REPAIR OF CONCRETE STRUCTURES USING

FIBER REINFORCED CONCRETE

By

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This is to certify that the

thesis entitled

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Has been accepted towards the partial fulfillment
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Bachelors of Engineering (Civil Engineering)

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Abstract

Fiber reinforced concrete is a concrete mix which utilizes fibrous material as reinforcement. These randomly oriented, uniformly distributed fibers exhibit a variety of properties when mixed with concrete. Steel fibers, however, show that they aid in controlling drying and plastic shrinkage, also reducing permeability thus reducing bleeding of water. FRC does not increase the flexure strength of concrete to such a remarkable extent, it does however increase overall structural strength , reduce steel reinforcement requirement, improve post cracking ductility, reduce crack widths and exhibits crack control which increases durability. They also increase resistance against abrasion and impact loading, due to low permeability also resists freeze and thaw.

After carefully testing the materials required for the concrete we moved to a comparison between FRC, PCC and RCC. This was a preliminary step required to set a base to decide whether the use of FRC in repair works would be feasible or not. The results showed that FRC showed a slightly higher compressive strength that PCC. This increment was not appreciable enough to be mentioned in great detail and it may have been due to slight changes in the mix and testing conditions due to human error and weather changes. FRC did, however show a higher deflection when it came to flexure testing, in comparison to PPC. This proved that FRC does in fact increase post cracking ductility. These results were a step in the right direction clearing a path for us in using them in repair works of concrete structures. The results of the comparison tests are described in detail in the chapters to follow.

Result obtained from flexure tests on the repaired reinforced concrete beams painted a clear picture of the capabilities of FRC. RCC beams repaired with showed a decreased loading capacity as compared to the beam repaired with PCC. However, FRC greatly enhanced ductility of the concrete member as compared to the PCC repaired member. The decreased loading capacity of the FRC repaired member was probably due to inadequate bonding with the beam and/or due to changes in the mix conditions. The results, conclusion and recommendations are discussed in the later parts of the document.

Tests on columns gave a clearer picture of the use of FRC in the repair or axially loaded compression members. FRC repaired columns greatly increased the compressive strength of the column as compared to the members repaired with PCC. PCC repaired columns showed medium crack widths, FRC showed a great reduction in crack widths and the cracks appeared with a significant delay as compared to the PPC repaired sample. There was also no spalling of the surface concrete in the FRC repaired sample. These results along with all others are also explained along with conclusions and recommendations in the chapters to follow.

This document provides a guideline on how Fiber Reinforced Concrete may be used in repair works, although further research is required in this field to understand the effects of these fibers in more detail. This document will provide preliminary steps in how to use FRC in repair works and what the outcome will be in comparison with the outcome of the repairing concrete members with Plane cement concrete.

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Chapter 1

Introduction

Fiber reinforced concrete (FRC) is a concrete matrix which incorporates reinforcement in the form of small, discrete, randomly oriented and uniformly distributed fibers. Various fibers can be used to reinforce concrete, like, steel fibers, carbon fibers, glass fibers, etc. Each kind of fiber gives different properties to the concrete mix. Depending upon the type of fiber used these properties may include, enhanced post cracking ductility, resistance to fatigue and impact loading, etc.

This research document focuses on the usefulness of Steel Fiber Reinforced Concrete (SFRC) in the repair of concrete structures. Concrete, by itself, has a very low tensile strength and low strain capacity at fracture. These deficiencies are traditionally overcome by adding reinforcing steel bars. Unlike routine reinforcement, fibers are discontinuous and are uniformly spread throughout the concrete mix. Fibers can also be used along with reinforcing steel bars for added strength at times and stability. Due to its ease of fabrication, SFRC is widely being used in tunneling purposes, mostly as shotcrete.

Steel fibers come in a variety of shapes to improve concrete-fiber bonds and to increase the efficiency of the fiber itself. Hooked steel fibers have been used in the research.

Steel fibers are usually use to control drying and plastic shrinkage. They also reduce the permeability of concrete, therefore, reduces bleeding of water. Along with these properties, the use of FRC does not enhance the flexural strength of concrete to such an extent that conventional reinforcement may be replaced as a whole. SFRC however, can improve structural strength, reduce steel reinforcement requirement, improve ductility, reduce crack widths and control them tightly which in turn increases durability. They also increase impact and abrasion resistance and also build resistance against freeze-thaw action.

These properties are further discussed in the later part of the document, along with its possible uses in the repair and rehabilitation of concrete structures. This research provides results of experiments carried out on various SFRC, RCC, PCC and SFRC and RCC composites. They serve not only as a controlled comparison but also as guidelines for further research in this particular field of study.

A comparison between the properties of SFRC and PCC is discussed in detail in the document. A repair comparison has also been discussed in detail.

Literature Review

Fiber reinforced concrete:

Fiber reinforced concrete is a type of concrete matrix incorporating reinforcement in the form of small fibers. These are distributed uniformly and oriented randomly in the concrete matrix. FRC can be reinforced with steel fibers, carbon fibers, synthetic or natural fibers depending upon the requirement.

The uniform distribution of reinforcement in the form of small fibers gives special properties to the concrete matrix. These include the increased post cracking ductility, strength against fatigue and impact loading etc. These properties cater for many problems that arise during the construction and repair works where FRC can be used very effectively.

FRC versus RCC:

Unreinforced concrete has a low tensile strength and a low strain capacity at fracture. These shortcomings are traditionally overcome by adding reinforcing bars or prestressing steel. Reinforcing steel is continuous and is specifically located in the structure to optimize performance. Fibers are discontinuous and are generally distributed randomly throughout the concrete matrix. Fibers are being used in structural applications with conventional reinforcement. Because of the flexibility in methods of fabrication, fiber reinforced concrete can be an economic and useful construction material. In slabs on grade, mining, tunneling, and excavation support applications, steel and synthetic fiber reinforced concrete and shotcrete have been used instead of welded wire fabric reinforcement. [1]

Certainly the most important for structural concrete are steel fibers; a few examples are shown in Fig. 1.1; hooks at the ends and various modifications of shape improve fiber-matrix bond and increase efficiency of the fibers. [1]

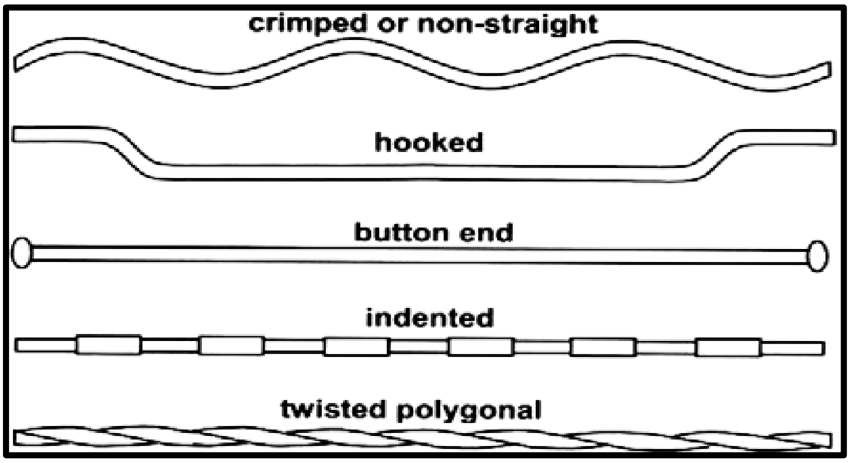


Fig.2.1 Examples of deformed Steel Fibers [1]

The influence of the fibers on cracking of cement-based matrix is explained in Fig. 2 large single cracks are replaced with dense systems of micro cracks, which may be acceptable from both safety and durability viewpoints. Fine fibers control opening and propagation of micro cracks as they are densely dispersed in cement matrix. Longer fibers up to 50 or 80 mm control larger cracks and contribute to increase the final strength of FRC. [1]

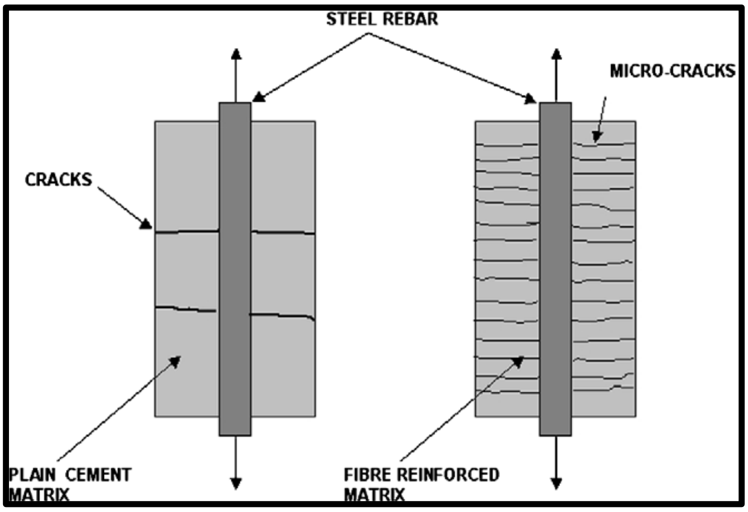


Fig. 1.2 Crack pattern in normal and fiber reinforced concrete in the members subjected to tension [1]

With the increase of fiber volume and efficiency, their influence on behavior of a FRC element modifies completely its behavior under load, as it is described in strain–stress diagrams. The conventional FRC element is characterized by initial linear increase of stress and after the 1st crack opening there is a slow decrease, the so called softening branch.In contrast, where the reinforcement is sufficient, after the 1st crack there is a strain hardening stage, which accompanies multiple cracking and considerable amount of energy is absorbed that is proportional to the area under the curve. The softening branch follows that stage. In Fig. 1.3 the main difference between conventional FRC and high performance fiber reinforced cement composites (HPFRCC) is defined. [1]

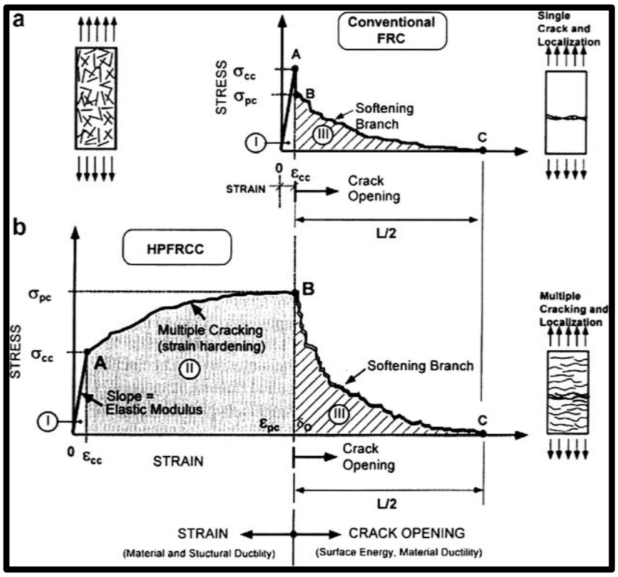


Fig.1.3 Comparison of typical stress–strain response in tension of HPFRCC with conventional FRC [1]

Fibers aligned in the direction of the tensile stress may bring about very large increases in direct tensile strength, as high as 133% for 5% of smooth, straight steel fibers. However, for more or less randomly distributed fibers, the increase in strength is much smaller, ranging from as little as no increase in some instances to perhaps 60%, with many investigations indicating intermediate values, as shown in figure 4. Splitting-tension test of SFRC show similar result. Thus, adding fibers merely to increase the direct tensile strength is probably not worthwhile. However, as in compression, steel fibers do lead to major increases in the post-cracking behavior or toughness of the composites. [1]

Production of FRC:

The FRC matrices have a higher cement content, higher ratio of fine to coarse aggregate than the ordinary concrete, so the mix design procedures for FRC are different from the ordinary concrete. The techniques applied for preparing an adequate mix design include the replacement of cement content up to 35% by fly ash. Also water reducing admixtures, particularly super plasticizers in conjunction with the air entraining admixtures are used to cater for the loss of workability of FRC composites. [1]

The presence of aggregates with sizes 5 mm and greater in higher proportions results in the loss of workability. Whereas, the particle sizes less than 5 mm has little effect on the compacting characteristics of the mix. Another factor influencing the workability is the aspect ratio (l/d) of the fibers. The higher the aspect ratio, the lower is the workability. [1]

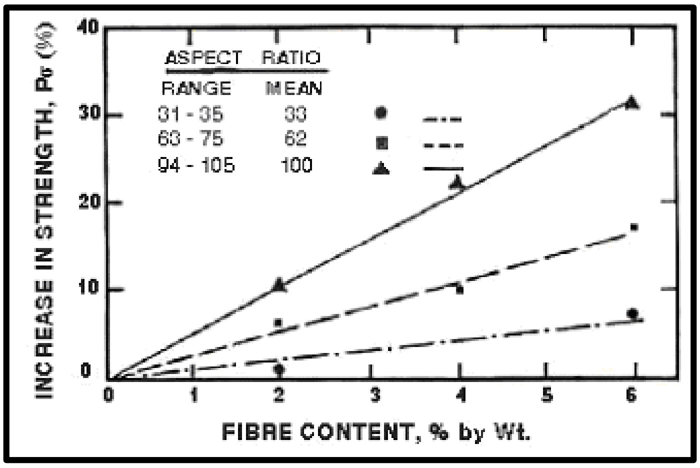


Fig. 1.4 Influence of fiber content on tensile strength [1]

The basic problem in the production of FRC is to introduce a sufficient volume of uniformly dispersed to achieve the desired improvements in mechanical behavior, while retaining sufficient workability in the fresh mix to permit proper mixing, placing and finishing. In general, the problems of both workability and uniform distribution increase with increasing fiber length and volume. [1]

One of the chief difficulties in obtaining a uniform fiber distribution is the tendency for steel fibers to ball or clump together. Clumping may be caused by a number of factors:

1. The fibers may already be clumped together before they are added to the mix; normal mixing action will not break down these clumps.
2. Fibers may be added too quickly to allow them to disperse in the mixer.
3. Too high a volume of fibers may be added.
4. The mixer itself may be too worn or inefficient to disperse the fibers.
5. Introducing the fibers to the mixer before the other concrete ingredients will cause them to clump together.

Most commonly, when using a transit mix truck or revolving drum mixer, the fibers should be added last to the wet concrete. The concrete alone, typically, should have a slump of 50-75 mm greater than the desired slump of the SFRC. Of course, the fibers should be added free of clumps, usually by first passing them through an appropriate screen. Once the fibers are all in the mixer, about 30-40 revolutions at mixing speed should properly disperse the fibers. Alternatively, the fibers may be added to the fine aggregate on a conveyor belt during the addition of aggregate to the concrete mix. The use of collated fibers held together by a water-soluble sizing which dissolves during mixing largely eliminates the problem of clumping. [1]

SFRC can be placed adequately using normal concrete equipment. It appears to be very stiff because the fibers tend to inhibit flow; however when vibrated, the material will flow readily into the forms. It should be noted that water should be added to FRC mixes to improve the workability only with great care, since above a w/c ratio of about 0.5, additional water may increase the slump of the SFRC without increasing its workability and place ability under vibration. The finishing operations with FRC are essentially the same as for ordinary concrete, though perhaps more care must be taken regarding workmanship.

Types of fibers in use:

The different types of fibers used for preparing FRC are

1. Steel Fibers
2. Glass Fibers
3. Synthetic Fibers
4. Natural Fibers

Steel fibers intended for reinforcing concrete are defined as short, discrete lengths of steelhaving an aspect ratio (ratio of length to diameter) from about 20 to 100, with any of several cross-sections, and that are sufficiently small to be randomly dispersed in an unhardened concrete mixture using usual mixing procedures. The composition of steel fibers generally includes carbon steel (or low carbon steel, sometimes with alloying constituents), or stainless steel. [2]

Concrete Repairs:

Concrete repair, refers to any restoring, replacing or renewing of concrete after initial placing. The need for repair can vary from minor replacement to normal disintegration over time or structural damages. In the repair of concrete structures, a few steps are imperative to take. Skipping any single step would result in either improper repair works or the damage being done again. Inadequate workmanship, material and procedures will always result in significant costs. [3][4]

Imperfections are to be repair to increase the durability and serviceability of a structure as whole. It is like removing a weak link from a heavy chain to strengthen the entire chain. Therefore it is highly important that all personnel be trained to make inconspicuous, durable, and well bonded repairs to the old structure. [3][4]

There are many procedures which can be adopted for repair but all of them are situations. Hence choosing the correct repair method is one of the most important aspects of repair works. If the correct procedure is not chosen it will result in inferior repair works, inadequate bonding and lower durability of the overall structure. The correct repair method can be rendered useless if it's coupled with poor workmanship, since repair works are usually done using manual techniques. Labor should be well trained in the kind of repair procedure they are adopting. [3][4]

Material to be used in the repair concrete should be fresh and of high quality to meet the specifications requirements. It is important to keep the repair mix as close to the old concrete as possible, to ensure uniformity in elasticity, thermal expansion coefficients, etc. stripping old concrete over and over again is cost intensive, and tedious. Which means that repair concrete should be placed ones, changing it again and again is not feasible or advisable. All material should be discarded if they seem unfit for the job. Such material can only be used in repair works if standard materials are unsuitable for the job and the owners and parties involved are informed about the need to use non-standard material and the consequences involved. [3][4]

Chapter 2

Experimental Investigations

Introduction:

This chapter covers the experimental investigation carried out during the project. It will include test design and apparatuses, specimen preparation, and experimental procedures. Tests were performed on the constituents of concrete and also on the casted specimen. Entire testing was in accordance with the American Society for Testing and Materials **(ASTM)** standards.

Limitations:

There were many factors working against our research, the greatest however and the first one we encountered was the unavailability of fibers which we could use in our research. We were not able to acquire carbon fibers. They were available in sheets which could not have been of any use to us in our research.

We were also not able to acquire various types of steel fibers either. After searching for months we tracked hooked steel fibers down at the Neelum-Jhelum Hydropower Project, south of Muzaffarabad in Azad Kashmir, Pakistan.

Our testing facility does not house a standard testing machine for testing the axial compressive strength of columns due to which we had to use a modified approach to fit the columns in the compression testing machine available in the structure laboratory. Modified Column dimensions and details are provided in the respective chapter.

Our facility does not house a testing machine which can determine the flexure strength of concrete beams. The machine was procured but was not functional by the time we had to test our samples. Due to which we lost precious time tracking down a machine which could have given us the required results. After constant searching we found a UTM capable of testing our samples in flexure at FAST University, Lahore.

In concrete replacement method, it is advised to use an epoxy resin to enhance bonding between the old and new concrete. Due to limited resources available to us we were not able to use epoxy resins in our repair works but we still managed to achieve the desired results.

Preliminary Tests for Mix Design

Production of normal strength concrete requires careful selection, controlling, and proportioning of all the constituents. These parameters influence the properties of concrete in both fresh and hardened state. A systematic approach was adopted during the project to attain the objectives. This was done to ensure uniformity in casted concrete

1) **Cement:**

Bestway cement was used during the project. It is a, Type 1 Portland Cement, general purpose cement with no special properties. The results of tests performed on cement are tabulated below along with their ASTM designations.

Test	Result	Specification
Type of cement	Type 1	ASTM C 150
Specific Gravity	3.10	ASTM C 188
Standard Consistency	30%	ASTM C 187
Initial Setting Time	123 min at 23^0C	ASTM C 191
Final Setting Time	170 min at 23^0C	ASTM C 191

All the results deduced from the above experimentation are under the specified ASTM limits.

2) **Water:**

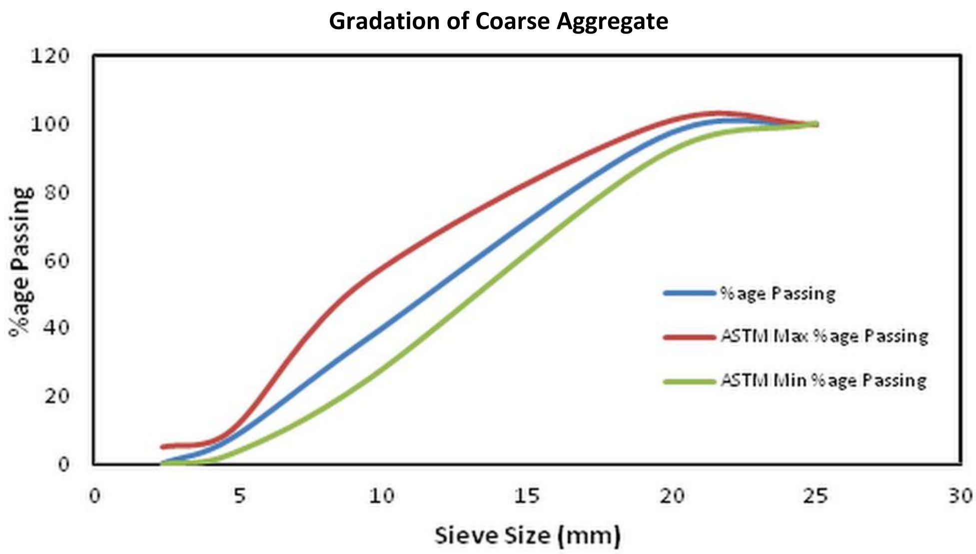
Ordinary potable water was used throughout the entire experimental work.

3) Coarse Aggregate:

Margalla crush was used during the entire experimental work. The nominal maximum size of the aggregate used was **12.5 mm**. The results of tests performed on coarse aggregates are tabulated below along with their ASTM specification.

Test	Result	Specification
Bulk specific gravity(O.D)	2.665	ASTM C 127
Bulk specific gravity(S.S.D)	2.673	ASTM C 127
Apparent specific gravity	2.678	ASTM C 127
Absorption Capacity	3.37%	ASTM C 127
Dry Rodded Unit Weight	2160 kg/m^3	ASTM C 29
Gradation	See Graph Below	ASTM C 136

Sieve Size (mm)	Wt Retained (gm)	%age Retained	Comm. %age Retained	%age Passing	ASTM Min %age passing	ASTM Max %age passing
25	0	0	0	100	100	100
19.5	42	4.2	4.2	95.8	90	100
9.5	587	58.7	62.9	37.1	25	55
4.75	297	29.7	92.6	7.4	0	10
2.36	74	7.4	100	0	0	5



4) Fine Aggregate:

Lawarancepur Sand was acquired for this project. The experiments performed on the sand are tabulated below along with results. All the experiments were performed according to the ASTM standards.

Test	Result	Specification
Specific Gravity (SSD)	2.85	ASTM C 128
Specific Gravity (Bulk)	2.81	ASTM C 128
Specific Gravity (Apparent)	2.93	ASTM C 128
Absorption Capacity	2.40%	ASTM C 128
Fineness Modulus	2.43	ASTM C 136
Gradation	See Graph Below	ASTM C 136

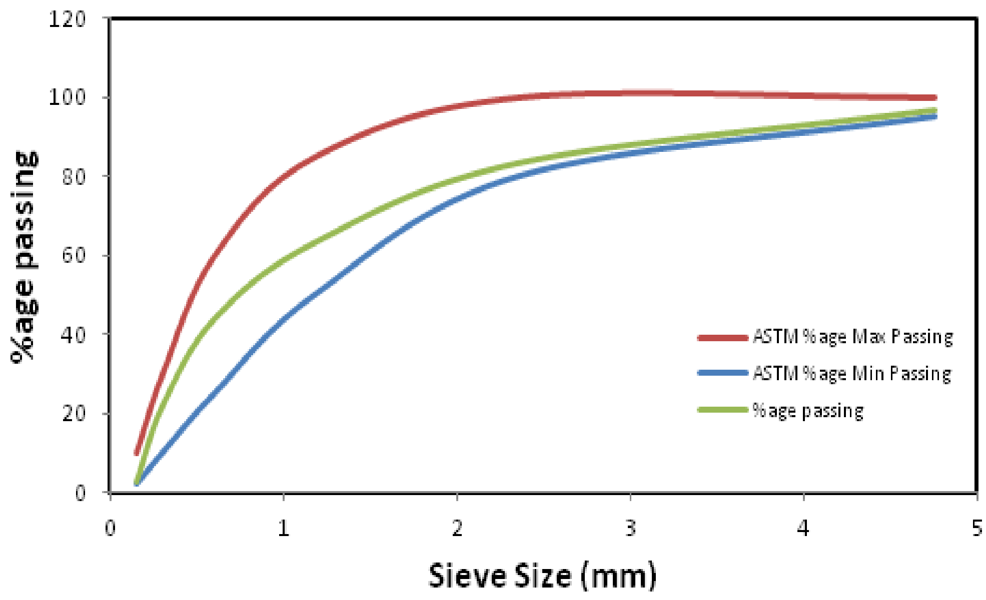
Gradation of Fine Aggregates:

Sieve Size (mm)	Wt Retained (gm)	%age Retained	Comm. %age Retained	%age Passing	ASTM Min %age passing	ASTM Max %age passing
4.75	16.2	3.24	3.24	96.76	95	100
2.36	66.3	13.26	16.5	83.5	80	100
1.18	100.6	20.12	36.62	63.38	50	85
0.6	96.5	19.3	55.92	44.08	25	60
0.3	110.1	22.02	77.94	22.06	10	30
0.15	96.4	19.28	97.22	2.78	2	10
Pan	15.2	3.04	100	0	-	-

Fineness Modulus= (3.24+16.5+36.62+55.92+77.94+97.22)/100

= **2.43**

Gradation of Fine Aggregates



Test Specimen:

Test specimens were prepared according to ASTM C 192M–95 designation. The details of the casted specimen are tabulated below.

Specimen	Dimension(mm)	No of samples
Cylinder 1	100 x 200	20
Cylinder 2	150 x 300	20
Beams	250 x 250 x750	8

Three cylinders PCC and FRC each were tested at curing of 7, 28 and 90 days. PCC and FRC beams were tested at 7, 28 and 90 days of curing. RCC Beams and column were tested after curing of 28 days. Molds were oiled before pouring of concrete. Concrete mixer was used for preparation of concrete. All specimens were compacted using a vibrating rod. Date of casting and type of sample was mentioned on each sample. For example FRCC-27/03/2013 means FRC Cylinders and date of casting was 27/03/13.

Mix Design

Concrete is a combination of Portland cement, mineral aggregates, water, air, and often includes chemical and mineral admixtures. The proportioning of concrete mixtures is commonly referred to as mixture design or mix design. Fresh and hardened properties of Concrete largely depend upon the physical properties of constituent materials as well as on the proportions of these constituent materials used in the concrete mix. Unlike other materials used in construction, concrete is usually designed specifically for a particular project using locally available materials. So after determining the properties of constituent involved in the concrete mix design was done to attain the required workability and strength.

Concrete mix proportions are calculated using ACI mix design procedure given by ACI 211.1-91. The results of the mix design are shown below:

W/C ratio = 0.5

Material	Quantity
Cement	405 kg/m^3
Fine Aggregate	712 kg/m^3
Coarse Aggregate	1288 kg/m^3
Water	202 kg/m^3

As the water cement ratio was low so plasticizer was used to give concrete the required workability. “Glenium 51” was used and its dosage was 2% of the cement used in the mix. According to mix design the 28 days strength of the concrete was 32 MPa. Additionally steel fibers were added in the mix to make FRC. The fibers were added 42 kg/m^3 of concrete prepared.

Fig.2.1 Steel Fiber used in Project

Slump Test

Slump test is an empirical method to determine the workability of the freshly mixed concrete. ASTM C143 standard was followed for the determination of slump of the concrete. The cone was dampened and was placed on the base tray of the apparatus. Concrete was poured in the cone in three layers and each layer was rodded 25 times with a tamping rod. Top surface was made smooth by removing extra concrete with a screeding. The mold was removed with a steady upward lit with no lateral disturbance. There was no significant change in the height of the concrete. So the concrete used in all the experimentation was "**True Slump**".

Fig. 2.2 Slump Test showing True Slump

Experimentation on Casted Specimen:

The laboratory tests were designed to obtain the strength of concrete specimens under different types of loading. Three types of tests were performed:

I. The uni-axial compressive strength test
II. The splitting tensile strength test
III. The flexural strength test.

Test specimens were prepared and cured according to ASTM C192 standard. The specimens were removed from their molds about 24 hours after casting and were stored in moist conditions at a temperature about 23.0°C until the time of test. It was ensured that the tests on the specimens were performed as soon as their removal from the curing tank. All tests were performed on specimens cured at 7, 28 and 90 days. Three samples were tested each and their average strength was considered.

1) Compressive Strength Test:

This test method consists of applying a compressive axial load to molded cylinders at a rate which is within a prescribed range until failure occurs. Compressive strength is determined by dividing the maximum load attained by the cross sectional area of the specimen.

Compressive strength is typically considered the most important mechanical property of concrete. In most structural applications, concrete is employed primarily to resist compressive stresses. Also compressive strength is generally used as a measure to determine the overall quality of concrete. All tests were performed on specimens cured at 7, 28 and 90 days. Three samples were tested each and their average strength was considered. Both PCC and FRC samples were casted. Fibers were added with ratio of 42kg/m3 of concrete. ASTM C617 standard was followed for capping of sample. Plaster of Paris was used to ensure that cylinders have smooth, parallel, uniform bearing surface.

Fig. 2.3 A failed specimen after compressive strength test

ASTM C 39 standard was followed to perform the test. “Controls” testing machine was used for the determination of compressive strength. The maximum loading capacity of the machine is 5000 KN. The rate of loading stress was 0.25 MPa/s. The Stress was applied till the failure of the specimen. Failure type 2 was observed in the samples.

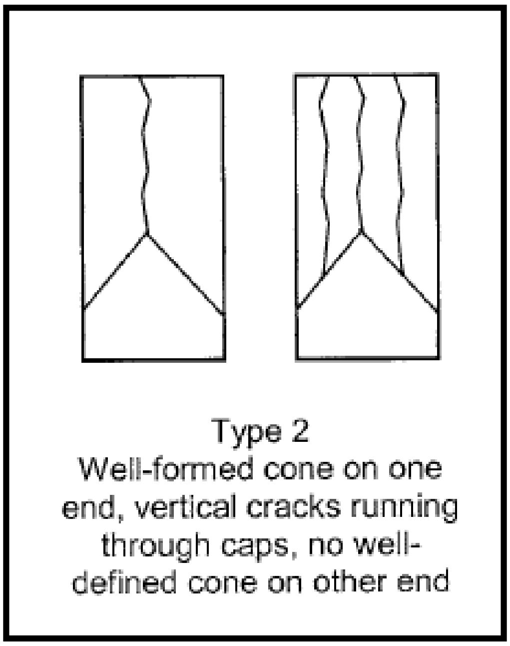


Fig. 2.4 A failed specimen after compressive strength test

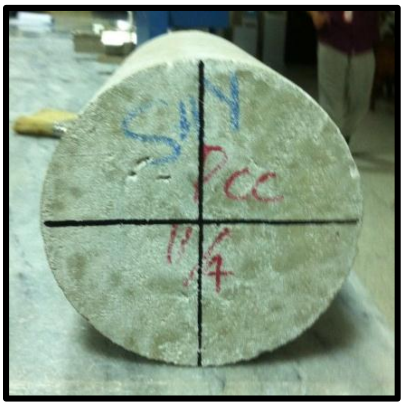
The above experiment performed and the results deduced from are correct to the best of our knowledge. Results will be discussed in the next chapter.

2) Splitting Tensile Strength Test:

This test method consists of applying a diametric compressive force along the length of a cylindrical concrete specimen at a rate that is within a prescribed range until failure occurs. Putting the maximum load sustained by sample in below formula gives the splitting tensile strength.

$$T=2P/(\pi LD)$$

ASTM C496 standard was followed for the determination of splitting tensile strength. Cylindrical test specimens were prepared having dimensions of 150mm (6in) diameter and 300mm (12in) length. FRC samples contained fibers at a ratio of 45 kg/m3 of concrete. Test was carried out on 3 samples each after curing of 7, 28 and 90 days respectively. Test specimens were prepared and cured according to ASTM C192 standard. Both PCC and FRC samples were casted.



Diametrical lines were marked on the cylinder along the length of the cylinder on both sides. Metallic bearing strips attached with the apparatus were then placed on these marked lines. “Controls” testing machine was used to conduct this experiment. Constant stress was applied at a rate of 1 MPa/min until the failure of the specimen.

Fig.2.5 A failed specimen after Splitting Tensile test

3) Flexural Strength Test:

This test method covers the determination of the flexural strength of concrete by the use of a simple beam with third point loading. The specimen is loaded with a constant stress until rupture occurs. Putting the value of maximum load sustained by the specimen in below formula gives modulus of rupture.

$$R=PL/(bd^2)$$

ASTM C78 standard was followed for the determination of flexural strength of the specimen. Three test specimen were casted of PCC and FRC each and were tested at curing of 7,28 and 90 days. The size of the test beam was 250mm x 250mm x750 mm with FRC samples having fibers with ratio of 45 kg/m3 of concrete. The clear span used for testing was 720mm. Test specimens were prepared and cured according to ASTM C192 standard.

Fig.2.6 SHIMADZU Universal Testing Machine

“SHIMADZU” Universal Testing Machine (UTM) was used to perform the experiment. The loading capacity of the machine was 1000KN. It was deflection controlled machine. Rate of deflection was 0.01 mm/min for PCC beams while 0.03 mm/min for FRC beams. The loading was applied up to a considerable value after the failure to sufficiently compare the properties of specimen and determine the differences in behavior.

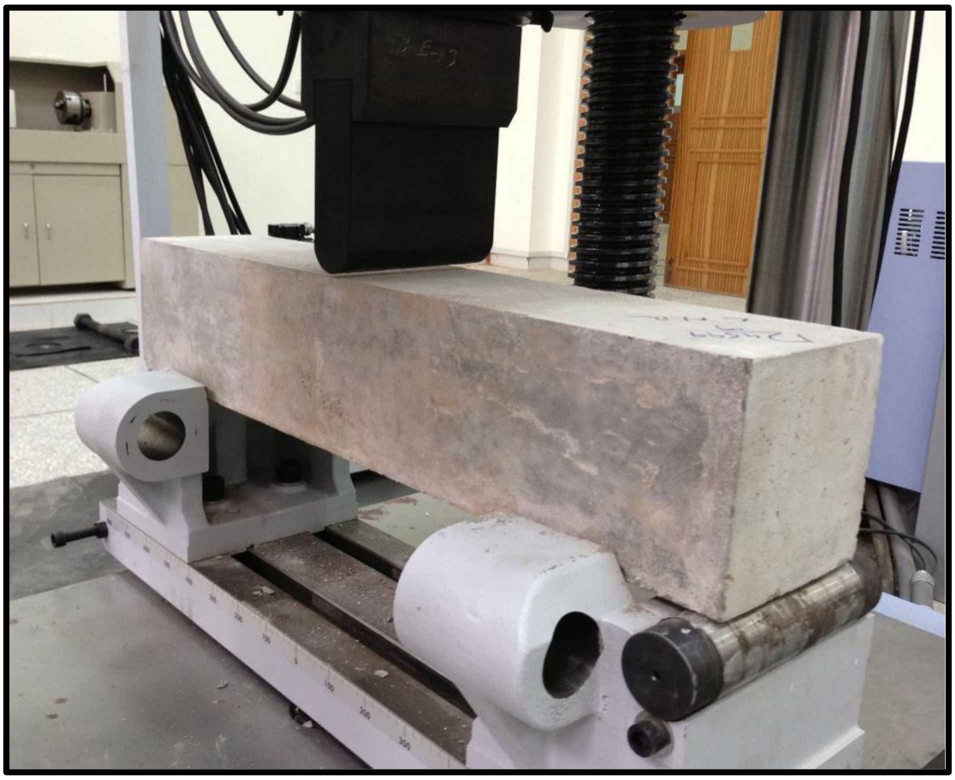


Fig. 2.7 FRC Beam under Flexural Loading

All the above stated information regarding properties of constituent materials used is inferred on the basis of tests performed within the laboratory and complies with the standard test procedures as specified by ASTM and ACI committees and the results are correct to the best of our knowledge. The result of the experiment performed on the casted specimen will be explained in the next chapter.

Test Results and Analysis

1) Compressive Strength Test:

The statistical analysis of uniaxial compressive strength test performed on cylinders to investigate the properties of PCC and FRC cylinders is explained below

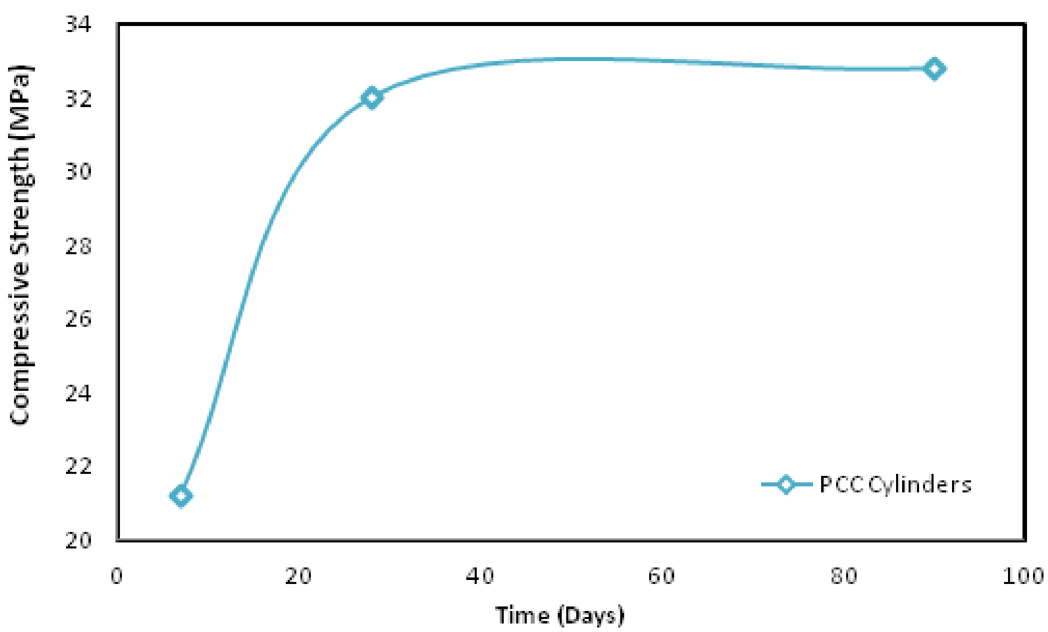
Compressive Strength Test on PCC Cylinders:

The statistical analysis of uniaxial compressive strength test performed on PCC cylinders is shown in table below.

Time (Days)	Strength Achieved (MPa)
7	21.2
28	32
90	32.8

The experiment performed with PCC Cylinders showed the regular trend of increase in strength with the increase in the number of curing days. The strength kept increasing up to 40 days and then achieved a constant value of 32.8 MPa. Here is a table of different values of strengths achieved with PCC cylinders.

Fig. Compressive strength vs. Time PCC Cylinders

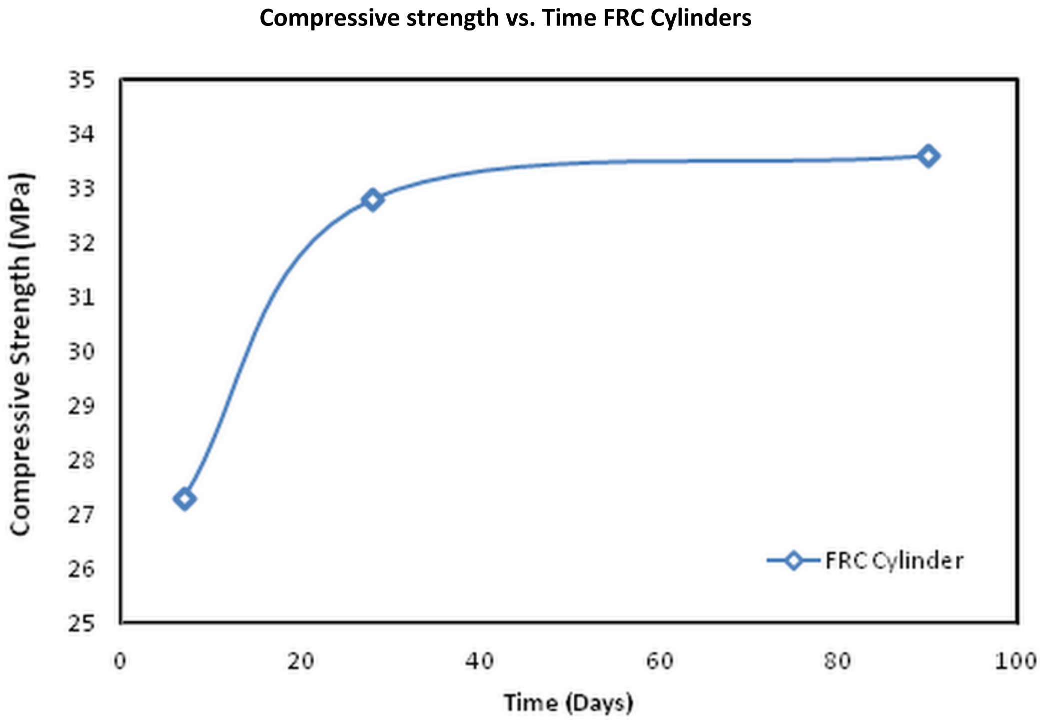


Compressive Strength Test on FRC Cylinders

The same test was carried out with FRC cylinders side by side while performing the tests on PCC. The statistical analysis of test performed on FRC cylinders is shown in table below.

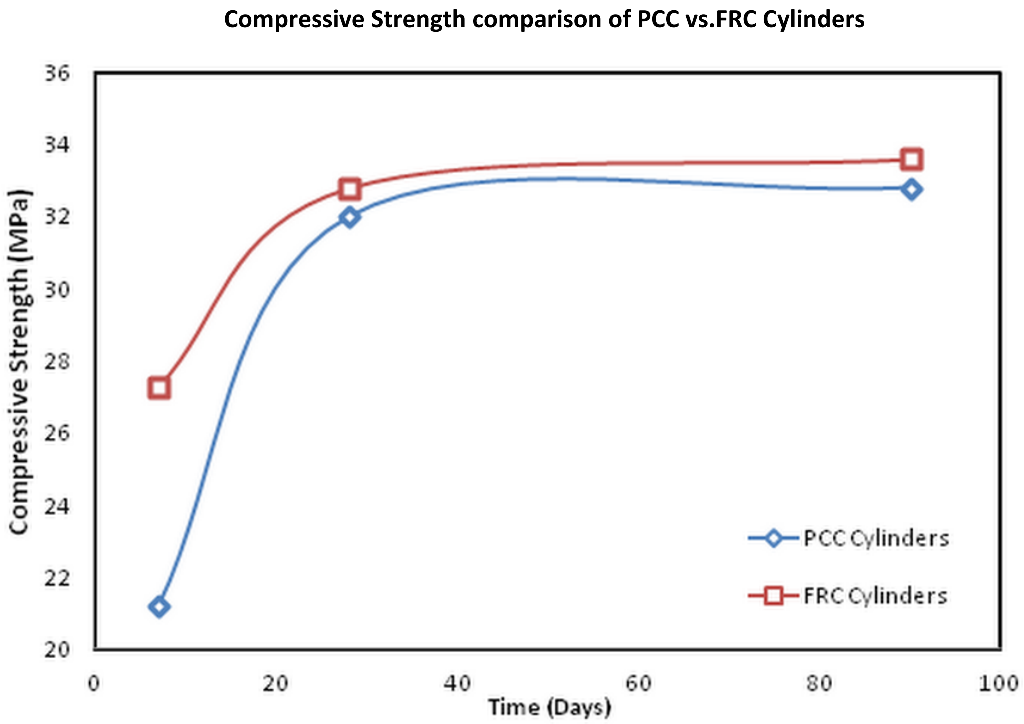
No. of Curing days	Strength Achieved (MPa)
7	27.3
28	32.8
90	33.6

The following graph shows the increase of strength of FRC cylinders with the increase in the number of curing days. With the use of FRC we were able to achieve a maximum compressive strength of 33.6 MPa. The graph shows the regular increase in strength up to 40 days of curing and then achieves at constant value of 33.6 MPa. The different strength values are enlisted in the following table:



Comparison of FRC vs. PCC in terms of Compressive Strength:

A comparison of behavior and strength of PCC and FRC cylinders is discussed, based on the results of the experiments performed on specimens.



The above graph compares the compressive strengths, achieved corresponding to the number of curing days, for samples with same mix ratios (PCC and FRC). Careful examination of the graph shows that the addition of fiber enhances the early strength gain of concrete matrix. As the curing progressed, the strength gained by FRC cylinders was slightly higher than PCC cylinders. The following table expresses the graph in numerical terms:

Time (Days)	Strength gained by PCC (MPa)	Strength gained by FRC (MPa)
7	21.2	27.3
28	32	32.8
90	32.4	33.6

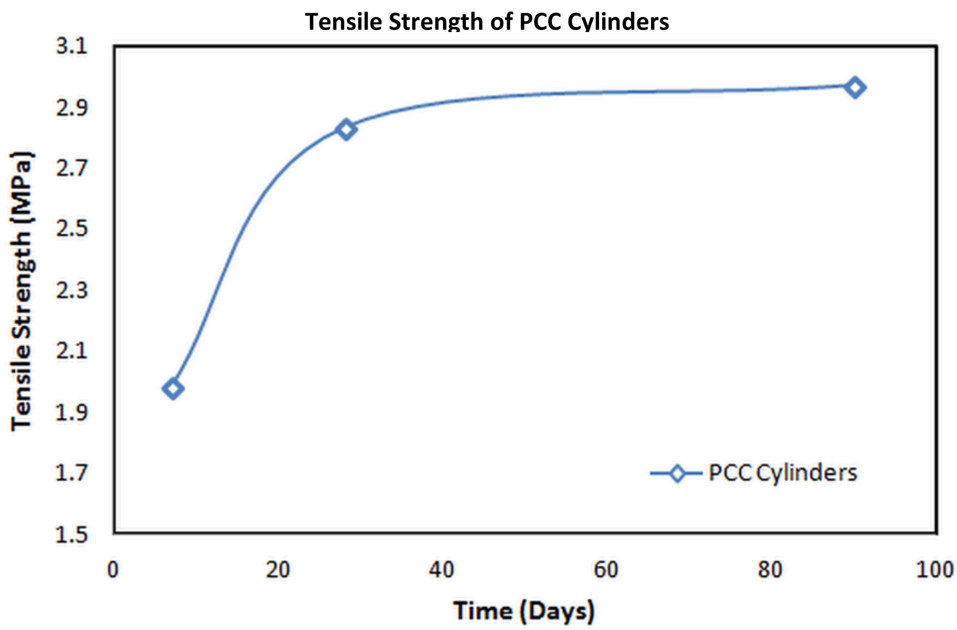
There is a marked difference of 5 MPa in the strength of FRC and PCC strength gain at 7 days. The early enhancement of compressive strength of FRC is attributed to the reinforcing effect of the fibers added to the concrete matrix. This reinforcing effect causes the fibers to bear more load by providing strength at early stages. While on the other hand, the strength gain at 90 days did not show any marked difference. This behavior confirms the fact that the fibers do not significantly enhancethe compressive strength of the concrete. So, the behavior of FRC in improving the compressive strength gain was clearly understood by this comparison.

2) Splitting Tensile Test:

For the splitting tensile strength evaluation, tests were performed after curing of 7, 28 and 90days. The statistical analysis of test performed on PCC cylinders is shown in table below.

Time (Days)	Max. Load (KN)	Splitting Strength (MPa)
7	140	1.98
28	201.7	2.83
90	212.3	2.97

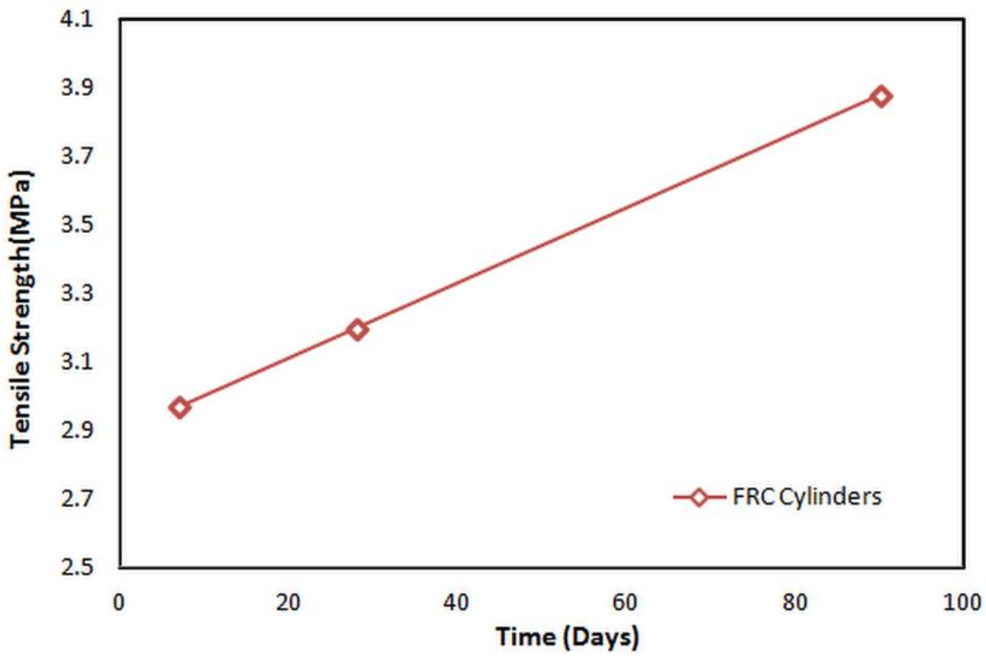
The samples casted with PCC were tested for splitting tensile strength at different intervals of curing. The trend in the below graph shows the increase in the splitting tensile strength of concrete matrix with the increase in the number of curing days. This behavior is attributed to the increase in the compressive strength of concrete and thus increasing the tensile strength of concrete. Also, the graph shows a nearly straight line after 40 days of curing. This is also attributed to the behavior of compressive strength which stays constant after 40 days of curing.



Similar test performed on samples reinforced with FRC Cylinders. The results are discussed below.

Time (Days)	Max. Load (KN)	Splitting Strength (MPa)
7	209.93	2.97
28	226.19	3.2
90	274.26	3.88

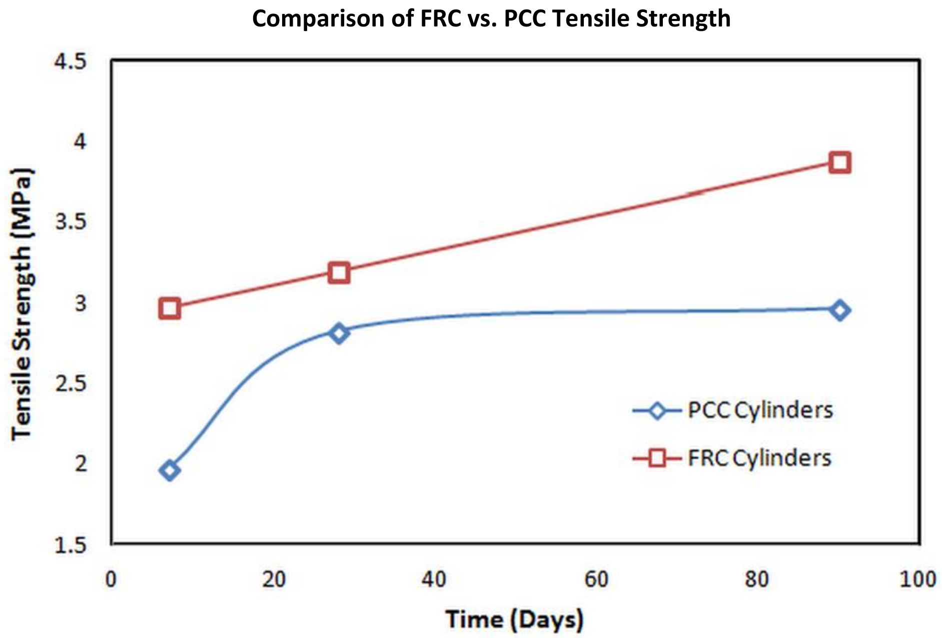
Tensile Strength of FRC Cylinders



The splitting tensile strength achieved with the FRC samples showed a similar trend of increase in splitting tensile strength with the increase in compressive strength with increase in duration of curing. The graph does not achieve a constant value after 40 days even though when the compressive strength has achieved a constant value. This is due to the enhancement of tensile strength of concrete with the introduction of steel fibers. Addition of fibers significantly improves the performance of concrete under tensile loads.

Comparison of FRC vs. PCC in terms of Splitting Tensile Strength:

A comparison of behavior and strength of PCC and FRC cylinders when subjected to tensile force is discussed below, based on the results of the experiments performed on specimens.



There is a marked difference in the behavior of PCC and FRC in terms of splitting tensile strength at same duration of curing. The introduction of fibers in the concrete matrix enhances the tensile strength. A keen look at the above graph shows the following key features:

- The splitting tensile strength of the FRC samples is higher than the PCC samples at corresponding same duration of curing. The tensile strength enhancement of the fibers gives rise to such a behavior.
- PCC samples attained a constant value of splitting tensile strength at 40 days i.e. in plain concrete; splitting tensile strength increases with the increase in the compressive strength of the matrix and becomes constant when the compressive strength is stabilized. On the other hand in FRC, the splitting strength increases beyond the mark of 40 days of curing even though the compressive strength is constant. This behavior is attributed to the reinforcing nature of fibers against the tensile splitting of concrete.

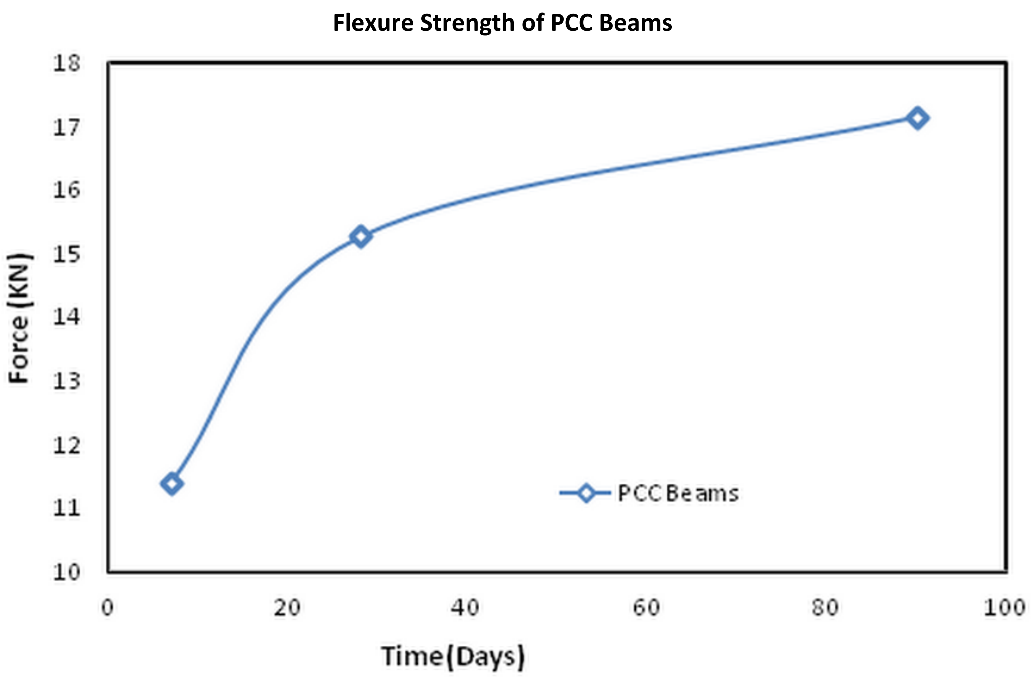
The resultof the above experiment shows that incorporation of fibers in the concrete will result in better tensile behavior and more ductile response.

3) Flexural Strength Test:

For the Flexural strength evaluation, tests were performed after curing of 7, 28 and 90days. The statistical analysis of test performed on PCC beams are shown in table below.

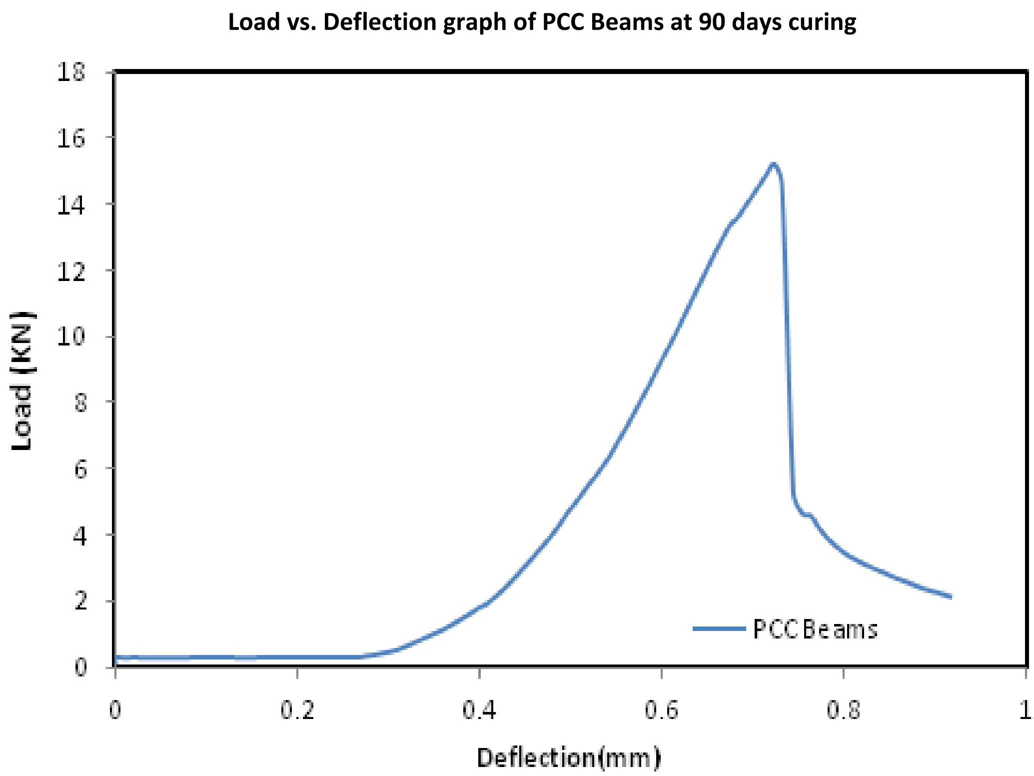
Time (Days)	Flexural Strength Max load (kN)
7	11.4126
28	15.2694
90	17.1553

Below is a graphical representation of the results achieved by testing PCC beams in flexure.



The usual trend of increase of flexural strength with increase of compressive strength was achieved. The steep slope of the graph till 30 days shows that the there is significant change in flexure strength with increasing curing duration. A gentle slope after 30 days of curing explains that there is no marked increase in flexural strength.

The following graph represents the deflection against the amount of load applied on the beam cured at 90 days.



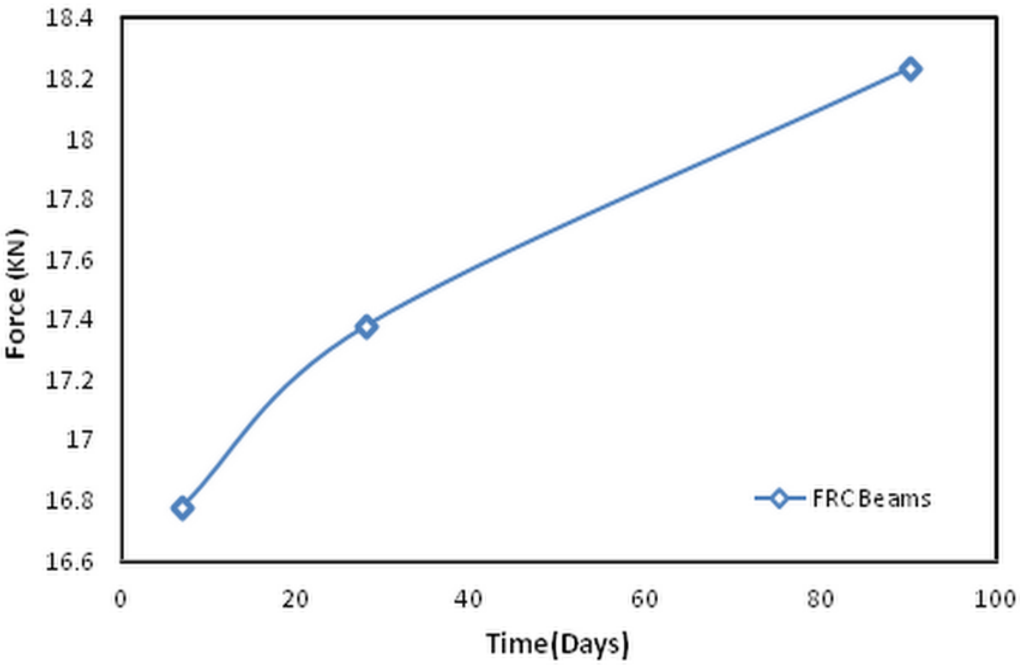
The graph shows a very brittle failure of the PCC beam at maximum load. The beam is taking a lot of load while showing no significant deflection. After the failure, there is no post cracking ductility of the PCC samples which is shown by abrupt drop in the graph after the maximum load is attained.

Similar experiment performed with FRC beams gave the following behavior in terms of maximum load. The results are tabulated below.

Time (Days)	**Flexural Strength (Max load KN)**
7	16.7791
28	17.3809
90	18.2365

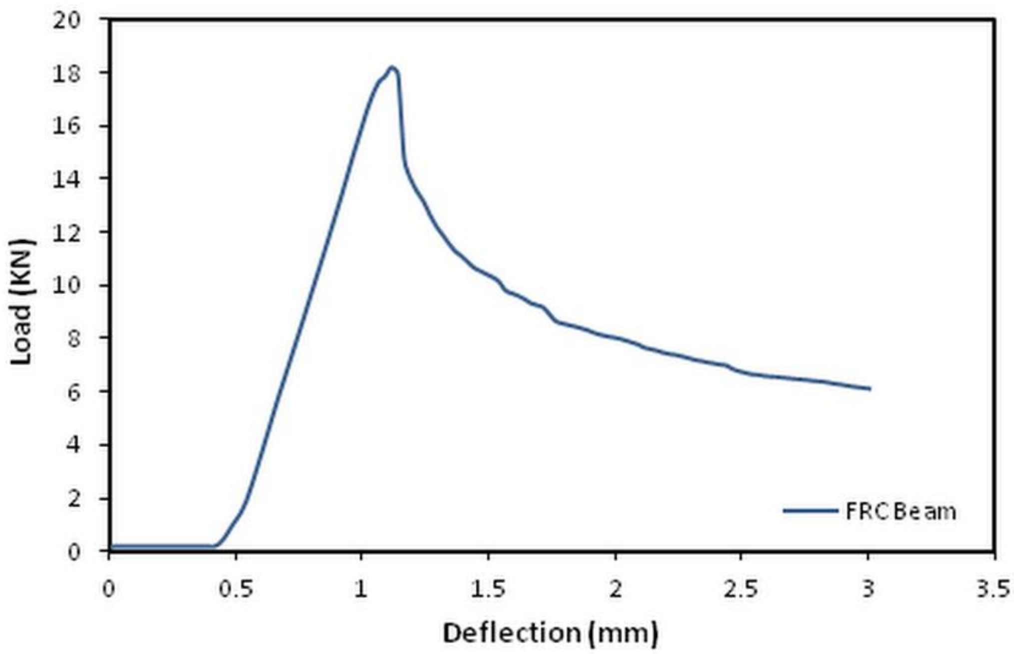
Below is a graphical representation of the results achieved by testing FRC beams in flexure. The usual trend of increase of flexural strength with increase of curing duration was achieved.

Flexure Strength of FRC Beams



A marked rate of increase in the strength of Fiber reinforced beams was noted in the results achieved. The reinforcing properties of fibers proved to be excellent in improving the flexural load carrying capacity throughout the curing period. Further shown is a graph of load vs. deflection of a FRC beam cured at 90 days.

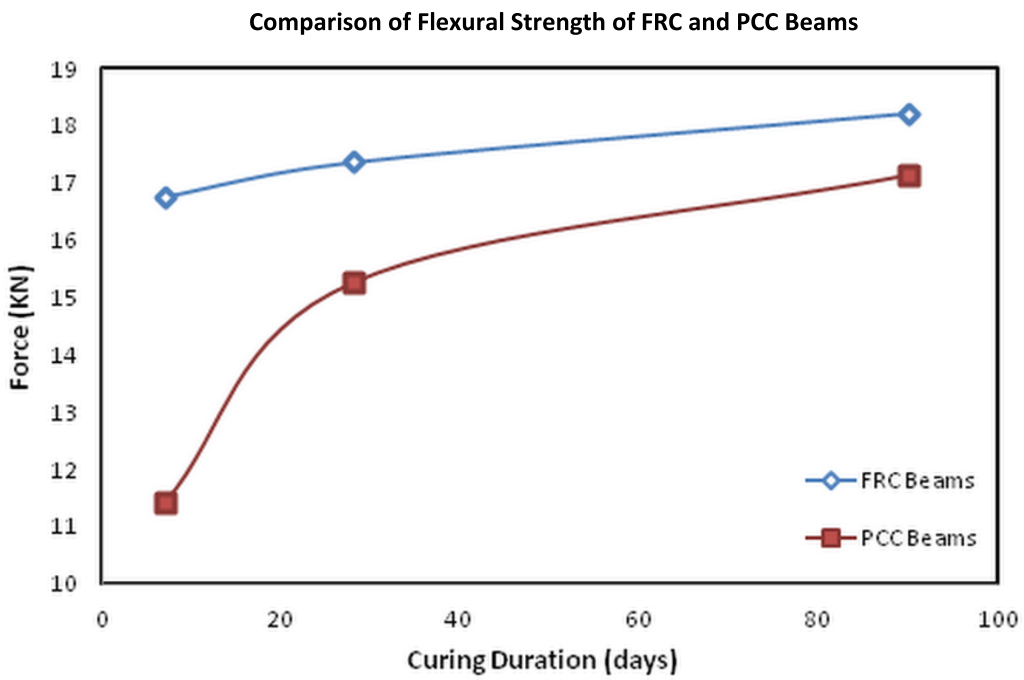
Load vs. Deflection graph of FRC Beams at 90 days curing



The above graph shows a very good ductile behavior of FRC beam against load applied. A gentle slope at the start shows that the beam is taking load and is allowing deflection as well. After failure, the beam showed good post cracking ductility. The beam was able to take higher load with ductile behavior even after the failure. This property, as studied from the literature, was practically proven through this experiment.

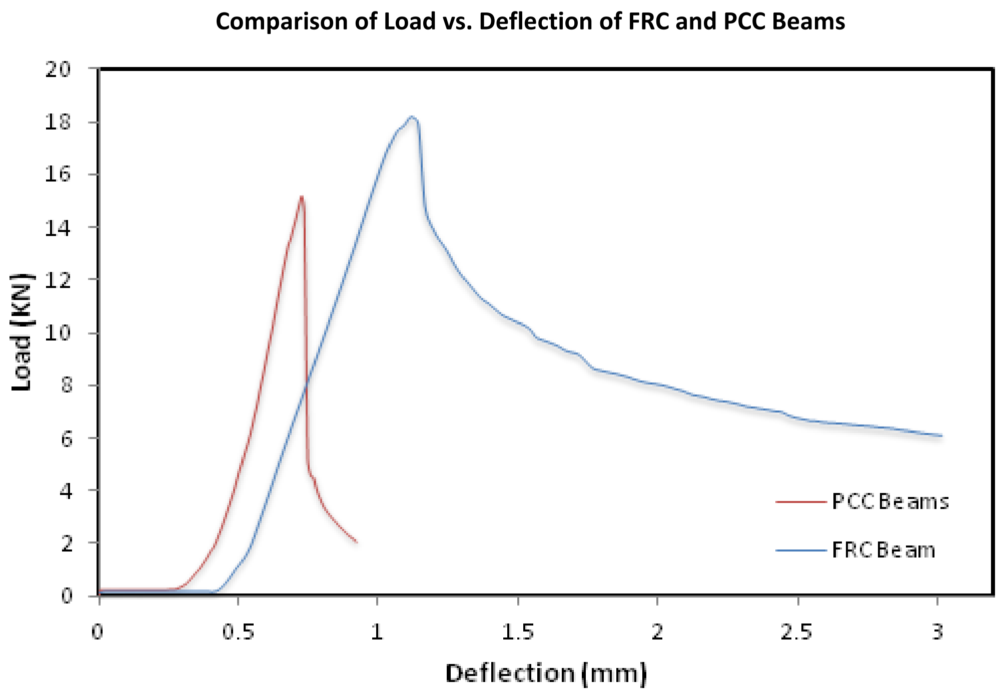
Comparison of FRC beams vs. PCC beams in terms of Flexure:

The comparison of maximum flexural load sustained by PCC and FRC is shown in the below graph.



It is clear that introduction of Fibers in the concrete mix enhanced the early strength of the beams. There is also a considerable change in the final flexural strength of the beam samples. The same attribute of reinforcing properties of fibers is the cause of the difference in the flexural strengths of PCC and FRC beams at same curing days.Addition of fibers increases the flexural toughness and enhances the flexural strength of the concrete.The gain in strength of PCC beam was high till 30 days of curing shown by steep slope of graph. After curing of 30 days the increase in flexural strength was not considerably high. While in case of FRC there was almost linear increase in strength throughout curing period.

The graph shown below of load vs. deflection draws a comparison between PCC and FRC beams.



When the load deflection curves of the samples of both FRC and PCC cured at 90 days are compared, there is a remarkable difference in the load carrying capacity and post cracking behavior. The increase in the flexural strength is due to enhanced flexural toughness of the beam caused by the addition of the fibers. The steep slope of the PCC curve shows the brittle behavior of the beam. On the other hand a gentle slope of FRC curve shows a more ductile response. In addition to the strength enhancement, fibers add to the post cracking ductility of the ordinary plain concrete matrix. Even after failure the FRC beam was able to withstand appreciable load. The bridging of cracks due to fibers enhanced post-cracking ductility.The comparison of both the curves at and after the failure shows that FRC beams are capable of improving ductile properties before and after failure.

The following conclusions were drawn from the performed tests and comparison of results;

- FRC improves the Max Flexural Load carrying capacity of the plain concrete matrix.
- Post cracking ductility is enhanced by the introduction of fibers to the concrete.

Chapter 3

Application of FRC in the Repair Work

The main purpose of the research work was to determine the feasibility of using FRC as a repair concrete matrix in rehabilitation of RC structures. For this purpose, a number of samples (beams and columns) were casted and cured. The specimens were damaged and then repair FRC mix was applied. Carrying out of the repair work is fully explained further in this chapter.

Specimen Specifications:

Standard beam specimen were casted with the following specifications

Feature	Specification
Length (mm)	750
Cross-Section (mm x mm)	150 x 150
Bottom Reinforcements	2 no. 13 bars
Stirrups	No. 10 bars
C/C Spacing of the Stirrups (mm)	100
Side cover and End cover (mm)	25

Column specimen prepared had the following dimensions:

Feature	Specification
Length (mm)	450
Cross-Section (mm x mm)	150 x 150
Reinforcements	4 no. 13 bars placed at 4 corners
Ties	No. 10 bars
C/C Spacing of the ties (mm)	100
Side cover and End cover (mm)	25

Mix Ratio:

Earlier mix design covered in chapter 3 was used for casting of specimen while mix ratio of 1:2:4 was used for the repair purposes.

Preparation of Specimens:

Three beams and three column specimen were prepared with RC having specifications written above. These specimens were cured for 28 days to gain strength. After the completion of curing, damage was induced in the test specimens. It was made sure to keep the intensity of damage to be same in all the beam specimens.

Procedure to Induce Damage:

A 50 mm deep cut was made on the tension side of the beam specimens running from one side to the other at a distance of 75 mm right and 75 mm left from the mid of the beam, with the help of concrete cutter. The concrete between the cuts was then scrapped off from the tension side with gentle blows of wedge and hammer up to the depth of 25mm in order to expose the reinforcement. Care was taken to avoid crack propagation deep into the specimen and up to the best of our efforts the damage induced was kept same in all beam specimens.

Fig. 3.1 A damage induced Beam with formwork

One of the specimens was left unrepaired to be used as a controlled specimen and other two were repaired using PCC and FRC using concrete replacement method. The repaired samples were then cured and tested in flexure.

Similarly a cut of 50 mm was made at 75 mm towards top and 75 mm towards bottom of the mid-height of each column. This process was done on two opposite faces of the column. The concrete between cuts was scrapped off with gentle blows of wedge and hammer exposing the reinforcement.

Fig. 3.2 A damage induced Column with formwork

One of the specimens was left unrepaired to be used as a controlled specimen and other two were repaired using PCC and FRC using concrete replacement method. The repaired samples were then cured and tested in uni-axial compressive strength test

Repair:

For both the beams and columns, the test was performed on the following three types of specimen and results were compiled;

Type of specimen	Repair Method	Condition
Beam	Control Specimen	Damaged & no repair applied
	Repaired with PCC	Damaged &repaired with PCC
	Repaired with FRC	Damaged & repaired with FRC

Column	Control Specimen	Damaged & no repair applied
	Repaired with PCC	Damaged &repaired with PCC
	Repaired with FRC	Damaged & repaired with FRC

Control Specimen was kept damaged and no repair was applied in order to determine the strength of the specimen. While the other two specimens were subjected to repair using PCC and FRC mixes.

The mix ratios of the repair concrete applied are as follow

Type of concrete mix	Mix ratio	Slump
PCC	1 :2 :4	True Slump
FRC	1 :2 :4	True Slump

Same composition of repair mixes were applied to both beam and column repairs. True slump was maintained in order to rule out the problem of surface cracking due to drying shrinkage. Once the damaged was done, the damaged surface was washed with splash of water and brushed to remove loose concrete pieces and dust. Two boards of plywood were clamped against the sides of each beam and column specimen to be repaired. The prepared PCC and FRC mixes were added and compacted with help of vibratory compactor. Surface of the sample was made smooth and was left for 24 hours. After this, the specimen was put into the curing tank for 28 days to allow the repair mix to gain strength.

Fig. 3.3 A PCC repaired Column with formwork

Experimentation on Repair Specimens:

The following tests were performed on the repair specimen;

- Flexural strength tests on beams
- Axial compressive strength test on columns

I. Flexural Strength Test:

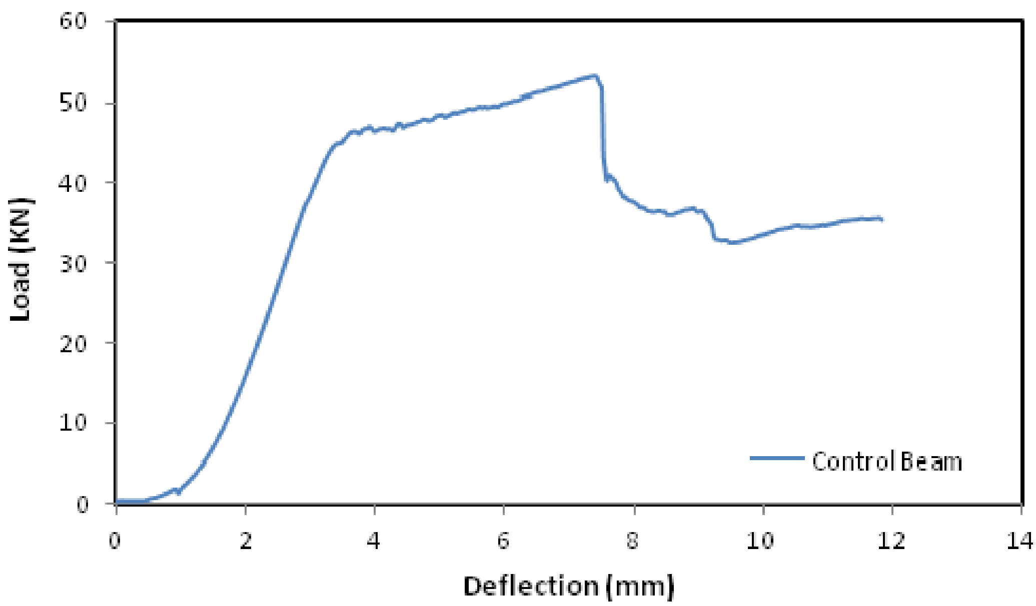
Three point loading test conforming to ASTM standard C78 was performed on the Control and Repaired Specimen. The specifications of the test were as follow

Type of Beam Specimen	Type of Repair mix used	Rate of loading
Control Specimen	No repair applied	0.1 mm/min
Specimen repaired with PCC	PCC (1 :2 :4 , w/c = 0.50)	0.1 mm/min
Specimen repaired with FRC	FRCC (1 :2 :4 , w/c = 0.50, Fibers = 45 kg/m3)	0.3 mm/min

I. Control Specimen:

The graph below shows Load vs. Deflection behavior of the control beam.

Load vs. Deflection Graph of Control Beam



The behavior of the control beam was quite irregular and the graph shows two major peaks. The first peak in the curve corresponds to the start of crack development under the point of application of load. Once the crack development has started, slope of the graph changes. This is due to the fact that the method of application of load was controlled by deflection and to keep the rate of deflection constant once the crack development started, the machine had to reduce the rate of application of load to reach the failure point Peak 2.

Taking the maximum value, the failure load was determined as 52 (KN). The vertical drop in the graph shows that beam failed and development of large flexural crack. The beam showed poor post cracking ductility. The entire load after failure of the beam was carried by the provided reinforcements. The objective to disturb the desirable ductile behavior of the beam was met. Following table relates the two peak values of load in the graph with respective deflections:

Peak	Load (KN)	Deflection (mm)
First Peak	48	4.3
Second Peak	52	7.2

Fig.3.4 A failed Control Beam

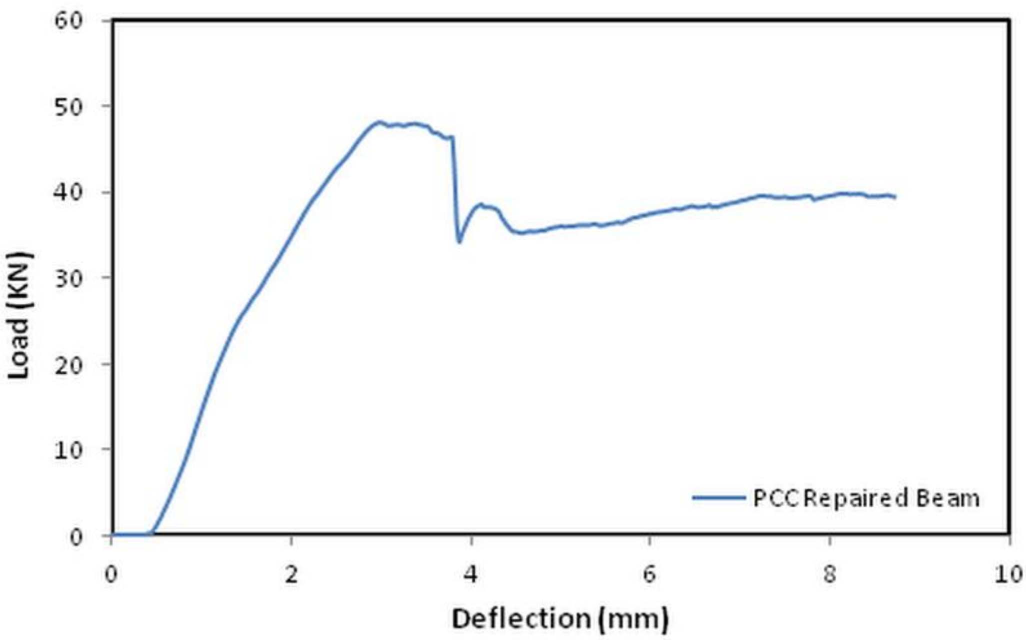
Conclusion:

1. The beam showed visible large flexural crack under the point of application of load.
2. No post cracking ductility after the point of failure.
3. Load carrying capacity was greatly reduced after the development of flexure crack

II. PCC repaired Specimen:

The following graph shows the behavior of a PCC repaired beam under loading.

Load vs. Deflection Graph of PCC Repaired Beam



The initial part of the load deflection curve is linear (approximately) depicting regular load deflection behavior. After failure, the beam showed no signs of ductile behavior and a vertical drop in the curve can be observed in the graph corresponding to the brittle behavior after failure. After failure, the irregular horizontal line represents the load taken directly by the steel reinforcement. The following table gives a numerical representation of the above plotted graph:

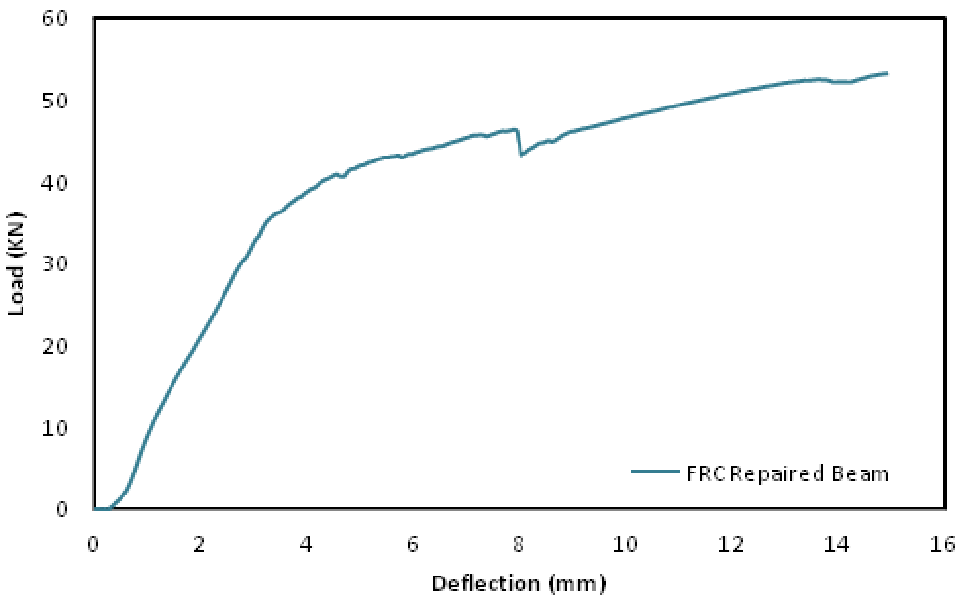
Point in graph	Load (kN)	Deflection (mm)
Failure point	49.5	2.8
End of the vertical drop in the curve after failure	35.2	4

The deflections achieved with PCC applied repairs were significantly low as compared to the controlled damaged specimen whereas there was no marked difference in the load carrying capacity.

III. FRC Repaired Specimen:

Flexural Strength test on the beam sample repaired with FRC showed the following behavior:

Load vs. Deflection Graph of FRC Repaired Beam



The initial part of the curve is straight showing regular deflection increment with the increase in load. From the graph, we cannot define a failure point clearly. The change in slope of the curve at the edge of straight part of the curve corresponds to the crack initiation. The deflection keeps on increasing with the load and there is no sudden drop in the curve. However, after a large amount of deflection, a minute break in the curve is observed corresponding to a deflection of 8 mm.This drop is due to flexure crack development in the repaired FRC mix portion directly under the application of load. Since fibers resist propagation of the cracks, the beam was able to withstand significant amount of deflection and load.

The following table is a numerical crux of the above plotted graph:

Points on the curve	Maximum Load (kN)	Deflection (mm)
End of initial linear curve	40	5
Break point in the graph	48.5	8.5
End of the curve	52	15

This behavior represents excellent property of post cracking ductility. This desirable feature required in most of the structural repairs is favorable in case of the large deflections due to earthquakes, settlements etc. So the objective of achieving post cracking ductility with use of steel fibers in repairs was achieved.

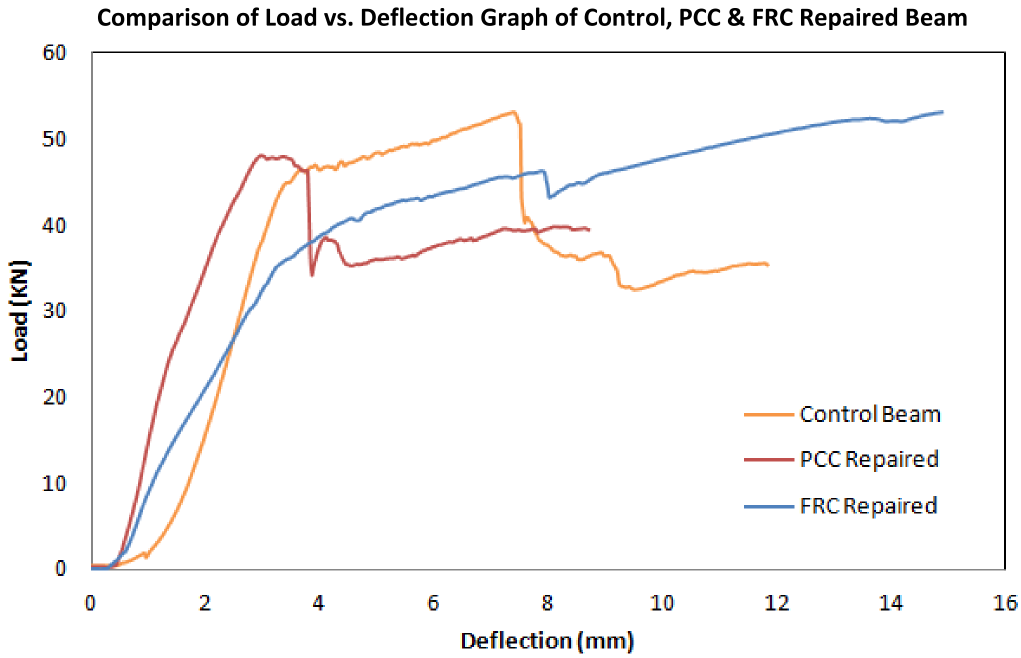
Fig.3.5 A failed FRC Repaired Beam

Conclusion:

The use of steel fibers in repair imparts excellent ductile property before and after and the cracking.

IV. Comparison of FRC and PCC Repaired Specimen:

The below graph shows a comparison of behavior of PCC and FRC repaired beam



The comparison of three beams interms of load vs deflection curve shows poor post cracking ductility of Control and PCC repaired specimen. The slight horizontal portion of the graph after failure in these beams corresponds to load taken directly by the reinforcement. On the other hand, FRC repaired beam shows excellent pre and post cracking ductility. There is no abrupt drop in the graph showing excellent ductile behavior. Continuous rise in curve after a small vertical drop is attributed to bridging of the cracks by steel fibers and the load taken directly by the reinforcement after the cracking of concrete.

Comparison of Fiber and PCC Repair Work In Terms of Ductile Behavior:

The comparison of the above explained results leads to observation that fiber repairs can significantly increase the ductility of the repaired structure as compared to PCC. On the other hand, the obtained test results show a bit lower load carrying capacity of the sample repaired with FRC as compared to PCC. The property of enhancement of ductility of damaged structures can be useful in the rehabilitation of structures in earthquake zones where the abrupt variation of loads produce large deflections causing brittle failure. Moreover, the areas where large structures are subjected to differential settlement, such repairs can be done to cater for the problem of low ductility encountered with plain concrete matrix.

Test on Columns:

II. Axial Compressive Strength test:

Column specimens were tested under axial loads in standard compressive test machine. Following test specifications were followed:

Type of Specimen	Rate of Loading (MPa/s)
Control Specimen	0.25
FRC repaired	0.25
PCC repaired	0.25

Machine used was Load controlled with constant loading rate of 0.25 MPa/s. The results of maximum load carried by the specimensare shown in the table below.

Specimen	Load (KN)
Control Specimen	642.4
PCC repaired Specimen	665.5
FRC repaired Specimen	734.9

I. Test on the Control Specimen:

The following observations were made whencontrol column specimen was subjected to axial compressive load in standard compressive test machine

1. Early appearance of surface cracks
2. Spalling of concrete outside the concrete core
3. Large crack widths

Maximum compressive load taken by the control specimen = 642.4 kN

II. Test on PCC repaired Specimen:

Test results obtained with PCC repair mix were

1. Medium crack width
2. Minimum spalling
3. Increased axial load carrying capacity
4. Delayed appearance of cracks on the surface

Maximum axial compressive load taken = 665.5 kN

These results show and improved behavior against spalling off of surface concrete. The load carrying capacity of the column was increased from 642.4 KN (Control Specimen) to 665.5 KN (PCC applied repair).

Conclusion:

The application of PCC repair on column specimen improved resistance against surface cracking, delayed the appearance of surface cracks, reduced the crack opening and increases a small amount of load carrying capacity.

Fig.3.6 A PCC Repaired Column after failure

III. Test on Fiber Repaired Sample:

With the use of fiber repair concrete mix, the test results came up with the following results:

1. Significant delay in the appearance of surface cracks
2. Appreciable reduction in crack opening
3. Considerable increase in load carrying capacity of the column specimen
4. No spalling off of the surface concrete

Maximum axial compressive load taken by the column specimen = 734.9 kN

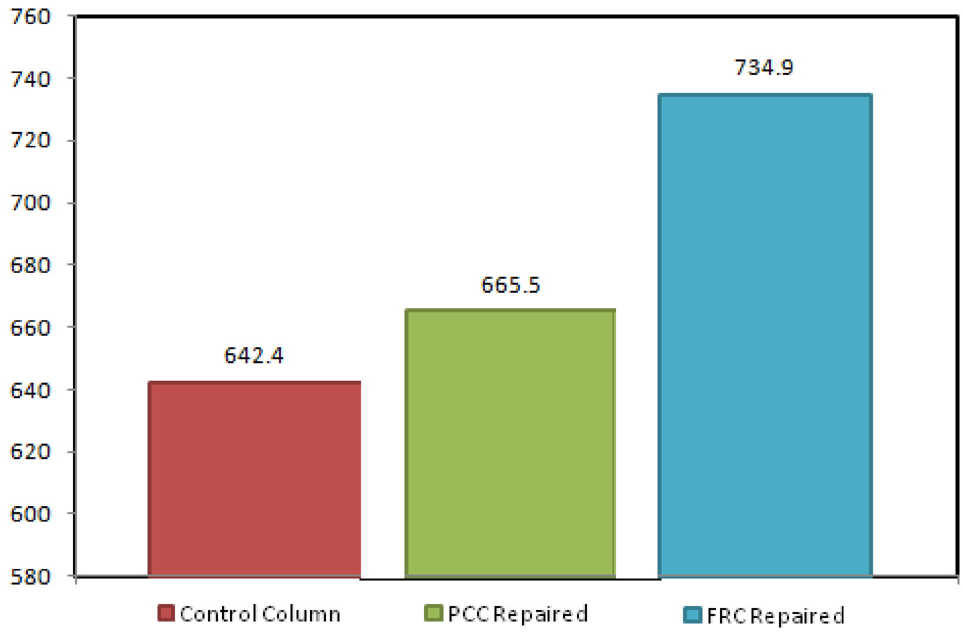
Conclusion:

Appreciable enhancement in the reduction of surface spalling, crack widths, delayed appearance of the surface cracks, no spalling off of the surface concrete, good bonding with the existence concrete surface. These properties represent excellent repair potential of beam-column joints subjected to surface spalling, strengthening of columns showing spalling, columns exposed to the external atmosphere, rehabilitation of columns in earthquake and flood affected areas.

Fig. 3.7 A FRC Repaired Column after failure

IV. Comparison between the FRC and PCC repair in columns:

The below column chart compares the load resisted by the control, PCC repaired and FRC repaired column.



The comparison of above explained results gives a clear idea that FRC is a better repair option for improving the resistance against surface cracking, crack propagation, reducing crack widths, significant increase in the load carrying capacity of the columns. These properties are particularly useful in practical applications where the columns are subjected to eccentric loading producing tension on faces of columns resulting in spalling.

Chapter 4

Proposed Repair Methodology

On the basis of our research, we have proposed a methodology for the repair of RC structures using fiber reinforced concrete (FRC).Our concrete repair method is most feasible in situations where damage to concrete is of an appreciable area and when the depth of damage approaches or goes though behind the reinforcement.

Type of damages

Damages can be due to a number of reasons, which may include the following and multiple others as well.

1) Excess Concrete Mix Water

Excessive water reduces strength, increases curing and drying shrinkage. It also increases porosity, creep and reduces the abrasion resistance of concrete. This results in reduced grade of concrete and more open environmental degradation. [3]

Fig.4.1 A concrete slab showing cracks due to excessive water in mix [5]

2) Cyclic Freezing And Thawing

This is a dominant problem in colder climate regions. Moisture in the concrete when freezes it exhibit nearly 15% volumetric expansion causing cracks in the concrete. [3]

Fig. 4.2 A Concrete member showing cracks due to freezing and thawing [6]

3) Construction Defects

Construction defects arise due to work that was not carried out in a 'good and workmanlike manner' in accordance with good practice or a particular design. Some of the more common types of damage to concrete caused by construction are rock pockets and honeycombing, form failures, dimensional errors, and finishing defects.[3]

Fig. 4.3 A Concrete Column with inadequate cover and exposed reinforcement [5]

4) Abrasion And Erosion Damage

Concrete members who transport fluids, carrying silt, sand, rocks at high velocities are usually subject to abrasion and erosion. This is restricted to the concrete surface but continuous exposure can cause a great extent of damage. [3]

Fig. 4.4 A Concrete member erosion with exposed reinforcement [9]

5) Cavitation Damage

Cavitation damage occurs when high velocity water flows encounter discontinuities on the flow surface. Discontinuities in the flow path cause the water to lift off the flow surface, creating negative pressure zones and resulting bubbles of water vapor. These bubbles travel downstream and collapse. If the bubbles collapse against a concrete surface, a zone of very high pressure impact occurs over an infinitely small area of the surface. Such high impacts can remove particles of concrete, forming another discontinuity which then can create more extensive Cavitation damage. [3]

Fig. 4.5 Cavitation in spillway of Glen Canyon Dam [8]

6) Acid Exposure

Acid rapidly damages concrete, it reacts with Portland cement converting it into calcium salts which wash away. [3]

Fig. 4.6 A concrete member damaged due to acid attack [7]

7) Structural overloads

Overloading causes very easily detectable damages to concrete members. Cracks begin to appear in distinct patterns which indicate to where the stress is being applied and also the nature of the stress. [3]

Fig. 4.7 A Crack in a concrete member due to structural overload [5]

8) High Impact Loads

Depending on the intensity of the impact, the damage may vary from surface micro-cracking up to massive fissures in the concrete. These cracks may also extend well below the reinforcement in a single blow. [3]

Fig. 4.8 A Crack in a concrete member due to High impact loads [5]

The above mentioned causes of damage to concrete all result in the same outcome. For the sake of our research only a few causes of damage were studied and repairs were made. In all studies cases the unsound concrete has to be completely removed. If the damage is restricted to the cover only, then the cover is to be removed and the underlying reinforcement has to be exposed to the new concrete. If the damage is more severe, that is, the damage has extended beyond the concrete cover and the reinforcement has been exposed already, then the concrete is to be removed at least one inch below the reinforcement for adequate bonding. This is mainly due to the face that epoxy resins are not used in bond development at all. [3]

Special care has to be taken in the preparation of the damaged surface during repair. It is very important to make sure that the sound concrete does not suffer micro fractures during surface preparation otherwise the bond between the new and the old concrete will be inadequate.

Since we place full amounts of concrete on the damaged sections, without the help of any binding mortar or epoxy resins, it is very important to note that if the damaged area, (holes, etc.) are not of a significant size, the new concrete will not make a proper bond with the old concrete. It is quite similar to providing a certain development length to reinforcing bars for a sound bond to be formed.

Procedure:

The first step in the repair is to approximate the extent of damage in the structural member requiring repairs. When the extent of damage is identified, the subsequent steps shall be followed to carry out the repair.

1) Removal of old unsound concrete:

An outline should be marked on the damaged area inorder to identify the portion of unsound concrete. The identification of unsound concrete can be done effectively using non-destructive methods such as Schmidt Hammer. This will give an idea of the areas of the removal of unsound concrete. After marking the outline, it should be removed using gentle blows of wedge and hammer. Care must be taken with blows so that the underlying sound concrete is not cracked. This process of removal can be made more effective by making a cut with saw cutter up to required depth and then using sand blasting, bush hammers etc. to remove the unsound concrete.

The extent of damage to the concrete will determine depth of concrete to be removed. When the damage extends below the reinforcement, it is advised to remove the concrete up to at least 25 mm below the reinforcement. If the deterioration is extensive through the member, it is necessary to remove full depth of concrete.

2) Surface preparation:

After the removal of the unsound concrete, the surface of the structural member should be made rough. Use of sand blasting and bush hammer gives good surface roughness in addition to the removal of unsound concrete. If the equipment for these processes is not available, wedge can be used for making surface rough. Surface is made rough to ensure effective bonding of repair concrete with existing concrete.However, it is necessary that the blows do not induce fissures in the sound concrete. Once the process of surface preparation is complete, repair concrete can be applied.

3) Preparation of FRC Repair mix:

It is advisable to use the same mix ratio of concrete as the existing concrete. However, if this information is not available, a standard mix design procedure shall be followed to prepare a suitable mix.For steel fibers 2 percent by volume is considered a practical upperlimit for field placement with the necessary workability [4].It is ideal to maintain true slump of the repair concrete. However, practical application requires suitable workability which can be achieved with the use of super plasticizers and keeping water-cement ratio minimum. This is done in order to eliminate the possibility of surface cracking and shrinkage which may lead to poor bonding of repair concrete with existing concrete.
Introduction of epoxy resins will appreciably increase the bonding of existing and repair concrete. Hence they epoxy resins should be used,wherever possible without disturbing the other properties of repair concrete.

4) Setting up of form work

Form work defining all the exposed boundaries should be setup to facilitate the pouring of repair concrete while providing enough space for compaction. An example of such form work set up is shown in the figure below.

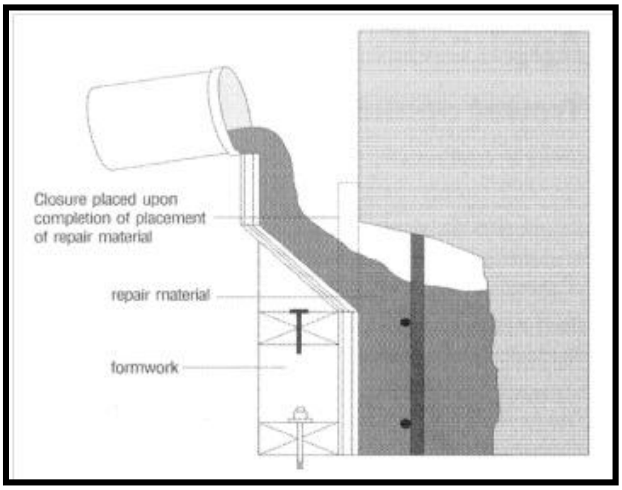


Fig. 4.9 Form work set up for repair work [10]

5) **Placement of repair concrete:**

Once the form work has been setup, the surface to be repaired should be made wet with water and repair concrete should be poured. Necessary compaction should be provided. Once the repair concrete has been placed, the surface should be made smooth. It should be ensured that the final surface of the repaired mix is in level with existing concrete.

6) **Curing:**

Adequate curing of the repaired surface is of prime concern. Proper arrangement should be made for the curing of the repaired surface with help of wet jute bags etc. The surface should not be allowed to dry out completely during the early days of curing otherwise it will lead to the development of surface cracks. After 28 days of curing, the repair of the structural member is complete. The non-destructive test should be performed in order to check the gained strength of the applied repair mix.

The research was carried out using steel fibers. Similar procedure can be employed for repair using other fibers available in the market. Addition of fiber in the mix will depend upon the type of fiber being used. This method provides a general outline of the repair method and can be modified according to need of situation at hand.

Summary:

Concrete can be damaged due to number of reasons which can affect the strength and serviceability of the structure. The repair needs to be applied in order to restore the structure. FRC when employed in repair behaves better than Plain Concrete. The repair methodology proposed as a result of the research involves the analysis of the extent of damage done to the structure. The extent of damage will determine the depth of unsound concrete to be removed. After the removal of unsound concrete up to appropriate depth, the surface should be made rough to ensure adequate bonding of applied repair with existing concrete. Loose concrete is removed using wire brush and surface is made wet. Once the process of surface preparation is complete, the repair mix can be applied. ACI standard mix design procedure is used with addition of steel fibers up to 2 percent of volume of concrete to prepare the repair mix. Lowest possible slump for adequate workability is maintained. Form work enclosing all the exposed boundaries with ease of compaction is set up. Repair concrete is applied with proper compaction and surface is made smooth. Adequate curing of the repaired surface is done to avoid the development of surface cracks due to shrinkage. 28 days of curing is done of repair mix to gain adequate strength.

Chapter5

Conclusion & Recommendations

Conclusions:

The following conclusions were drawn from the careful interpretation of experimental results achieved with Fiber Reinforced concrete:

1. Fiber Reinforced concrete used for repair and construction works gives excellent pre and post cracking ductility
2. FRC Repair significantly increases the load carrying capacity of axially loaded columns
3. With the use of FRC Repair a marked improvement in the tensile behavior of the concrete
4. FRC causes an appreciable reduction in spalling, surface cracking, reduction in crack-width
5. FRC causes higher early strength gain in concrete as compared to PCC
6. Decreased permeability of the concrete with use of FRC reduces the probability of damages caused by percolation of harmful chemicals
7. It is much better to use FRC for repair and construction of critical portions of the structures

The above conclusions derived from the experimental work leads to the fact that Fiber Reinforced Concrete is suitable for the repair and construction of RC structures due to its wide range of improved properties in comparison with Plain Concrete.

Recommendations for future work:

The research was carried out using one type of steel fiber. The other types of fibers can also be tested which may lead to identification of new dimensions of application of FRC in repair works. Furthermore, research is to be done to find the exact reasons of the reduced load carrying capacity observed in flexure for RCC repaired beam and improvements can be devised in order to improve both the aspects of strength and ductility in flexural repairs.

Research needs to be done in order to determine the most suitable cases of damage where fibers prove to be more cost-effective and efficient than the other methods of repair in practice.

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