 80 for steel fibres.

1.4.3 Fibre quantity

Generally quantity of fibres is measured as percentage of cement content by weight. As the volume of fibres increase, as a result increase in strength and toughness of concrete occurs.

1.4.4 Orientation of fibre

The orientations of fibres play a key role in determining the capacity of concrete. In RCC the reinforcements are placed in desired direction. But in FRC, the fibres will be oriented in random direction. The FRC will have maximum resistance when fibres are oriented parallel to the load applied.

1.5 FIBRE MECHANISM

Fibre work with concrete utilizing two mechanisms: the spacing mechanism and the crack bridging mechanism. The spacing mechanism requires a large number of fibres well distributed within the concrete matrix to arrest any existing micro crack that could potentially expand create a sound crack. For typical volume of fractions of fibres utilizing small diameter of fibres or micro fibres can ensure the required number of fibres for micro crack arrest.

The second mechanism termed crack bridging requires larger straight fibres with adequate bond to concrete. Steel fibres are considered a prime example of this fibre type that is commonly referred as large diameter fibres or micro fibres.

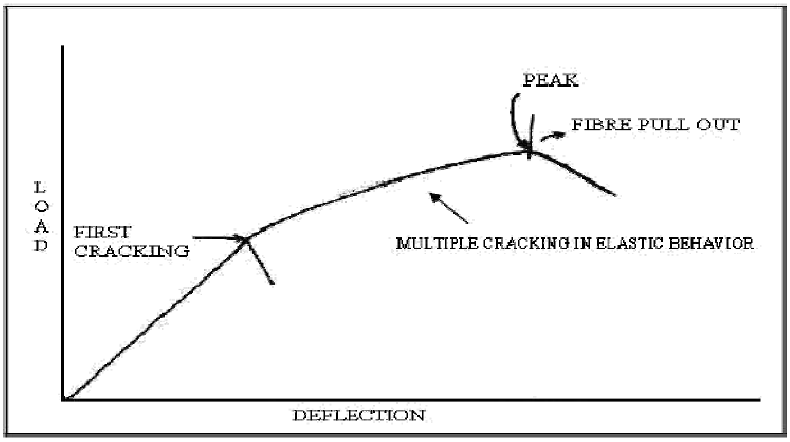

Fig 1.1 Fibre Mechanism (Bayasi and Kaiser, 2001)

1.5.1 Fibre- Matrix Interaction

The tensile cracking strain of cement matrix is much lower than the yield or ultimate strain of fibres. As a result, when a fibre reinforced composite is loaded the matrix will crack long before the fibres can be fractured. Once the matrix is cracked composite continues to carry increasing tensile stress. The peak stress and strain of the concrete composite are greater than those of the matrix alone during the inelastic range between first cracking and the peak. Multiple cracking of matrix occurs as indicated in fig.1.1.

1.5.2 Bridging Action:

Pullout resistance of fibres (dowel action) is important for efficiency. Pullout strength of fibres significantly improves the post-cracking tensile strength of concrete. As an FRC beam or other structural element is loaded, fibres bridge the cracks. Such bridging action provides the FRC specimen with greater ultimate tensile strength and, more importantly, larger toughness and better energy absorption.

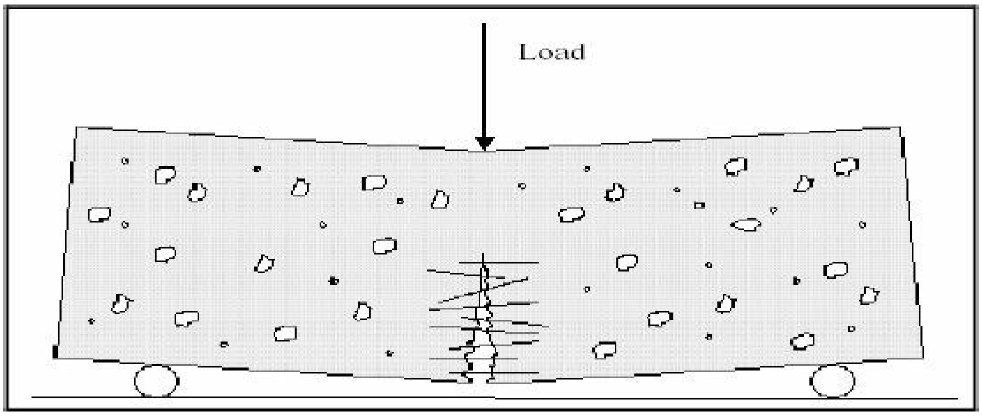

Fig 1.2 Pullout Mechanism (Bayasi and Kaiser, 2001)

1.6 STEEL FIBRE REINFORCED CONCRETE

Fibre reinforced concrete is a composite material comprised of Portland cement, aggregate, and fibres. Normal unreinforced concrete is brittle with a low tensile strength and strain capacity. The function of the irregular fibres distributed randomly is to fill the cracks in the composite. Fibres are generally utilized in concrete to manage the plastic shrink cracking and drying shrink cracking. The applications of steel fibre reinforced concrete have been varied and widespread, due to which it is difficult to categorize. The most common applications are tunnel linings, slabs, and airport pavements.

1.6.1 Composition of Steel Fibre Reinforced Concrete

The components of Steel Fibre Reinforced Concrete (SFRC) can be explained with the help of the fig. 1.3.

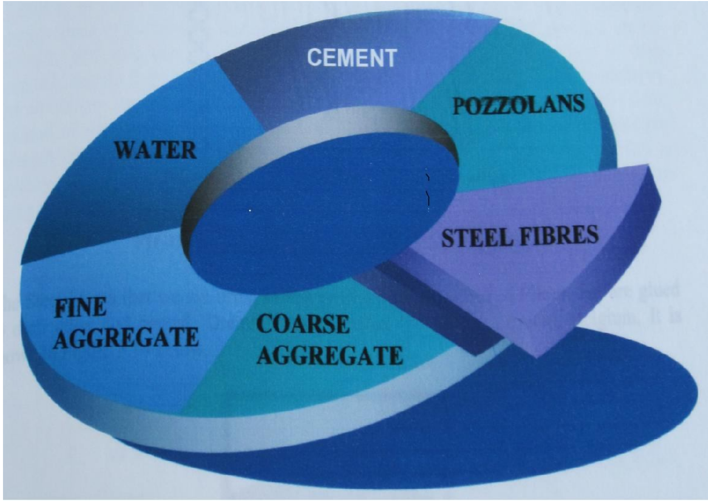

Fig 1.3 Components of Steel Fibre Reinforced Concrete

(Bayasi and Kaiser, 2001)

Concrete containing hydraulic cement, water, fine aggregate, coarse aggregate and discontinuous discrete Steel fibres is called Steel Fibre Reinforced Concrete. It may also contain pozzolans and other admixtures commonly used with conventional concrete. Fibres of various shapes and sizes produced from steel, plastic, glass and natural materials are being used. However, for most structural and non-structural purposes, steel fibre is commonly used of all the fibres.

1.6.2 Steel Fibres:

This research focuses on steel fibres. Steel fibre length ranges from 1/4 to 3 inches (1.5 to 75 mm) and aspect ratio ranges from 30 to 100. Fibre shapes are illustrated below.

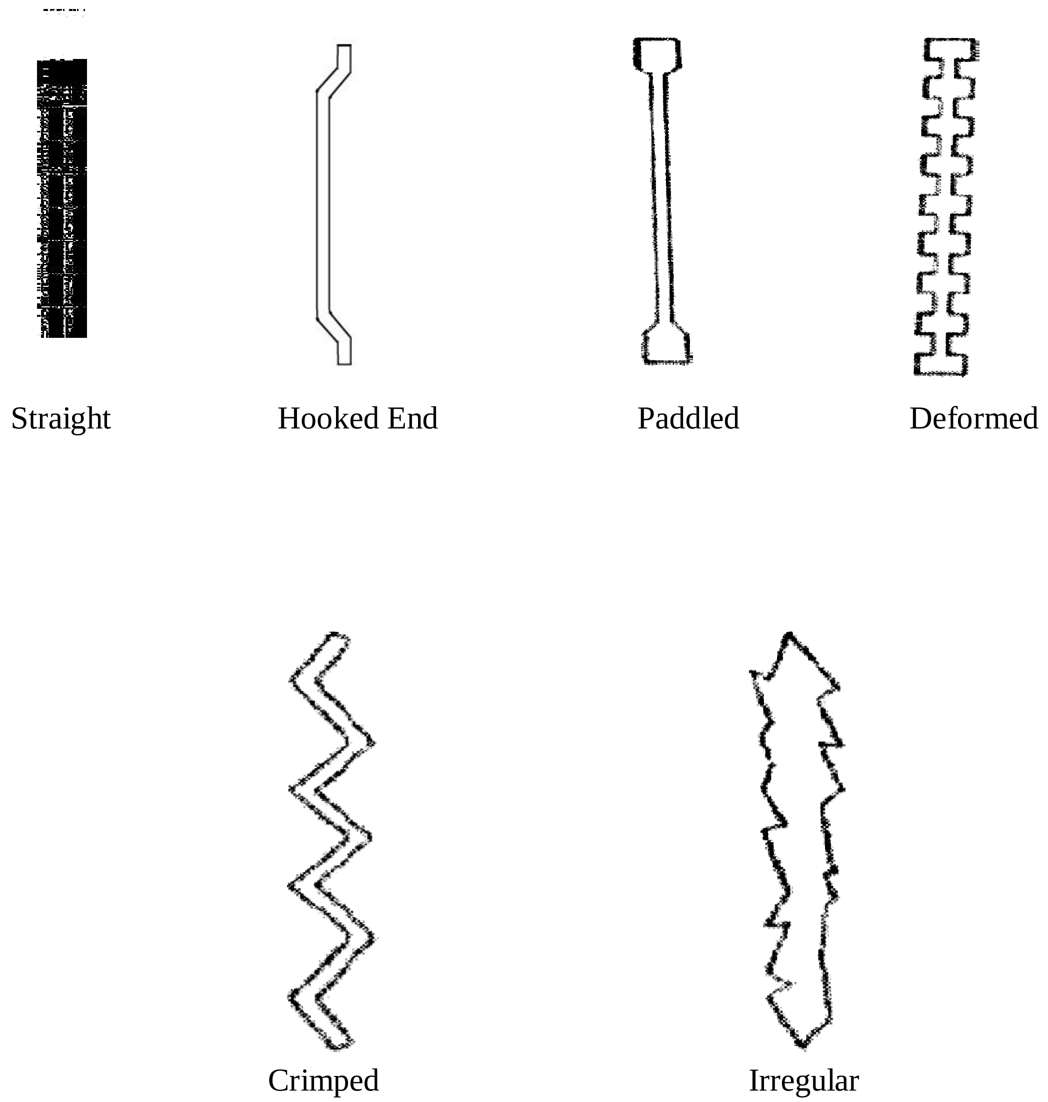

Fig1.4 Different shapes of Steel Fibre

1.7 Behaviour of Steel Fibre Reinforced Concrete under conventional loadings:

Behaviour of Steel Fibre Reinforced concrete under direct compression:

Maximum stress a material can sustain under crush loading is known as compressive strength. The compressive strength of a material that fails by shattering fracture can be defined within fairly narrow limits as an independent property. However, the compressive strength of materials that do not shatter in compression must be defined as the amount of stress required to distort the material an arbitrary amount. Compressive strength is calculated by dividing the maximum load by the original cross-sectional area of a specimen compression test.

1.7.1 For Plain Concrete:

The stress strain curve of concrete under uniaxial compression shows a linear behaviour up to about 30% of the ultimate strength (f_u) because under short term loading the micro cracks in the transition zone remain undisturbed. For stresses above this point, the curve shows a gradual increase in curvature up to about 0.75 f_u to 0.9 f_u, then it bends sharply almost becoming flat at the top and finally descends until the

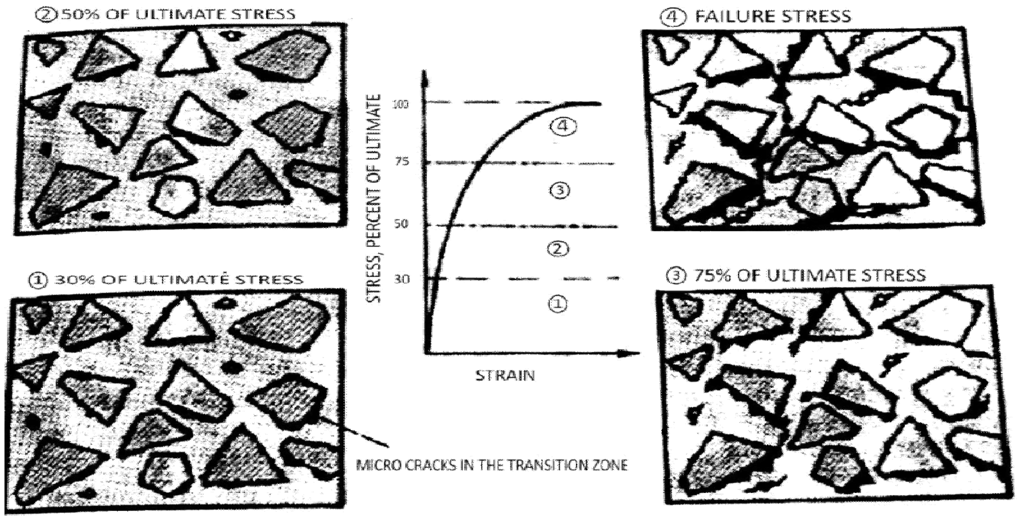

Fig1.5 Relation between Concrete Performance and Extent of Cracking

specimen is fractured. From the shape of the stress strain curve it seems that, for a stress between 30 to 50% of f_u (Ultimate strength) the micro cracks in the transition zone show some extension due to stress concentration to the tips however, no cracking occurs in the mortar matrix. Until this point crack propagation is assumed to be stable in the sense that crack lengths rapidly reach their final values it the applied stress is held constant. For a stress between 50 to 75% of f_u increasingly the crack system tends to be unstable as the transition zone crack begins When the available internal energy exceeds the required crack release energy, the rate of crack propagation will increase and the system becomes above 75% of f_u when complete fracture of the test specimen can occur by bridging of mortar and transition zone cracks.

Based on the described cracking stages, the behaviour of concrete can be viewed at two levels: First, randomly distributed micro cracks are formed or enlarged under low level of stresses. When tile stress level reaches a specific value, these micro cracks begin to localize (strain localization) and to coalesce into a macro crack. This macro crack will agate until the stress reaches its critical stage. Steady state propagation of this macro crack will result in the strain softening mechanism observed for concrete. This general view of cracking of concrete makes it clear that the first linear elastic portion of loading up to strain localization cannot be described by fracture mechanics but can be quantified using damage mechanics.

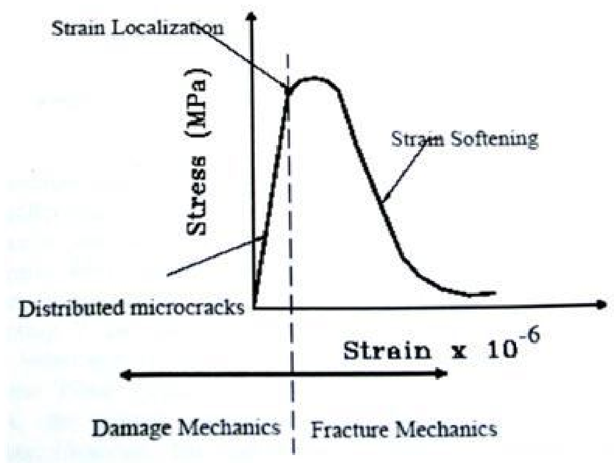

Fig.1.6 Schematic representation of behaviour of Concrete

1.8 BEHAVIOUR OF STEEL FIBRE REINFORCED CONCRETE

Compressive strength is little influenced by steel fibre addition. High compressive this can be achieved using silica fume or fly ash. However, the use of steel fibres the mode of failure of high strength concrete from an explosive brittle one to a more ductile one, again showing the increased toughness of SFRC and its ability to absorb energy under dynamic loading.

1.8.1 Behaviour of Steel Fibre Reinforced concrete under compression:

The fibre type, volume fraction and aspect ratio play important roles in determining the compressive ductility and energy absorption capacity of fibre reinforced concrete. The material behavio ur is generally enhanced as the volume fraction and aspect ratio of fibres increase up to limits after which the problems with fresh mix workability and fibre dispersability start to damage the hardened material properties. As the increases in both fibre volume fraction (V_r) and aspect ratio l/d lead to improvement of the same nature in the compressive behaviour of the material, their combined effect has been generally analyzed using the Fibre Reinforcing Index (V_r) 1/d. in general. The higher the fibre reinforcing index, the higher is ductility and energy absorption capacity of fibre reinforced concrete. However, for high values of fibre reinforcing index, the problems with workability and fibre dispersability of fresh mix tend to deteriorate the compressive behaviour of the hardened material.

Due to their material properties, steel fibres do not at all influence the strength parameters of concrete. Under compressive loading, when micro cracking occurs because of transverse tension forces, steel fibres cause crack-closing forces, on the one hand. This leads to an increase of compressive strength. On the other hand, porosity increases when steel fibres are mixed in with the fresh concrete. This effect decreases the compressive Strength of steel fibre reinforced concrete. Both effects in combination have the tendency to cancel each other out.

The influence of fibres in improving the compressive strength of the matrix depends on whether mortar or concrete (having coarse aggregates) is used and on the magnitude of compressive strength. The use of steel fibres in lower strength concretes increases their compressive strength significantly compared to plain unreinforced matrices and is directly related to volume fraction of steel fibre used fibres to concrete increased marginally the compressive strength and the strain corresponding to peak stress.

1.8.2 Behaviour of Steel Fibre Reinforced Concrete under flexure:

In numerous investigations, it has been displayed that the flexure, shear, torsion, punching, dynamic impact behaviours of structural elements improved by the use of Steel Fibre Reinforced Concrete. The positive effects of SFRC on the flexure behaviour of the structural elements are given as follows:

- Increases moment capacity and cracking moment,
- Increase the ductility,
- Increases crack control,
- Increases rigidity,
- Preserves the structural integrity after beam exceeds the ultimate load.

1.9 FACTORS AFFECTING THE FLEXURAL BEHAVIOUR OF STEEL FIBRE REINFORCED CONCRETE

1.9.1 Influence of Steel Fibre Volume Fraction:

With the increase in volume fraction of steel fibres to be added in concrete, the post-crack increase in load is significant. This increase essentially provides the improvement in flexural strength and a stable post-crack behaviour. The bending capacity also increases as the fibre volume fraction increases.

1.9.2 Influence on Fibre length:

The influence of fibre length is very significant for straight fibres. However, it is an established fact that, longer fibres with higher aspect ratios provide better performance in both strength increase and energy absorption as long as they can be mixed, placed, compacted and finished properly. Since hooked-end fibres provide good anchorage, an increase in aspect ratio of hooked-end fibres has less influence compared with straight steel fibres. However, the difference between fibre lengths becomes even less significant at higher volume fractions.

1.9.3 Influence of Fibre geometry:

Three different fibres on the basis of geometry, namely hooked-end fibres, corrugated fibres and deformed-end fibres with equal length influenced the flexural behaviour of Steel Fibre Reinforced Concrete. Concrete with hooked-end fibres have higher tensile strength and post-crack response than the other two types. The drop after the first peak is much more pronounced for corrugated and deformed-end fibres. There are number of factors that influence the behaviour and strength of SFRC in flexure. They are fibre orientation and fibre shape, fibre bond characteristics (fibre deformation). Also, factors that influence the workability of SFRC such as water cement ratio, density, air content and the like could also influence its strength. The ultimate strength in flexure could vary considerably depending upon the volume fraction of fibres, length and bond characteristics of the fibres and the ultimate strength of the fibres. Depending upon the contribution of these influencing factors, the ultimate strength of SFRC could be either smaller or larger than its first cracking strength.

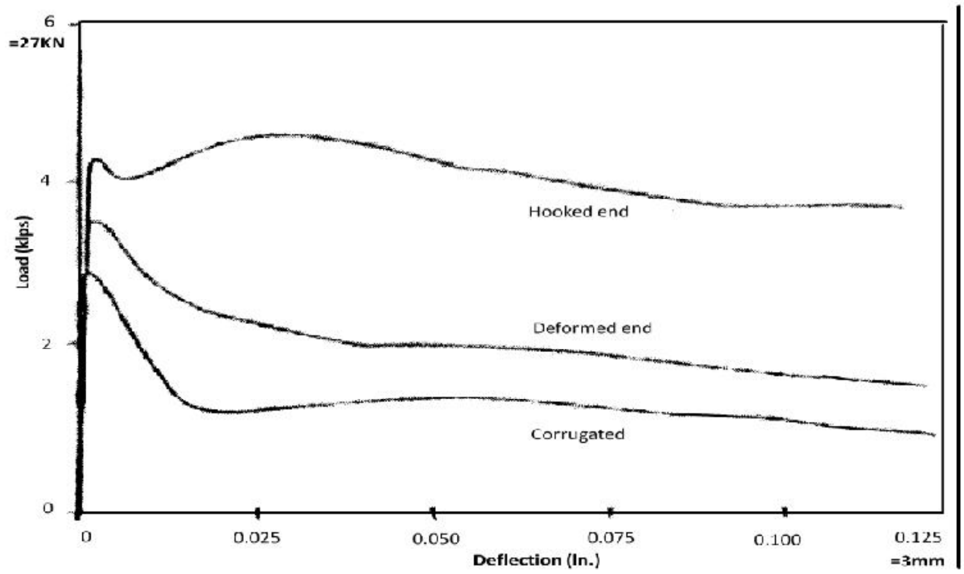

Fig.1.7 Comparison of Effects of Steel Fibre Shapes on Load-Deflection Curves.

1.9.4 Flexural behaviour of Steel Fibre Reinforced concrete:

Generally, there are three stages of the load-deflection response of SFRC specimens tested in flexure. The three stages are:

1. A more or less linear response up to point A. The strengthening mechanism in this portion of the behaviour involves a transfer of stress from the matrix to the fibres by interfacial shear. The imposed stress is shared between the matrix and fibres until the matrix cracks at what is termed as "first cracking strength" or "proportional limit".
2. A transition nonlinear portion between point A and the maximum load capacity at point B (assuming the load at B is larger than the load at A). In this portion, and after cracking, the stress in the matrix is progressively transferred to the fibres. With increasing load, the fibres tend to gradually pull out from the matrix leading to a nonlinear load-deflection response until the ultimate flexural load capacity at point B is reached. This point is termed as "peak" strength.
3. A post peak descending portion following the peak strength until complete failure of the composite. The load-deflection response in this portion of behaviour and the degree at which loss in strength is encountered with increasing deformation is an important indication of the ability of the fibre composite to absorb large amounts of energy before failure and is a characteristic that distinguishes fibre-reinforced concrete from plain concrete.

This characteristic is referred to as toughness.

The nonlinear portion between A and B exists, only if a sufficient volume fraction of fibres is present. For low volume fraction of fibres (V_f < 0.5%), the ultimate flexural strength coincides with the first cracking strength and the load-deflection curve descends immediately after the cracking load.

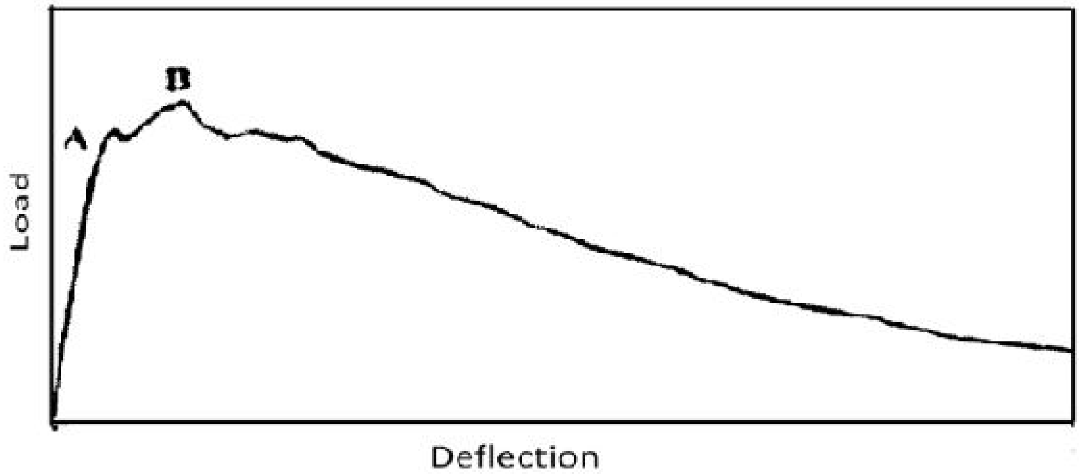

Fig.1.8 Load Deflection Curve of Steel Fibre Reinforced Concrete Specimens

1.10 APPLICATIONS OF STEEL FIBRES

The uniform dispersion of fibres throughout the concrete mix provides isotropic properties not common to conventionally reinforced concrete. The applications of fibres in concrete industries depend on the designer and builder in taking advantage of the static and dynamic characteristics of this new material. The main area of FRC applications are

1.10.1 Runway, Aircraft, Parking, and Pavements

For the same wheel load FRC slabs could be about one half the thickness of plain concrete slab. Compared to a 375mm thickness' of conventionally reinforced concrete slab, a 150mm thick crimped-end FRC slab was used to overlay an existing asphaltic-paved aircraft parking area. FRC pavements are now in service in severe and mild environments.

1.10.2 Tunnel Lining and Slope Stabilization

Steel fibre reinforced shortcrete (SFRS) are being used to line underground openings and rock slope stabilization. It eliminates the need for mesh reinforcement and scaffolding.

1.10.3 Blast Resistant Structures

When plain concrete slabs are reinforced conventionally, tests showed(llj that there is no reduction of fragment velocities or number of fragments under blast and shock waves. Similarly, reinforced slabs of fibrous concrete, however, showed 20 percent reduction in velocities, and over 80 percent in fragmentations.

1.10.4 Thin Shell, Walls, Pipes, and Manholes

Fibrous concrete permits the use of thinner flat and curved structural elements. Steel fibrous shortcrete is used in the construction of hemispherical domes using the inflated membrane process. Glass fibre reinforced cement or concrete (GFRC) , made by the spray-up process, have been used to construct wall panels. Steel and glass fibres addition in concrete pipes and manholes improves strength, reduces thickness, and diminishes handling damages.

1.10.5 Dams and Hydraulic Structure

FRC is being used for the construction and repair of dams and other hydraulic structures to provide resistance to cavitation and severe errosion caused by the impact of large waterboro debris.

1.10.6 Other Applications

These include machine tool frames, lighting poles, water and oil tanks and concrete repairs.

1.11 OBJECTIVES OF RESEARCH

After studying about the properties of fibres, its scope in concrete world can be well judged. The objective of the present study is to evaluate following properties:

- Compressive strength
- Splitting tensile strength
- Flexural strength

- Toughness as measured by toughness indices

The above properties were studied for the various concrete mixes obtained by introducing two types of steel fibres (hooked end fibres and corrugated fibres) at certain volume fraction in concrete.

1.12 ORIENTATION OF THESIS

The thesis report consists of five chapters:

Chapter 1-Provides introduction about steel fibres, their properties, mechanism, their behaviour under compression and flexure and their applications.

Chapter 2- Deals with the study of various researchers on Steel Fibres and their effect on mechanical properties (compressive strength, flexural strength and splitting tensile strength).

Chapter 3- Deals with the scheme of experimentation, materials used and variables involved. Information about concrete mix design is also illustrated in this chapter.

Chapter 4- Presents the results, and their analysis for the strength properties such as compressive strength, splitting tensile strength and flexural strength.

Chapter 5- Summarizes and concludes the findings of the study. Few recommendations for further studies are also discussed.

References are placed at the end.

1.13 SUMMARY

This chapter discussed about the (i) Types, properties of Steel Fibres in civil Engineering work, (ii) mechanisms used, (iii) behaviour under compression and flexure, (iv) objective of the thesis and (v) orientation of thesis.

CHAPTER 2 LITERATURE REVIEW

2.1 GENERAL

Plain unreinforced concrete is the brittle material, with low tensile strength and low strain quality. The role of randomly distribute discontinuous fibres is to bridge across the cracks to provide some post-cracking ductility. This can be done if the fibres are sufficiently strong, sufficiently bonded to material, and permit the FRC to carry significant stress over the relatively large strain capacity in the post-cracking stage. The most important aspect controlling the performance of steel fibres in concrete are –Aspect ratio, volumetric concentration, and geometrical shape. Steel fibres are defined as short discrete length of steel having an aspect ratio in the range of 20-100 with any cross-section and that are sufficiently small to be randomly dispersed in an unhardened concrete mixture using usual mixing procedure. Based on shape, steel fibres are categorized as straight, hooked, paddled, deformed, crimped, and irregular. These are incorporated in concrete so to increase the tensile strength of concrete by working as crack arrestors and prevent the propagation of the cracks. These fibres are uniformly distributed and randomly arranged. This concrete is named as fibre reinforced concrete. The main reasons for adding fibres to concrete matrix is to improve the post cracking response of the concrete, i.e., to improve its energy absorption capacity and apparent ductility, and to provide crack resistance and crack control. Also, it helps to maintain structural integrity and cohesiveness in the material. The initial researches combined with the large volume of follow up research have led to the development of a wide variety of material formulations that fit the definition of Fibre Reinforced Concrete.

2.2 EFFECT OF FIBRE ON WORKABILITY

Vairagade et al., (2012) studied the introduction to Steel Fibre Reinforced Concrete on Engineering Performance of Concrete. The efficiency of all fibre reinforcement is dependent upon achievement of a uniform distribution of the fibres in the concrete, their interaction with the cement matrix, and the ability of the concrete to be successfully cast or sprayed. Essentially, each individual fibre needs to be coated with cement paste to provide any benefit in the concrete. Regular users of fibre reinforcement concrete will fully appreciate that adding more fibres into the concrete, particularly of a very small diameter, results in a greater negative effect on workability and the necessity for mix design changes. The slump changed due to the different type of fibre content and form. The reason of lower slump is that adding steel fibres can form a network structure in concrete, which restrain mixture from segregation and flow. Due to the high content and large surface area of fibres, fibres are sure to absorb more cement paste to wrap around and the increase of the viscosity of mixture makes the slump loss.

Wafa (1990) studied Properties and Applications of Fibre Reinforced Concrete. It was studied that the conventional slump test (ASTM CI43-78) and the inverted slump cone test (ASTM C995-83) were conducted to compare the performance of the plastic concrete reinforced with the two different types of fibres. The time it takes an inverted lamp cone full of FRC to be emptied after a vibrator is inserted into the concrete is called the inverted-cone time. It should vary between 10 and 30 seconds. The hooked fibres performed well during mixing because no balling occurred even though the fibres were added to the mixer along with the aggregate all at one time. The straight fibres had to be sprinkled into the mixer by hand to avoid balling. It took approximately 2 minutes to add the straight fibres to the mix, resulting in a 2 minutes extra mixing time. Fig 2.1 made it clear that the effect of fibre content on both slump and inverted cone time. It is clearly seen that as the fibre content increased from 0.0 to 2.0 percent, the slumps value decreased from 230 to 20mm, and the time required to empty the inverted cone time increased from 20 to 70 secon'ds. For the highest fibre volume percentage used (Vf = 2.0 percent) it was noticed that the FRC in the test specimens was difficult to consolidate using the internal vibrator.

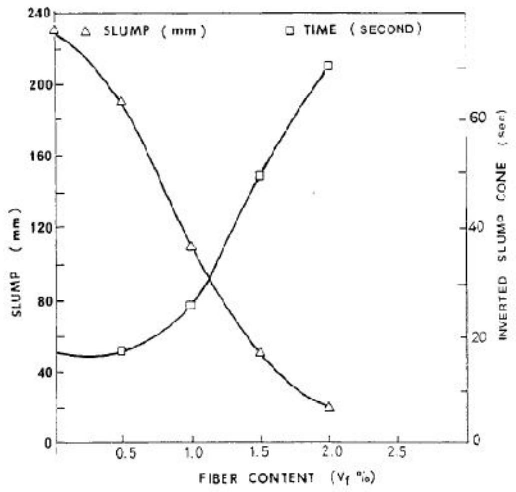

Fig 2.1Effect of Fibre Content on Workability (Wafa 1990)

2.3 MECHANICAL PROPERTIES OF STEEL FIBRE REINFORCED CONCRETE

In this section the various mechanical properties like compressive strength, Split tensile strength, Flexural strength are discussed in details.

2.3.1 Mechanical Properties of Steel Fibre Reinforced Concrete

Ibrahim et al., (2013) studied effects on mechanical properties of industrialised steel fibres addition to normal weight concrete. Five mixes of concrete grade were produced with the addition of steel fibres (SFs) at different volumetric percentages: 0% (as control specimen), 0.50%, 0.75%, 1.00% and 1.25% by absolute concrete weight. SFs with aspect ratio, *l/d* = 80 with 0.75 mm diameter and hooked at both ends were used in this study. The effects of adding SFs in concrete on its mechanical properties were measured for the cube compressive strength. Super-plasticizer admixture was added during the mixing process in order to increase the workability of the fresh concrete. All proportions of concrete mixes were remained exactly the same for all five concrete batches including the one with the added 0.50%, 0.75%, 1.00% and 1.25% of Steel fibres dosages.

Fig 2.2 Physical appearance of fresh SFRC in the drum mixer (Ibrahim et al., 2013)

The micromechanical advantages f or adding SFs in plain concrete obviously can be seen by its post-cracking effects, ductility and energy absorption. The SFs when uniformly dispersed throughout the specimens, acting as a reinforcement and help for better distribution of stresses. Therefore, the cracks occurred in SFRC specimens are smaller in size compared with plain concrete (and even m ore will break up at ultimate load).

Table 2.1 Average Mechanical Properties of Concrete with Different Volume Fraction of Steel Fibres (Ibrahim et al., 2013)

Concrete cube compressive strength test(N/mm²)			
Concrete Batch	7-days	14 -days	28- days
1-Plain concrete	19.7	25.9	35.1
2 (.50%)	18.6	23.0	31.9
3(.75%)	21.3	25.0	32.8
4(1.0%)	24.7	28.3	34.2
5(1.25%)	25.5	30.3	34.6

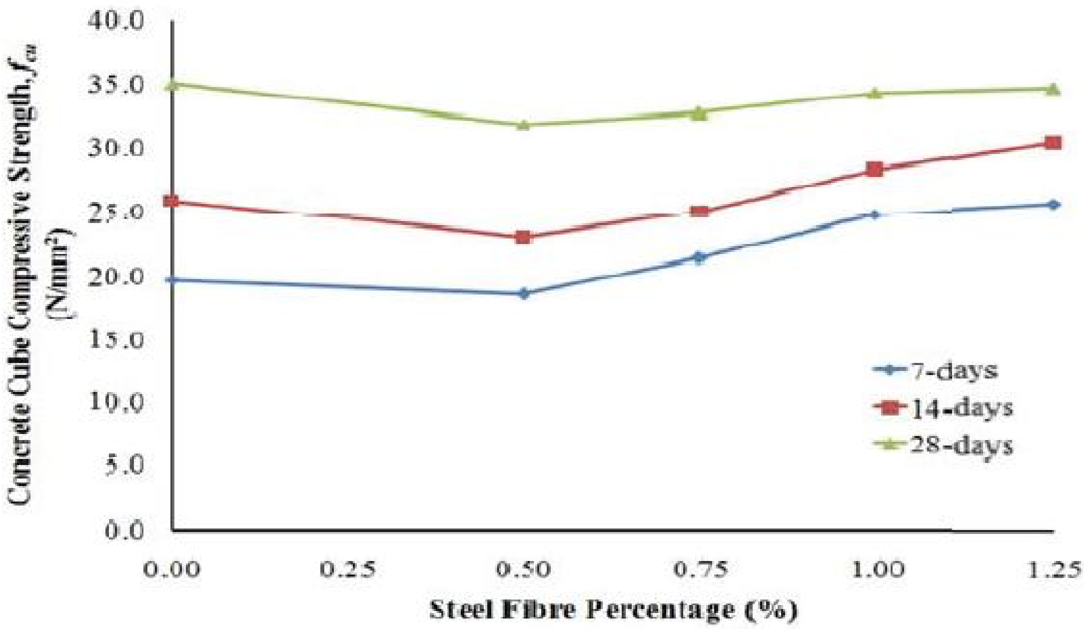

Fig 2.3 Relationship Between Concrete Cube Compressive Strength and Steel Fibre Percentage (Ibrahim et al., 2013)

From the graphs and calculations it can be observed that all SFRC (except for 0.50% SFs) gained early cube compressive strength at 7-days and even higher than plain concrete. SFRC specimens show an increase in strength at 28-days and much better than plain concrete. The study also found that both the cube compressive strengths indicated that there is not much effect for SFRC volumetric percentage less than 1% due to the slow growth strength rates at 28-days. Comparing the results of the cube compressive strength for SFRC with 1.00% and 1.25% of Steel Fibres volumetric percentages, the strengths at 28-days are not much differ from each other.

Alengaram et al., (2014) studied the effect of steel fibres on the enhancement of flexural and compressive toughness and fracture characteristics of oil palm shell concrete. For the test Ordinary Portland cement was used in addition with a polycarboxylic-ether (PCE) based superplasticizer, commercially known as Glenium Ace 388. Hooked-end type steel fibres of length 60 mm with aspect ratio of 80 were used as steel fibres. The mix proportion for the five mixes prepared was binder: water: sand: aggregate ratio of 1:0.33:0.65:1.70 for all mixes. The cement content was fixed at 550 kg/m^3

Table 2.2 Mix proportion (Alengaram et al., 2014)

S.no.	Mix	GGBS replacement (%)	Steel fibre (%)
1	K1	50%	0%
2	K2	50%	0.5%
3	K3	50%	0.75%
4	K4	50%	1.0%
5	N1	0%	0%

The results of compressive strength for the mixes mentioned above were detailed in table 2.2 and in fig. 2.1.

Table 2.3 Compressive Strength Results (Alengaram et al., 2014)

Mix	Compressive strength (MPa)
K1	33.51
K2	36.78
K3	43.57
K4	45.96
N1	42.28

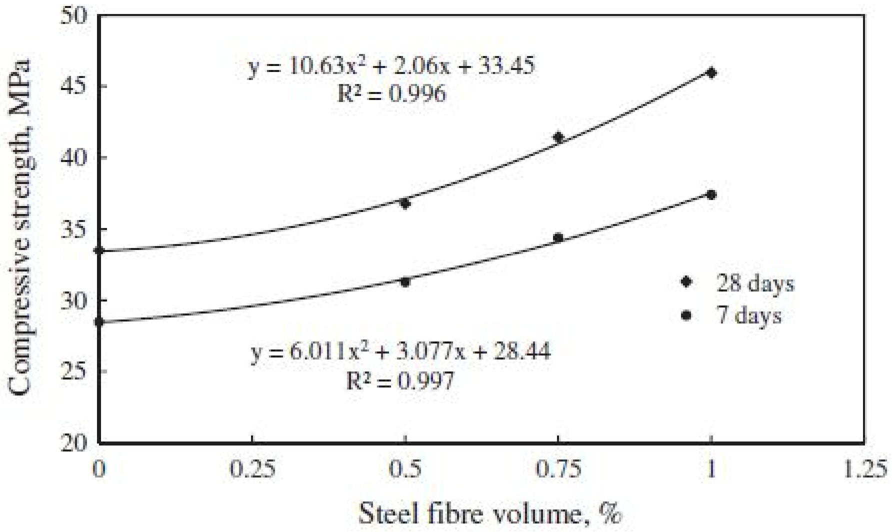

Fig.2.4 Relationship of Steel Fibre Volume with 7 and 28-day Compressive Strength (Alengaram et al., 2014)

The influence of steel fibre and GGBS on the compressive strength of concrete can be seen from fig.2.1. The 28-day compressive strength was found about 23% higher than that of 7-day for 1.0% of fibre volume. This could be attributed to the presence of GGBS in addition to the increase in fibre content. The hydration of GGBS is slower at the earlier ages, and it could have contributed to weaker bonding of steel fibres with the binder matrix at 7 days. The increased in the GGBS hydration at 28 days could have led to stronger fibre–matrix bond, and thus effect of steel fibre was more pronounced at this stage.Table 2.2 made clear that the compressive strength results were different only due to the presence of GGBS in concrete.

Khaloo et al., (2014) studied the mechanical performance of self-compacting concrete(SCC) reinforced with steel fibres. Mechanical characteristics were obtained through compressive strength with cube specimen of 150x150x150mm. Compressive strength of concrete with steel fibre of volume fractions (0.5%, 1%,1.5%,and 2%) was investigated

Table 2.4 Compressive Strength Results of SCC Specimens (Khaloo et al., 2014)

Compressive strength(MPa)			
specimen	7 days	28 days	91 days
MS-SCC	29.4	39.7	47.3
MS-SCC – F0.5	26.7	38.0	46.3
MS-SCC – F1.0	24.2	35.1	43.2
MS-SCC – F 1.5	23.2	33.9	40.3
MS-SCC- F 2.0	22.4	32.3	40.2
HS-SCC	47.4	59.5	66.3
HS-SCC – F0.5	46.0	59.1	65.4
HS-SCC – F1.0	42.2	58.2	61.8
HS-SCC– F1.5	42.1	57.0	60.5
HS-SCC- F2.0	40.4	55.2	59.1

The results of the compressive strength at 7 days, 28 days, 91 days with the different fibre volume fraction are shown in the table 2.4. It can be observed, compressive strength decreases by increasing the percentages of fibres. Strength reduction might be due to decreasing of workability of the concrete. Increasing the percentage of steel fibres results in decrease of concrete workability which in turn causes reduction in compaction levels of vibrated concrete. Compressive strength decreases by adding more fibre volume fractions from 0.5% to 2%. The decrease in compressive strength for 28-day specimens is 0.7%, 2.2%, 4.2%, and 7.5%, respectively, with respect to the plain SCC specimen.

Zheng et al., (2013) studied Compressive and tensile properties of reactive powder concrete with steel fibres at elevated temperatures. In this paper it is presented the effect of temperature on the compressive and tensile properties of reactive powder concrete. Mixtures were prepared with steel fibre contents of 0%, 1%, 2% and 3%. Steel fibres were added in the same proportion as the concrete volume. 108 cube specimens (70.7 x 70.7 x 70.7 mm) were cast.

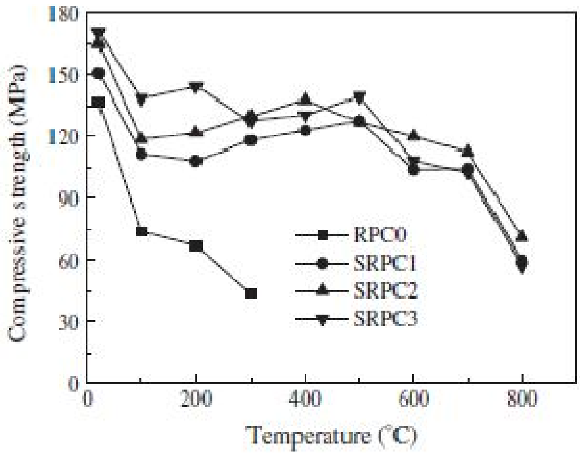

Fig 2.5 Compressive Strengths of Cube Reactive Powder Concrete (RPC) at Different Temperatures (Zheng et al., 2013)

The compressive strength of RPC0 decreases sharply at 100ºC, and decreases continuously between 200 and 300ºC. The free water begins to evaporate, hairline cracks and pores form, causing compressive strength loss. The compressive strengths of SRPC1, SRPC2 and SRPC3 increase in the 200–600ºC temperature range in comparison with compressive strength at 100ºC. The compressive strengths of SRPC1, SRPC2 and SRPC3 at 600ºC are 103.9, 119.83, 108.14 MPa, respectively. This result is attributed to dry hardening, which increases the strength at temperatures between 150 and 350º. Between 20 and 300ºC, the compressive strength of SRPC3 is larger than the compressive strengths of SRPC1 and SRPC2. Compressive strength increases between 20 and 300ºC with an increase in steel fibre content.

Mueller et al., (2011) studied the effect of steel fibres on mechanical properties of high-strength concrete. This paper deals with a role of steel fibres having different configuration in combination with steel bar reinforcement. It reports on results of an experimental research program that was focused on the influence of steel fibre types and amounts on flexural tensile strength, fracture behaviour and workability of steel bar reinforced high-strength concrete beams. Two type of steel fibres were used and their configurations are (two straight with end hooks with different ultimate tensile strength and one corrugated) were used. The compressive strength of the concrete mixes varied between 90 and 115 MPa and the fibre content was 1% by volume. It was shown that low fibre volume has little effect on compressive strength. concrete mixture, the HSSFRC were made for different fibre amounts (20, 40, 60 kg/m3) and fibres types F1, F2 and F3. The mixtures for production of HSSFRC were essentially the same just the amounts of steel fibres were different. Average compressive and splitting strengths in specimens with different fibre contents are given in Fig 2.5 . Following these figures, the strength increases as the fibre content becomes higher. The compressive strength for all HSSFRC specimens was higher than for HSC ones.

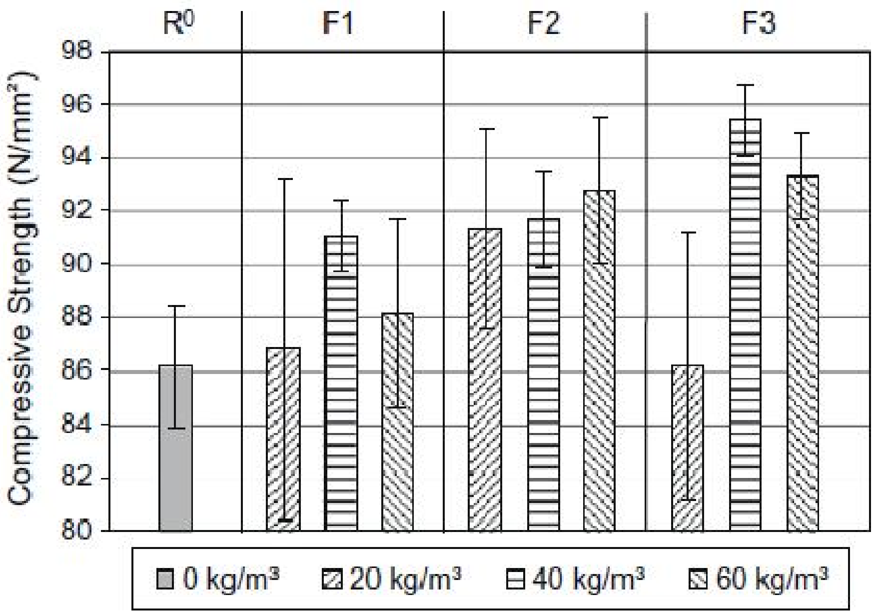

Fig 2.6 Average compressive strength of cubes (Mueller et al., 2011)

Singh et al., (2008) discussed the results of an experimental investigation carried out to study the properties of plain concrete and steel fibre reinforced concrete (SFRC) containing fibres of mixed aspect ratio. The specimen incorporated three different volume fractions, i.e., 1.0%, 1.5% and 2.0% of corrugated steel fibres and each volume fraction incorporated mixed steel fibres of size 0.6 x 2.0 x 25 mm and 0.6 x 2.0 x 50 mm in different proportions by weight. A fibre combination of 65% 50 mm + 35% 25 mm long fibres can be adjudged as the most appropriate combination to be employed in SFRC for compressive strength. The specimens used for compressive strength tests were 150x150x150 mm cubes. The results of compressive strength tests conducted on plain concrete and SFRC specimens with different fibre volume fractions, each fibre volume fraction containing different combinations of mixed steel fibres, are presented in fig given below.

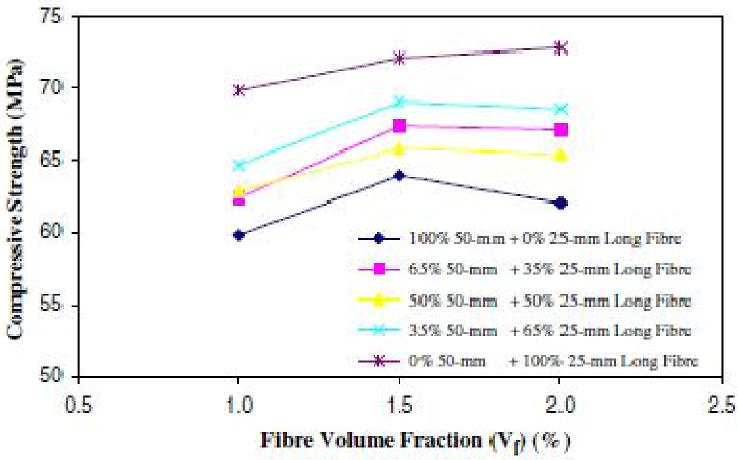

Fig 2.7 Cube compressive strength of fibrous concrete with mixed aspect ratio of fibres at different fibre volume fractions.(Singh et al., 2008)

The results show that in general, there is an increase in compressive strength varying from 3% to 26% on addition of fibres to the concrete. It can also be observed that there is an increase in compressive strength varying from 3% to 21%, 11% to 25% and 7% to 26% for concrete mixes having 1.0%, 1.5% and 2.0% volume fractions of fibres. The maximum increase in compressive strength for other mixes was observed at fibre volume fraction of 1.5%. In general, it may be concluded that on increasing the percentage of short fibres in concrete mix and with increase in the gross fibre content in the mix, the compressive strength increases. A careful examination of the results indicates that a fibre combination of 65% 50 mm + 35% 25 mm long fibres can be taken as the most appropriate combination for compressive strength.

Song et al., (2004) studied the mechanical properties of high-strength steel fibre-reinforced concrete .It was investigated that mechanical properties of high-strength steel fibre-reinforced concrete. The properties included compressive and splitting tensile strengths, modulus of rupture, and toughness index. The steel fibres were added at the volume fractions of 0.5%, 1.0%, 1.5%, and 2.0%. The compressive strength of the fibre-reinforced concrete reached a maximum at 1.5% volume fraction, being a 15.3% improvement over the HSC. The compressive strength test, performed on 15 of the standard test cylinders, followed ASTM C39 test for compressive strength of cylindrical concrete specimens. The cylinders were loaded, in a testing machine under load control, at the rate of 0.3 MPa/s until failure. The production of concrete, the constituent materials were initially mixed without fibres. The fibres were then added in small amounts to avoid fibre balling and to produce the concrete with uniform material consistency and good workability. For concrete mixes with a 2.0% volume of fibres, extra time was required for mixing. The freshly mix steel fibre-reinforced concrete was placed in two equal layers into a cylinder mold to cast a standard 150x300 mm cylindrical concrete specimen for a compressive strength test

Table 2.5 Strength test results and strength-effectiveness on HSFRC and HSC (Song et al., 2004)

Fibre volume fraction(%)	Compressive Strength	
	Measured (MPa)	Strength-effectiveness(5)
0	85	-
.5	91	7.1
1.0	95	11.8
1.5	98	15.3
2.0	96	12.9

The compressive strength development of HSFRC versus HSC appears Fig. 1, declaring that the compressive strength f 0 c of HSC was 85 MPa and of HSFRC provided an improvement at each volume fraction. The improvement, as the strength-effectiveness in Table 1, was 7.1% at 0.5% fraction, 11.8% at 1.0% fraction, 15.3% at 1.5% fraction, and reduced to 12.9% at 2.0% fraction, being a reduction small compared to the maximum improvement at 1.5% fraction. The compressive strength improvement of HSFRC ranged from 7.1% to 15.3% at the volume fractions of 0.5%

to 2.0%, comparable to the improvements of 4.3–10.4% for normal- strength concrete at the same fractions.

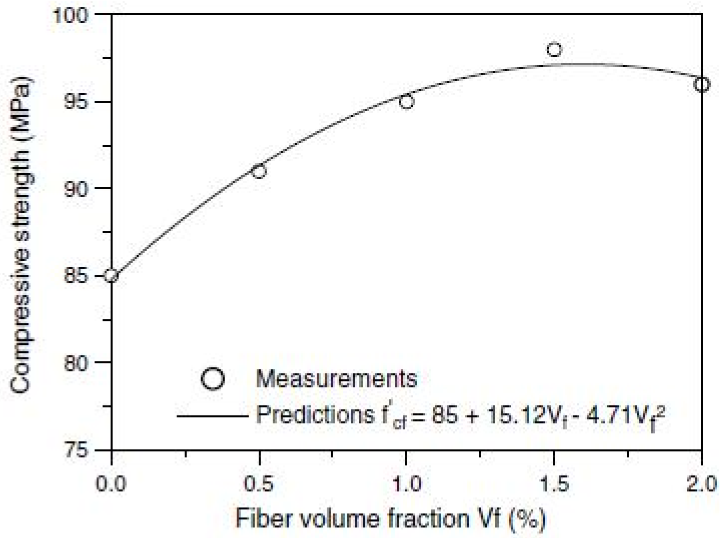

Fig 2.8 Effect of fibre volume on compressive strength. (Song et al., 2004)

Kusterle et al., (2000) studied Compressive stress strain relationship of steel fibre-reinforced concrete at early age. Hooked end fibres were used for the experiment of aspect ratio of 60. The material and mixes of SFRC plate was ordinary Portland cement 450 kg/m3, aggregate 1770kg/m3, super-plasticizer: 1% of cement, water cement/ratio: 0.45. The steel fibre contents for compressive strength tests were 20, 40 and 60 kg/m3; fibre content at compression was 60 kg/m3, fibre length of 30 mm and of diameter of 0.5 mm. The compressive test describes the state of tunnel concrete more closely than the well known bending beam and plate tests:

- In many cases, the tunnel shell is subjected mainly to compressive load.
- The properties of steel fibre-reinforced concrete and shotcrete at early age have great significance for load bearing capacity and serviceability of a tunnel shell.

The cube specimens for compression strength were load-controlled and tested at the ages of 8, 10, 18, 36, 48 and 72 h.

Table 2.6 Development of Compressive Strength of Concrete and SFRC (Kusterle et al., 2000)

Age of concrete Hours	Compressive Strength N/mm²					
	8	10	18	30	48	72
Concrete without fibres	1.86	4.03	13.89	25.87	32.56	36.06
SFRC 20	2.35	5.11	18.63	26.33	32.65	37.52
SFRC 40	2.5	5.08	15.5	23.5	32.44	37.13
SFRC 60	1.8	3.8	15	25	33.3	37

The table shows that the compressive strength of SFRC after 8 and 10 h were achieved with a fibre content of 40 kg/m^3. As the concrete gets hardened after 30 h, the fibres has no influence on the compressive strength.

Fig 2.9 Steel Fibre distribution in the Cube of SFRC after the test of Compression Strength (Kusterle et al., 2000).

2.3.2 Flexural Strength.

Wight et al., (1994) studied flexural toughness of steel fibre reinforced concrete .The material used in the investigation was maximum aggregate size, water/cement ratio, fine/ coarse aggregate ratio, steel fibre percentage by volume and type of steel fibre used. The addition of steel fibres to concrete not only results in a large increase in flexural strength, but also a considerable increase in toughness. Flexural toughness can be measured in terms of the total area under load-deflection curve in flexure. The other extreme is the use of the area under load-deflection curve up to first crack load. This area represents only the energy absorbed up to the point where the fibres start to contribute to the load capacity.

Water cement ratio used in the investigation was 0.42, 0.51, 0.60. Volume fraction of the steel fibre used in the investigation were 0.00% , 0.75%, 1.50%. Brass coated steel fibres wth aspect ratio 100 were also used in the investigation.

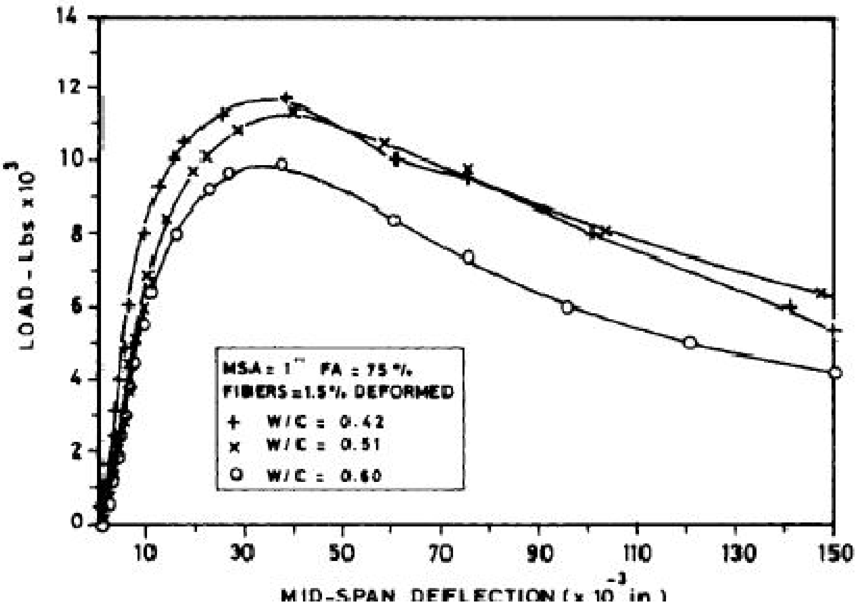

Fig 2.10 Load-Deflection diagram (Wight et al., 1994)

The approach for determining flexural toughness of S. F. R. C. is based on the assumption that the load-deflection curves for beams made of steel fibre reinforced concrete closely resemble that of a beam made of an elasto-plastic material, assuming the yield and ultimate moment capacities of the elasto-plastic beam are equal.

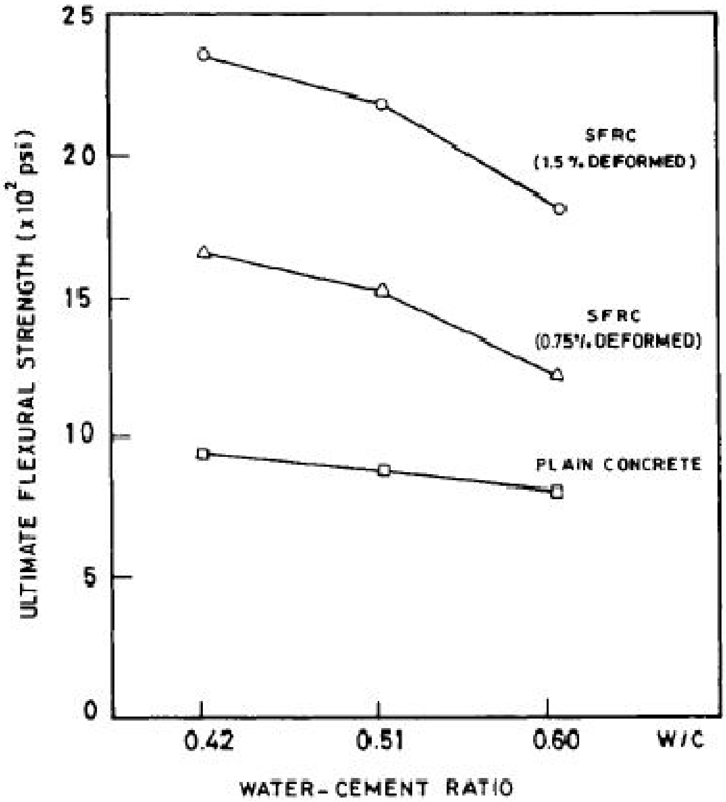

Fig 2.11 Ultimate Flexural Strength vs Water-Cement ratio (Wight et al., 1994)

The largest area were observed for concrete reinforced with 1.5% deformed steel fibres having high fine aggregate content, and low water-cement ratio. Flexural toughness data were analyzed based on the assumption that S.F.R.C. load-deflection diagrams are similar to those of elasto-plastic materials.

Alengaram et al., (2014) studied studied the effect of steel fibres on the enhancement of flexural and compressive toughness and fracture characteristics of oil palm shell concrete. For the test Ordinary Portland cement was used in addition with a polycarboxylic-ether (PCE) based superplasticizer, commercially known as Glenium Ace 388. Hooked-end type steel fibres of length 60 mm with aspect ratio of 80 were used as steel fibres. The mix proportion for the five mixes prepared was binder: water: sand: aggregate ratio of 1:0.33:0.65:1.70 for all mixes. The cement content was fixed at 550 kg/m^3 . One of the significant benefits on the addition of steel fibre in concrete is its improved post-cracking response. Three-point load was applied on notched 100 mm x 100 mm x 500 mm beam to determine the flexure strength.Depends on the method ASTM C1609-12, the toughness of FRC was determined using the area under the load–deflection curve of specimen subjected to bending. The ratio of the flexural toughness of specimens with fibre and without fibre (i.e. the ratio of flexural toughness of SFOPSC and OPSC) is taken as the flexural toughness ratio.

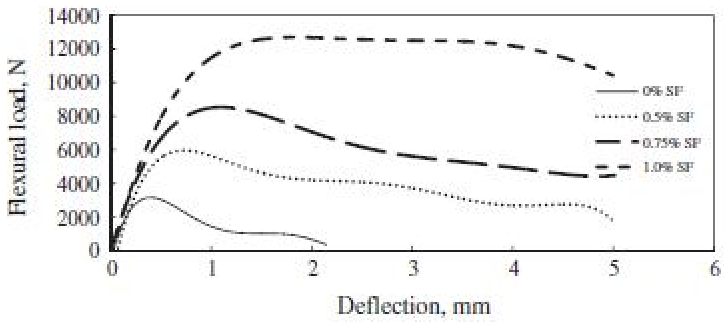

Fig 2.12 Load–Deflection Curve of SFOPSC Under Three Point Bending (Alengaram et al., 2014)

The addition of steel fibre was found to have significant effect as it dramatically increased the toughness of the OPSC, with increase of about 6, 9 and 17 times higher than that of the control concrete for the specimens with the addition of 0.5%, 0.75% and 1.0% of steel fibres, respectively. From the above diagram it can be investigated that not only the peak load was increased with the addition of steel fibres, but the post cracking response was found to be totally different for the control specimens compared to the specimens with fibres.

Table 2.7 Compressive strength results (Alengaram et al., 2014)

Mix	Compressive strength (MPa)
K1	33.51
K2	36.78
K3	43.57
K4	45.96
N1	42.28

Table 2.8 Flexural Toughness and Fracture Parameters of the SFOPSC (Alengaram et al., 2014)

Mix	Flexural Toughness (N/mm²)
K1	3364
K2	18983
K3	29956
K4	56032

Khaloo et al., (2014) studied the mechanical performance of self-compacting concrete reinforced with steel fibres. Flexural strength of concrete with steel fibre of volume fractions (0.5%, 1%,1.5%,and 2%) was investigated.

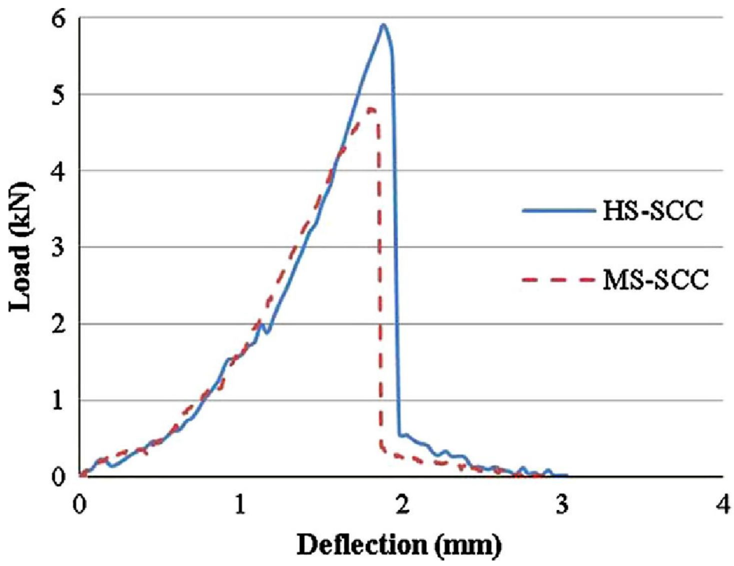

Fig 2.13 Load–Deflection Diagram for Plain Concrete Beams (Khaloo et al., 2014)

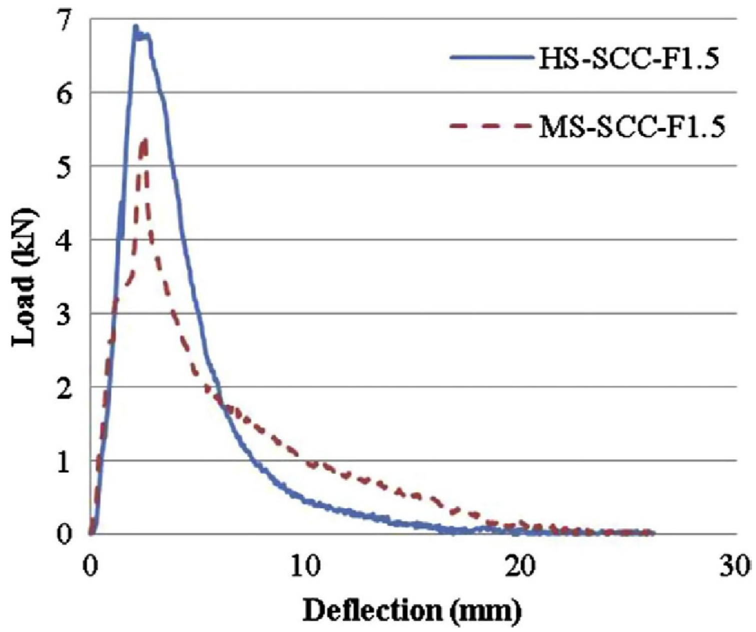

Fig 2.14 Load–Deflection Diagram for Reinforced Beams with 1.5% Steel Fibre Volume Fraction (Khaloo et al., 2014)

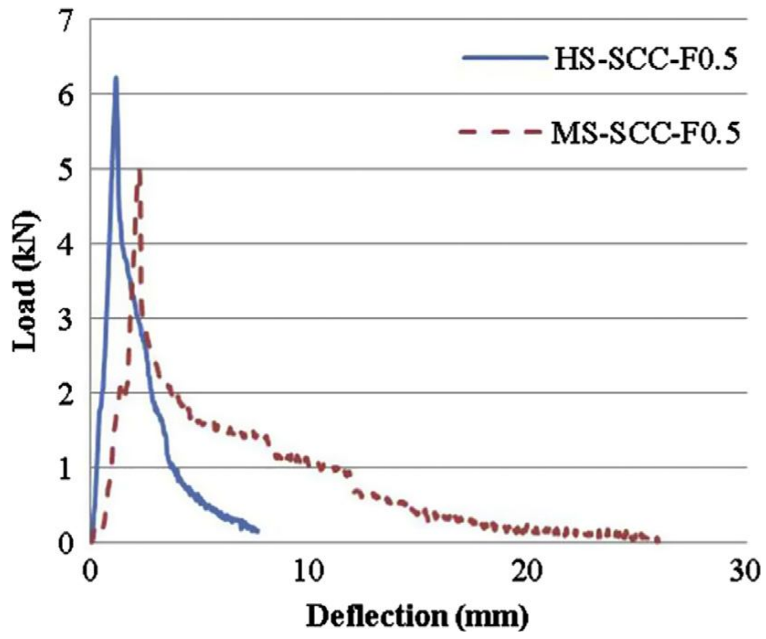

Fig 2.15 Load-deflection diagram for reinforced beams with 0.5% steel fibre volume fraction (Khaloo et al., 2014)

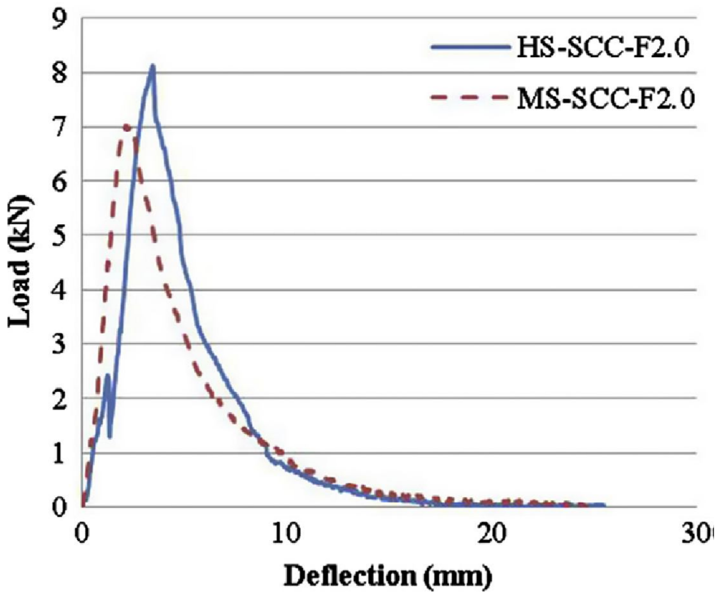

Fig 2.16 Load–deflection diagram for reinforced beams with 2% steel fibre volume fraction (Khaloo et al., 2014)

Table 2.9 Flexural strength and maximum bending load of beams at 28 days.

Specimen	Maximum load(KN)	Flexural Strength(MPa)
MS-SCC	4.81	4.41
MS-SCC F0.5	5.00	4.59
MS-SCC F1.0	5.32	4.88
MS-SCC F1.5	5.45	5.00
MS-SCCF 2.0	7.02	6.44
HS-SCC	5.90	5.41
HS-SCC F0.5	6.23	5.72
HS-SCC F1.0	6.44	5.91
HS-SCC F1.5	6.91	6.34
HS-SCC F 2.0	8.11	7.44

From Table 2.11, the addition of fibre volume fractions from 0.5% to 2% causes the flexural strength increases by 4.1%, 10.6%, 13.4%, and 46%, respectively, with respect to the plain SCC specimen (MS-SCC) at 28 days. Moreover, the addition of fibre volume fractions from 0.5% to 2% for high strength SCC class causes the flexural strengths increase 5.7%, 9.2%, 17.2%, and 37.5%, respectively, with respect to the plain specimen (HS-SCC) at the age of 28 days.

Ibrahim et al., (2011) studied effects on mechanical properties of industrialised steel fibres addition to normal weight concrete. . Five mixes of concrete grade were produced with the addition of steel fibres (SFs) at different volumetric percentages: 0% (as control specimen), 0.50%, 0.75%, 1.00% and 1.25% by absolute concrete weight. SFs with aspect ratio, *l/d* = 80 with 0.75 mm diameter and hooked at both ends w ere used in this study. The effects of adding SFs in concrete on its mechanical properties were measured for the cube compressive strength. Advantages of SFRC increases in concrete toughness, energy absorption capacity, tensile strength and improves concrete durability. Super-plasticizer ad mixture was a dded during the mixing pr ocess in order to increase the workability of the fresh concrete. All proportions of concrete mixes were rem ained exactly the same for all five conc rete batches including the one with the added 0.50%, 0.75%, 1.00% and 1.25% of Steel fibres dosages.

Table 2.10 Average mechanical pr operties for concrete with different SF volumetric percentages (Ibrahim et al., 2011)

Tensile strength (N/mm²)			
Concrete Batch	7-days	14 -days	28- days
1-Plain concrete	5.3	5.5	6.4
2 (.50%)	5.3	6.3	7.1
3(.75%)	4.4	6.6	7.3
4(1.0%)	4.9	6.5	7.8
5(1.25%)	5.4	6.9	7.9

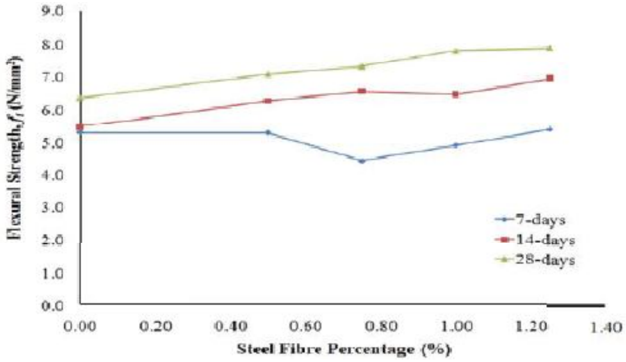

Fig 2.17 Relationship between concrete flexural strength (f_t) and steel fibre percentage (Ibrahim et al., 2011)

The flexural strength increased by 10.94% 1 4.06%, 21.88% and 23.44 % at 28-days for specimens with SF s volumetric percentages of 0.5%, 0.75%, 1.00% and 1.25%, respectively. The experimental investigation shows that SFRC is better than plain concrete especially under tensile and flexural load where SFs take part in absorbing the applied load.

Singh et al. (2008) studied Properties of steel fibrous concrete containing mixed fibres in fresh and hardened state. The specimen incorporated three different volume fractions, i.e., 1.0%, 1.5% and 2.0% of corrugated steel fibres and each volume fraction incorporated mixed steel fibres of size 0.6 x 2.0 x 25 mm and 0.6 x 2.0 x 50 mm in different proportions by weight. for static flexural strength tests - 100 mm x 100 mm x 500 mm beams. The specimens were cast in different batches.

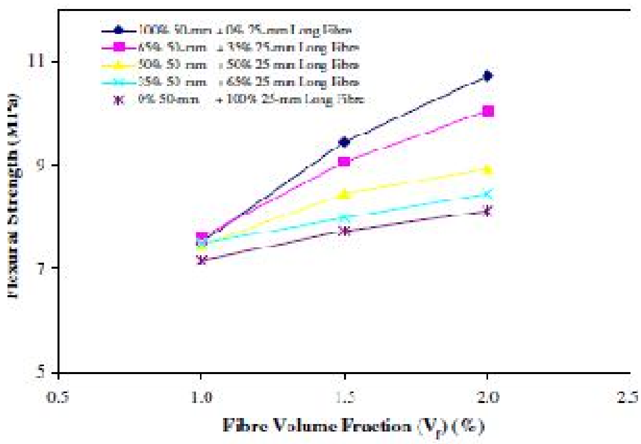

Fig 2.18 Static flexural strength of fibrous concrete with mixed aspect ratio of fibres at different fibre volume fractions(Singh et al., 2008)

The maximum increase in static flexural strength, taken as average of three batches, varied from 34% to 42%, 44% to 76% and 52% to 100% for concrete mixes having 1.0%, 1.5% and 2.0% volume fractions of fibres respectively. The maximum increase in static flexural strength of 100% was observed for concrete with 100% long fibres at fibre volume fraction of 2.0%. The fibre volume fraction and the use of mixed aspect ratio of fibres are more effective in influencing the ultimate load and deflection than the first crack load and the corresponding deflection. The first crack deflection is only slightly influenced by the fibre volume fraction and the use of mixed aspect ratio of fibres had insignificant effect on the first crack deflection.

2.3.3 Split Tensile Strength

Alengaram et al., (2014) studied studied the effect of steel fibres on the enhancement of flexural and compressive toughness and fracture characteristics of oil palm shell concrete. For the test Ordinary Portland cement was used in addition with a polycarboxylic-ether (PCE) based superplasticizer, commercially known as Glenium Ace 388. Hooked-end type steel fibres of length 60 mm with aspect ratio of 80 were used as steel fibres. The mix proportion for the five mixes prepared was binder: water: sand: aggregate ratio of 1:0.33:0.65:1.70 for all mixes. The cement content was fixed at 550 kg/m^3 . One of the significant benefits on the addition of steel fibre in concrete is its improved post-cracking response. Direct tensile strength increased up to 41% with the addition of 1.0% steel fibre.

Table 2.11 Mechanical properties of SFOPSC (Alengaram et al., 2014)

Mix	SplitTensileStrength(N/mm^2)
K1	2.49
K2	4.80
K3	5.80
K4	6.94

The splitting tensile test is an indirect and easier method to determine concrete tensile strength. The determination of concrete tensile strength is necessary to provide information on the maximum tensile load that a concrete member can sustain before cracking. In this investigation, it was found that the addition of steel fibre greatly improved the splitting tensile strength of the concrete. As found from this experimental investigation, the addition of 0.5%, 0.75% and 1.0% steel fibre volume enhanced the splitting tensile strength up to 93%, 133% and 178% respectively compared to the control concrete. When significant amount of tensile stress was introduced in concrete, micro-cracks and subsequently macro-cracks were formed. The increase in the load induces critical crack growth at the tip of macro-cracks which eventually led to failure of concrete. The steel fibres act as a means of stress transfer whereby the tensile stress was transferred across fibres, which subsequently delayed the propagation of macro-cracks and improved the splitting tensile strength of concrete.

Khaloo et al., (2014) studied the mechanical performance of self-compacting concrete reinforced with steel fibres. Splitting tensile strength tests with standard cylindrical specimens of 150 x 300 mm. Split tensile strength are increased by increasing the amount of fibres.

Table 2.12 Characterstics of Used steel fibres(Khaloo et al., 2014)

Length(mm)	Width(mm)	Thickness	Aspect ratio
20.6	18.8	0.5	20

Table 2.13 Splitting tensile strength results of SCC specimens(Khaloo et al., 2014)

Split tensile strength(MPa)			
specimen	7 days	28 days	91 days
MS-SCC	2.20	3.37	3.46
MS-SCC – F0.5	2.26	3.40	3.59
MS-SCC – F1.0	2.43	3.71	3.80
MS-SCC – F 1.5	2.48	3.97	4.01
MS-SCC- F 2.0	2.75	4.33	4.43
HS-SCC	3.16	5.02	5.28
HS-SCC – F0.5	3.44	5.14	5.30
HS-SCC – F1.0	3.61	5.21	5.38
HS-SCC– F1.5	3.88	5.41	5.70
HS-SCC- F2.0	4.33	5.88	6.02

Split tensile strength of the specimens at ages of 7, 28 and 91 days, and with different fibre volume fractions are shown in Table 2.15 From the table it can be seen that splitting tensile strength increases by the addition of fibres. Adding more fibre volume fractions causes more increase in splitting tensile strength. the addition of fibre volume fractions 0.5%, 1%, 1.5%, and 2% causes the splitting tensile strength to increase 0.9%, 10.1%, 17.8%, and 28.5%, respectively, with respect to the plain specimen at 28 days of curing. It can be observed that the fibre volume fractions influence the splitting tensile strength, in which an increase in fibres percentage leads to a rise in splitting tensile strength. Increasing the fibre volume fractions from 0.5% to 2% causes splitting tensile strength to increase 1.2%, 3.8%, 7.8%, and 17.1%, respectively, with respect to the plain concrete at 28 days of curing.

Zheng et al., (2013) studied Compressive and tensile properties of reactive powder concrete with steel fibres at elevated temperatures.This paper represented the effect of temperature on the compressive and tensile properties of reactive powder concrete. Mixtures were prepared with steel fibre contents of 0%, 1%, 2% and 3%. Steel fibres were added in the same proportion as the concrete volume. The tensile strength of RPC with steel fibres decreases at temperatures below 200ºC, increases at temperatures ranging from 200 to 300ºC, and decreases at temperatures above 300ºC.

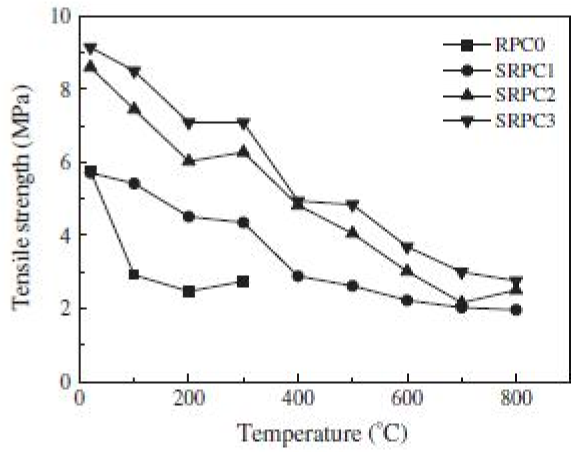

Fig 2.19 Tensile strengths of RPC at different temperatures(Zheng et al., 2013)

The tensile strength of RPC0 decreases sharply from 20 to 100ºC, gradually decreases at 100–200ºC, and finally increases between 200 and 300ºC. The tensile strengths of SRPC1, SRPC2 and SRPC3 decrease linearly from 20 to 200ºC. The tensile strengths of SRPC1, SRPC2 and SRPC3 are 4.51, 6.02 and 7.09 MPa, respectively, at 200ºC, which are 79%, 70.1%, 77.52%.The tensile strength loss at 100ºC results from cracks and pores due to the evaporation of free water. The tensile strength of SRPC1 at 300ºC is higher than the tensile strength at 200ºC.

Chapter-3

Experimental Work

3.1 GENERAL

The details of experiment programme in terms of material properties, test set-up for measuring different parameters and the testing procedure discussed in this chapter.

3.2 MATERIAL PROPERTIES

Cement, fine aggregates, coarse aggregates, recycled coarse aggregate, silica fume, steel fibre super-plasticizer and water is used for present investigation. The properties of these materials are discussed in the following sections.

3.2.1 Cement

Cement is a fine, grey powder. It is mixed with water and materials such as sand, gravel, and crushed stone to make concrete. The cement and water form a paste that binds the other materials together as the concrete hardens. The ordinary cement contains two basic ingredients namely argillaceous and calcareous. In argillaceous materials, clay predominates and in calcareous materials calcium carbonate predominates. Ordinary Portland cement of grade – 43 (J.K cement) conforming to Indian standard IS:8112-1989 has been used in the present study. The results of the various tests on cement properties are given in Table 3.1.

Table 3.1 Physical Properties of Ordinary Portland Cement

Sr. No.	Characteristics	Values obtained	Values as per IS 8112:1989
1.	Consistency	28.2%	-
2.	Initial setting time	127 minutes	Not less than 30 minutes
3.	Final setting time	183 minutes	Not greater than 600 minutes
4.	Fineness	281.3 m^2/kg	Not less than 225 m^2/kg
5.	Specific gravity	3.01	-
6.	Compressive strength (MPa)		
	3 days	33.4	23
	7 days	42.5	33
	28 days	49.9	43

3.2.2 Fine aggregates

The material which passes through 4.75 mm sieve is termed as fine aggregate. Usuallynatural sand is used as a fine aggregate at places where natural sand is not availablecrushed stone is used as a fine aggregate. The sand used for the experimental works islocally procured and conformed to grading zone III. The sieve analysis of fine aggregatesis shown in Table 3.2. The physical properties are provided in Table 3.3

Table 3.2: Sieve Analysis of Fine Aggregates

Sr. No.	Sieve No.	Weight retained (Grams)	Percentage retained (%)	Percentage Passing (%)	Cumulative percentage retained (%)
1.	4.75 mm	5	0.50	99.50	0.50
2.	2.36 mm	59	5.90	93.60	6.40
3.	1.18 mm	136	13.60	80.00	20.00
4.	600 mm	243	24.30	55.70	44.30
5.	300 mm	415	41.50	14.20	85.80
6.	150 mm	122	12.20	2.00	98.00
7.	Pan	20	2.00	-	-
					ΣF = 255

Table 3.3 Physical Properties of Fine Aggregates

Sr. No.	Characteristics	Value
1.	Type	Natural sand
2.	Specific Gravity	2.58
3.	Fineness Modulus	2.55
4.	Grading Zone	Type III

3.2.3 Natural Coarse Aggregate

The broken stone is generally used as a coarse aggregate. The nature of work decides the maximum size of the coarse aggregate. Locally available coarse aggregate having the maximum size of 20 mm was used in the present work. The properties of natural aggregate are presented in Table 3.4

Table 3.4: Sieve Analysis of Natural Coarse Aggregates

Sr. No.	Sieve size	Weight retained (kg)	% Retained	%Passing For NCA	Cumulative % weight retained
1.	20 mm	0	0	100	0
2.	12.5 mm	2.1865	72.883	27.117	72.833
3.	10 mm	0.6745	22.483	4.634	95.366
4.	4.75 mm	0.1390	4.633	0.01	99.99

3.2.6 Steel Fibre

Fibres made from mild steel drawn wire conforming to IS: 280-1976 with the diameter of wire varying from 0.3 to 0.6 mm has been practically used in India. The efficiency of Fibre distribution depends on the geometry of the fibre, the Fibre content, the mixing and compaction technique, the size and shape of the aggregates inclusion and the mix proportions. Mild steel fibres having 30 mm length and 0.6mm diameter i.e. having aspect ratio 50 which are both end hooked and corrugated having 35mm length, 2mm wide and .6mm thick approximately were obtained through stewols India Pvt Ltd. I have been used 1% and 1.5% volume fraction of fibres.

3.2.7 Water

Water is an important ingredient of concrete as it actively participates in the chemical reaction with cement. Since it helps to form the strength giving cement gel, the quantity and quality of water is required to be looked into very carefully. Potable water is generally considered satisfactory. In the present investigation, tap water is used for both mixing and curing purposes.

3.2.8 Super-Plasticizer

Conplast SP430, the super plasticizer supplied by Fosroc India Pvt. Limited is used in our investigations. It is a highly effective super plasticizer for concrete and mortar. It meets the requirements for super plasticizer according to BS 5075 Part 3, ASTM C-494Type A and Type F and IS: 9103-1999 (amended 2003). The dosage of the superplasticizer is fixed based on the requirements for workability. The technical data related to the super plasticizer used is provided in Table 3.8. This data is supplied by the manufacturers.

Table 3.5 Technical Data of Super-plasticizer

Sr. No.	Characteristics	Value
1.	Colour	Brown
2.	Specific gravity	1.20
3.	Air entrainment	Minimum 1%
4.	pH	7 to 8

3.3 MIX PROPORTIONS

All the mixes are designed by keeping the water content constant. The desired workability of the mix is kept at 80-90 mm slump. To achieve the required workability of concrete mix, water reducing admixture i.e. super plasticizer, namely conplast SP430 is added to the matrix at a desired dosage rate. Concrete mixture proportion and super plasticizer dosage rate is presented in Table 3.9.The mix ratio chosen was 1:1.52:1.88. The water cement ratio was taken as 0.46**.** The specimens incorporated steel fibres in the mix proportions of 100-0%, 50-50% and 0-100% by volume at a total volume fraction of 1.5%. In table 3.10 the mixes CCF-1.0, CCF-1.5 represent the cement corrugated fibre mixes with 100% addition of corrugated fibres at 1.0% and 1.5% of volume fraction respectively. Similarly, CHF-1.0, CHF-1.5 represent the cement hooked end fibre mixes with 100% addition of hooked end fibres at 1.0% and 1.5% of volume fraction. Furthermore the hybrid mixes designated by CCHF-1.0 and CCHF-1.5 represent mixes with 50-50% of addition of both fibre types at 1.0% and 1.5% volume fractions respectively.

Table 3.6 Mix Proportion of Control Sample

w/c ratio	Cement (kg/m^3)	Fine aggregate (kg/m^3)	Natural coarse aggregate (kg/m^3)	Water (kg/m^3)	Superplasticizer (% by weight of cement)
0.46	545	829	1026	251	0.1%

Table 3.7 Mix Proportions for Different Samples

Designation	Cement (kg/m^3)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)	Steel fibre (kg/m^3)	Water (kg/m^3)	w/c
Control Mix	545	829	1026	-	251	0.46
CCF-1.0	545	829	1026	78	251	0.46
CCF-1.5	545	829	1026	116	251	0.46
CHF-1.0	545	829	1026	78	251	0.46
CHF-1.5	545	829	1026	116	251	0.46
CCHF-1.0	545	829	1026	39-39	251	0.46
CCHF-1.5	545	829	1026	58-58	251	0.46

3.4. CASTING OF SPECIMENS

In this section casting procedure for compressive strength test, splitting tensile strength and flexural strength test are discussed.

3.4.1 Casting for Compressive Strength Test

150 x 150 x 150 mm cube is used to study the compressive strength of various mixes. The quantities of cement, coarse aggregate, fine aggregate, steel fibre and water for each batch replacement was weighed separately. The cement, steel fibres were mixed dry to a uniform colour separately. Fine aggregate was mixed to this mixture in dry form. The coarse aggregates were mixed to get uniform distribution throughout the batch. Water added to the mix. Firstly, 50 to 70% of water was added to the mix and then mixed thoroughly for 3 to 4 minutes in mixer. The cubes are filled with fresh concrete using vibrating table. Immediately after casting cubes, the specimens are covered with gunny bags to prevent water evaporation. Three cubes are casted for each parameter. The compressive strength test is carried out for 28 days. Therefore, six identical specimens are casted for each concrete mix.

3.4.2 Casting For Splitting Tensile Strength Test

Cylinders used in the study have diameter of 150 mm and height of 300 mm. The quantities of cement, coarse aggregate, fine aggregate, steel fibre and water for each batch replacement was weighed separately. The cement and steel fibre were mixed dry to a uniform colour separately. Fine aggregate was mixed to this mixture in dry form. The coarse aggregates were mixed to get uniform distribution throughout the batch. Water added to the mix. Firstly, 50 to 70% of water was added to the mix and then mixed thoroughly for 3 to 4 minutes in mixer. The moulds were filled with fresh concrete and were vibrated properly. After casting the cylinders were covered to prevent evaporation of water. Four cylinders were casted for each mix. The tests were carried out on 28 day.

3.4.3 Casting for Flexural Strength Test

The flexural strength of concrete is determined by casting beams of size 700 mm × 150 mm × 150mm. The quantities of cement, coarse aggregate, fine aggregate, steel fibre and water for each batch replacement was weighed separately. The cement, steel fibres were mixed dry to a uniform colour separately. Fine aggregate was mixed to this mixture in dry form. The coarse aggregates were mixed to get uniform distribution throughout the batch. Water added to the mix. Firstly, 50 to 70% of water was added to the mix and then mixed thoroughly for 3 to 4 minutes in mixer. The moulds were filled with fresh concrete and were vibrated properly. After casting the cylinders were covered to prevent evaporation of water. Four beams were casted for each mix. The tests were carried out on 28 day.

3.5 TESTING OF SPECIMENS

In this section test setup for the tests (compressive strength test, splitting tensile strength test and flexural strength) tests are discussed.

3.5.1 Setup for Compressive Strength Test.

Three identical specimens are crushed 28 days. The compressive strength is calculated by dividing the failure load by average cross sectional area. The compressive strength testing machine of capacity 5000 KN is used for determining the maximum compressive loads carried by concrete cubes. The compressive strength test machine which used in all tests is shown in Fig 3.3. At the test age the specimens are taken out of the curing tank and kept outside for 10 minutes. Then one specimen is placed on the steel plate of the machine such that the specimen is tested perpendicular to the casting position. Then the test is carried out at the loading rate of 5 KN/s specified IS: 516 - 1959.

Fig 3.1 Testing for compressive strength

3.5.2 Setup For Split Tensile Strength Test

The cylinders were tested by placing them uniformly in the compression testing machine of capacity 5000 KN. Specimen were taken out from curing tank at the age of 28 days of standard curing and tested after surface water dipped down from specimens. This test was performed on Compression Testing Machine (CTM) as shown in fig 3.4. The test is carried out at the loading rate of 1 KN/s specified IS: 5816 - 1999.

The magnitude of tensile stress acting uniformly to the line of action of applied loading is given by formula

$$f_{ct} = \frac{2P}{\Pi l d}$$

Where,

f_{ct} = Split tensile strength in N/mm^2

P = maximum applied load to specimen in Newton

l= length of the specimen (in mm)

d = cross sectional dimension of the specimen (in mm)

Fig 3.2 Testing for splitting tensile strength

3.5.3 Setup for Flexural Strength Test

The beams were tested by placing them uniformly in the universal testing machine of capacity 1000 KN. Specimen were taken out from curing tank at the age of 28 days of standard curing and tested after surface water dipped down from specimens. This test was performed on universal testing machine (UTM) as shown in fig 3.5. The test is carried out at the loading rate of 70 KN/min.

The magnitude of flexural stress acting uniformly to the line of action of applied loading is given by formula

$$f_b = \frac{p \times l}{b \times d^2}$$

f_b = flexural strength in N/mm^2

p = maximum applied load to specimen in Newton

l = length of the span on which the specimen was supported

b = measured width of the specimen

d = measured depth of the specimen at point failure

Fig 3.3 Testing for flexural strength

3.5.4 Toughness

Toughness was calculated by ASTM C1018 standard .This standard defines a toughness Index I as the ratio of the absorbed energy up to a given deflection to the absorbed energy up to first crack. The standard toughness indices defined in ASTM C1018 are I_5, I_{10} and I_{20} defined for deflections of 3 δ, 5.5 δ and 15.5 δ where δ is the deflection at first crack. The toughness indices I_5,I_{10},I_{20} are calculated by taking the ration of energy absorbed to a certain multiple of first crack deflection and energy consumed up to first crack and RSFs ($R_{5,10}$,$R_{10,20}$) are calculated directly from toughness indices. After obtaining load deflection curve the toughness indices for each specimen was calculated.

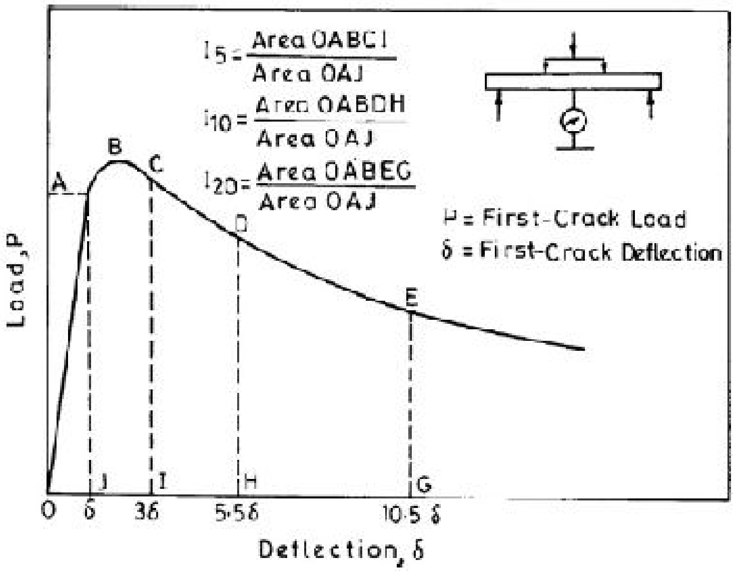

Fig:3.4 Definition Of Flexural Toughness Indices (ASTM C-1018).

The toughness calculated at the deflection δ, is consider the pre-peak toughness, while the other three (3δ, 5.5 δ, 10.5 δ) are post-peak toughness. The residual strength represents the average post-cracking load that the specimen may carry over a specific deflection interval, is determined as $R_{5,10} = 20(I_{10}-I_5)$ and $R_{10,20} = 10(I_{20}-I_{10})$.

3.6 CLOSING REMARKS

The experimental programme described in this chapter includes the significant material properties and specifications of the ingredients of concrete and the testing procedure. The specimen details and the test set-up have been discussed.

CHAPTER 4 RESULTS AND DISCUSSIONS

4.1 GENERAL

In this chapter results of Compressive strength, split tensile strength, flexural strength and toughness of all mix combinations are discussed. All the tests were conducted in accordance with the methods described in Chapter-3. The results are presented and discussed in the section below:

4.2 COMPRESSIVE STRENGTH TEST

Three cubes from each batch of concrete mix were cast and cured for 28 days in order to determine compressive strength. The results of compressive strength tests conducted on plain concrete and SFRC specimens with different fibre volume fractions, each fibre volume fraction containing different combinations of mixed steel fibres, are presented in Table. It can be observed that for a particular mixed aspect ratio, there is an increase in compressive strength as percentage of fibres is increased. The results show that in general, there is an increase in compressive strength varying from 13.8% (for 1.0% hooked fibre) to 32.47% (1.5% hooked fibre) on addition of fibres to the concrete. Table 4.1 shows the value of compressive strength of cube tested at 28 days.

Table 4.1 Compressive Strength results for all mixes

Mix type	Compression strength (MPa) at 28 days
Control Mix	42.5
CCF-1.0	49.3
CCF-1.5	51.5
CHF-1.0	48.4
CHF-1.5	56.3
CCHF-1.0	57.81
CCHF-1.5	58.01

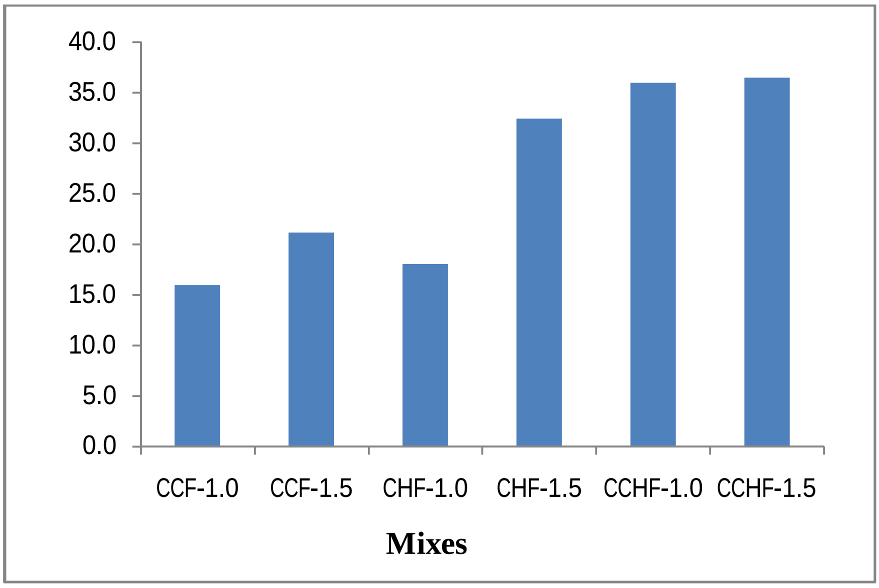

Fig 4.1 Compressive Strength Result for Different Mixes

- As seen in table 4.1 the addition of corrugated fibre in concrete increases the compressive strength of concrete. The addition of 1% volume fraction corrugated fibre increases the strength by 16% whereas 1.5% volume fraction increases the compressive strength by 21%.
- Similarly, addition of 1% and 1.5% volume fraction hooked end fibre increases the compressive strength by 17% and 33% respectively.
- From the fig. It is clear that addition of both corrugated and hooked end fibre by the volume fraction of 1% increases the strength by 36% as compared to the control mix.
- Also, the addition of corrugated and hooked end fibre by 1.5% by the volume fraction results in an increase in strength by 37%. Hence, it is concluded that in order to achieve more strength both corrugated and hooked end fibres can be used.

4.3 SPLIT TENSILE STRENGTH TEST

Split tensile strength studies were carried out at the age of 28 days. The results showed that there is an increase in tensile strength with the addition of fibres in concrete. The maximum increase of 65% was observed with addition of mix proportion of fibres when added by 1.5 % of volume fraction. The results are presented in the table 4.2. Fig. 4.2 depicts the percentage increase in different mix combinations with respect to control concrete.

Table 4.2 Split Tensile Strength for Different Mixes

Mix type	Split tensile strength (MPa) at 28 days
Control mix	3.28
CCF-1.0	4.60
CCF-1.5	5.01
CHF-1.0	4.80
CHF-1.5	5.17
CCHF-1.0	5.20
CCHF-1.5	5.43

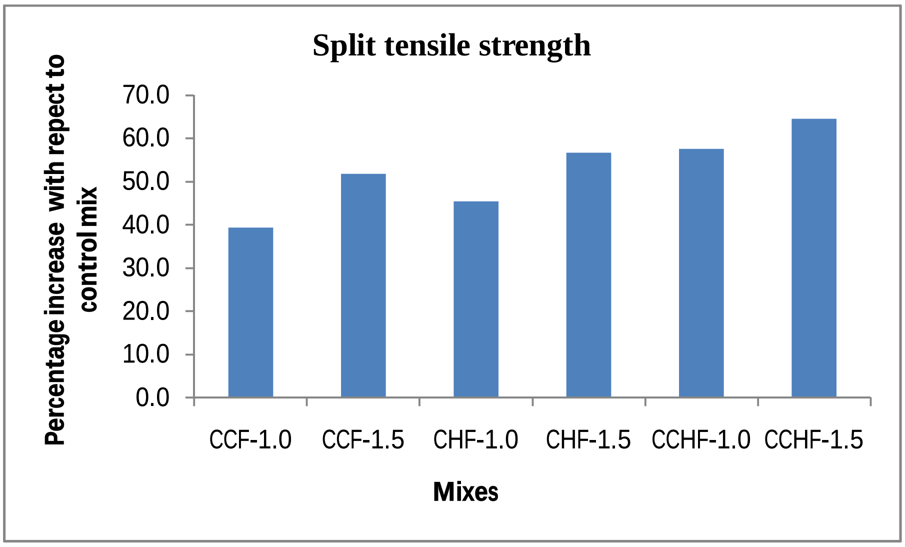

Fig 4.2 Comparison of Split Tensile Strengths of Mixes With Respect To Control Mix

From the above fig 4.2 the following observations were made

- With the addition of corrugated fibres by 1% volume fraction the split tensile strength was increases by 40%.
- If the volume fraction of corrugated fibres was increases by 1.5%, the increase in split tensile strength by 53%.
- By the addition of hooked end fibres at volume fraction of 1.0%, 1.5%, the split strength of the specimen is increased by 47% and 57%.

- With the addition corrugated and hooked end fibres at volume fraction of 1.0%, the split tensile strength got increased by 58%.
- When both corrugated and hooked end fibres were added with the volume fraction of 1.5%, the split tensile strength increases by 64%.

4.4 FLEXURAL STRENGTH TEST

Flexural strength studies were carried out at the age of 28 days. The results are given in the table 4.3. The data is further in the form of bar graphs in Fig 4.3**.**

Table 4.3 Flexural Strength Results for Different Mixes

Mix type	Flexural strength(MPa) at 28 days
Control mix	4.46
CCF-1.0	5.21
CCF-1.5	5.61
CHF-1.0	5.19
CHF-1.5	5.79
CCHF-1.0	6.64
CCHF-1.5	6.73

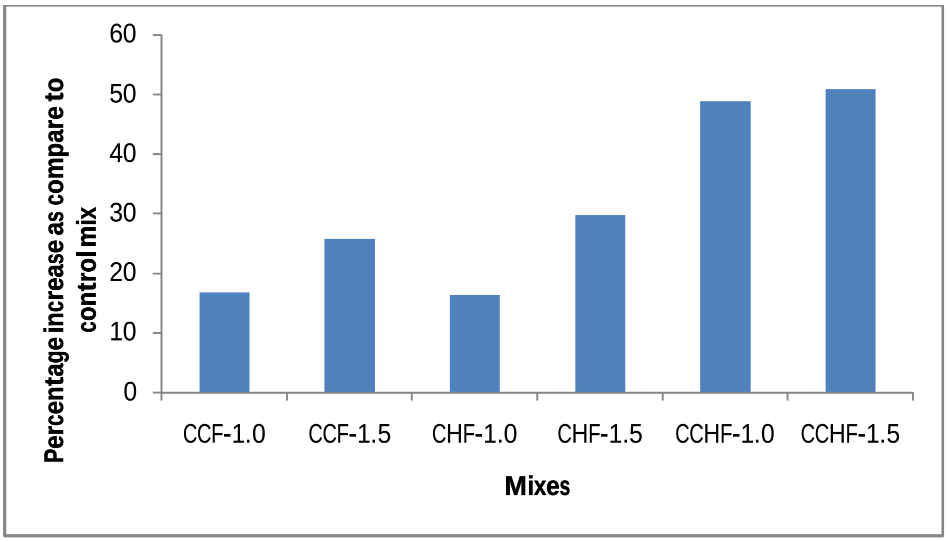

Fig 4.3 Percentage Increase in Flexural Strength as Compare to Control Mix

From the results presented above it can be observed that:

- The flexural strength was increases 16% by the addition of corrugated fibres at volume fraction of 1.0%.
- With the addition of corrugated fibres at volume fraction of 1.5%, the flexural strength increased by 25%.
- As the addition of hooked end fibres at volume fractions of 1% and 1.5%, the flexural strength increases by 16% and 29%.
- If both corrugated and hooked end fibres were added by the volume fraction of 1.0%, the flexural strength increases by 48%.
- With the addition of both corrugated and hooked end fibres by the volume fraction of 1.5%, the flexural strength increases by approximately 50%.

4.5 TOUGHNESS

Fibres are added to concrete not to improve the strength, but primarily to improve the toughness, or energy absorption capacity. Commonly, the flexural toughness is defined as the area under the complete load-deflection curve in flexure; this is sometimes referred to as the total energy to fracture. Alternatively, the toughness may be defined as the area under the load-deflection curve out to some particular deflection, or out to the point at which the load has fallen back to some fixed percentage of the peak load. Probably the most commonly used measure of toughness is the toughness index which was incorporated in ASTM C1018.

Table 4.4 Toughness Indices and Residual Strength for Different Mixtures

	ASTM C 1018						
	Toughness indices			Toughness index ratio		Residual strength factor	
Mix	I_5	I_{10}	I_{20}	$I_{5/10}$	$I_{10/20}$	$R_{5,10}$	$R_{10,20}$
Control mix	1	1	1	1	1	1	1
CCF-1.0	3.85	5.90	6.80	1.52	1.15	41	45.02
CCF-1.5	4.31	6.79	10.06	1.57	1.48	49.6	32.70
CHF-1.0	3.74	5.05	6.09	1.35	1.20	42.2	50.01
CHF-1.5	3.93	6.32	9.85	1.60	1.55	47.8	35.30
CCHF-1.0	4.36	6.89	10.17	1.69	1.57	52.20	37.80
CCHF-1.5	4.38	7.01	10.31	1.72	1.64	55.20	35.70

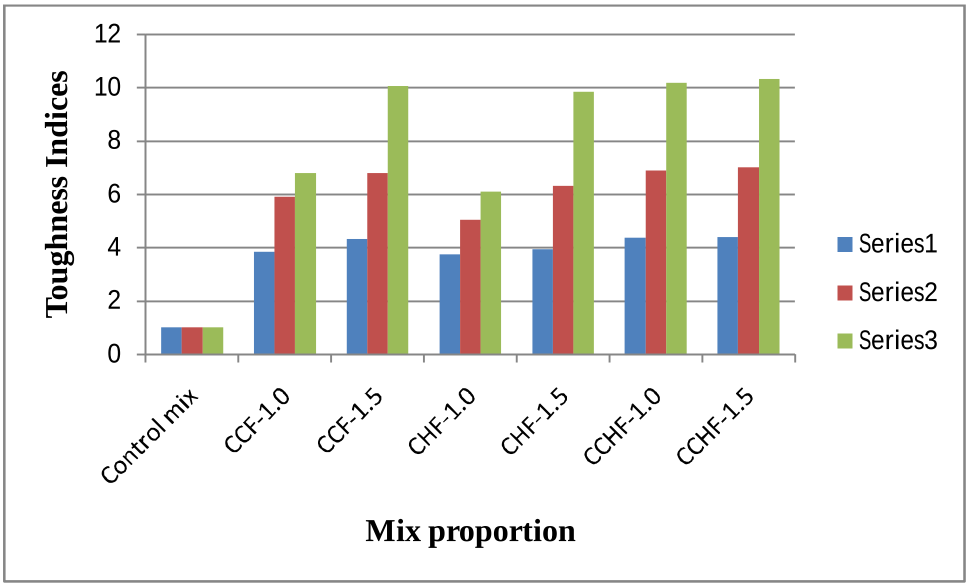

Fig 4.4 Toughness Indices and Mix Proportions

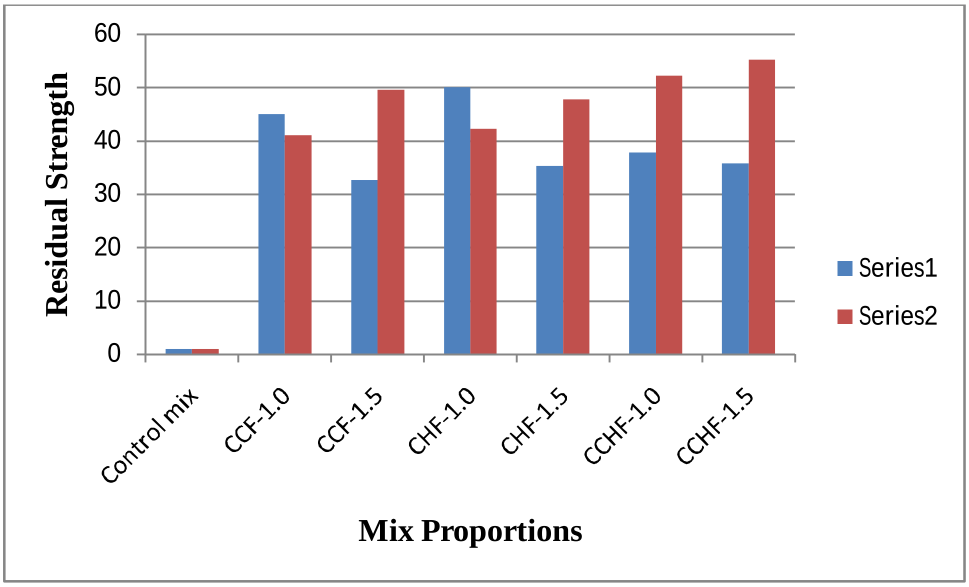

Fig 4.5 Residual Strength And Mix Proportions

CONCLUSIONS

In the present study the mechanical properties of concrete containing different percentage of hooked end and corrugated steel fibres were studied. Apart from this, test results of two hybrid mixes containing both fibre types at different volume fractions are also presented. Based on the experimental results of the current study, the following conclusions may be drawn:

1. An increase of the order of 16% and 21% in compressive strength over plain concrete is observed in case of SFRC mixes containing corrugated steel fibres at 1.0% and 1.5% volume fractions respectively. Also, an increase of 17% in compressive strength with the addition of hooked end fibres at 1.0% volume fraction and 32% increase at 1.5 % volume fraction is observed. The increase in the compressive strength of SFRC mixes is in range 16% to 36% depending upon the fibre type and fibre volume fraction. The hybrid mixes give over all better results as compared to other SFRC mix combinations.
2. There is an increase of 40% in split tensile strength with the addition of corrugated fibres and 46% with the hooked end fibres at 1.0% volume fraction in respective mix combinations. An increase of 52% and 53% in split tensile strength is also noticed with the addition of corrugated and hooked end fibres at volume fraction of 1.5 % respectively.
3. All steel fibre reinforced concrete mix combinations have shown improved toughness behaviour as compared to control concrete. The results indicate that concrete containing a fibre combination of 50% corrugated steel fibres + 50% both end hooked steel fibres at 1.0% and 1.5% volume fractions can be adjudged as the most appropriate combinations to be employed in steel fibre reinforced concrete for flexural toughness.

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