CAPITAL UNIVERSITY OF SCIENCE AND TECHNOLOGY, ISLAMABAD

Experimental Evaluation of Nylon Fiber Reinforced Concrete (NFRC) for Shear Strength Enhancement of Deep Beams

by

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A thesis submitted in partial fulfillment for the degree of Master of Science

in the

Faculty of Engineering
Department of Civil Engineering

2019

This work is dedicated to my lovely parents who helped me throughout my life.
This work is dedicated to my honorable teachers who guided me to face the challenges of life with patience and courage.

CERTIFICATE OF APPROVAL

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Acknowledgements

I would like to thank Almighty Allah for his countless blessing. I am also grateful to my family for their continuous support. I would like to pay special gratitude to **Engr. Dr. Munir Ahmed** for his guidance and supervision, without which, this was not possible. I am grateful to all who assisted me during this study especially Engr. Fayyaz khan, Engr. Abdul Wahab khan, and Mr. Junaid for their kind support and help in lab work.

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Abstract

Reinforced cement concrete (RCC) deep beams are mostly used to transfer load of structure to foundation in the form of concrete girders in high rise buildings, in pile caps, and footing walls. The load is transferred through brittle mode of shear transfer mechanism in deep beams. This is the reason that the factor of safety is kept more in RCC deep beams design. Recently, researchers have started using sisal, steel, polypropylene, and glass fibers to enhance the concrete toughness index, energy absorption, and shear strength of concrete deep beams. However, a synthetically available nylon fiber, which is abundantly available in local market and cheaper than steel fibers, has not been investigated yet in perspective of energy absorption and shear strength enhancement of deep beams.

In the present study, therefore, nylon fibers are investigated in perspective of improving the load carrying capacity (shear strength), reducing diagonal cracks and enhancing ductility of concrete deep beams. This research has been divided in two phases. In the first phase, basic mechanical properties such as compressive strength, splitting-tensile strength, flexure strength, total energy absorption, and toughness index are investigated. For the preparation of concrete mix, ratio of 1:2.5:3.5:0.6 for cement, sand, aggregate and water respectively were used. To start with, 25mm long nylon fibers with fiber contents of 4% and 5% according to mass of cement were used for NFRC mix. The Plain and Reinforced Concrete were used as a reference for NFRC with and without reinforcement respectively. The concrete cylinders and beamlet samples are tested for compressive, splitting and flexural strength by using ASTM standard of C39/C39M-17, C496/C496M-11 and C293/C293M-16 respectively. The loading rates were 0.30 MPa/s for compressive strength, 1.2 MPa/m for splitting strength, and 1.2 MPa/m for flexural strength test in accordance with ASTM standards. An enhancement of about 25% and 21% in the splitting tensile and flexure strength respectively was observed for NFRC. A little reduction of 13% and 3% was observed in the compressive strength of NFRC with 4% and 5% fiber content respectively.

In the second phase, total 12 deep beam samples of sizes 150 mm widths, 300 mm depths, and 900 mm lengths are cast with two each for deep beam plain concrete (DBPC), deep beam plain reinforced concrete (DBPRC), 4% nylon fiber reinforced concrete with rebars (DBNFRC-4%), 5% nylon fiber reinforced concrete with rebars (DBNFRC-5%) respectively. After 28 days, standard specimens were tested for one point loading using 2000 kN capacity Servo-hydraulic Testing Machine (STM). The result obtained for DBNFRC-4% and DBNFRC-5% are compared with DBPRC samples. An enhancement of 22.9% and 11.3% is observed in the first crack loading capacity of DBNFRC-4% and DBNFRC-5% respectively when compared to DBPRC. An enhancement of 23.9% and 9.2% is observed in the highest load carrying capacity of DBNFRC-4% and DBNFRC-5% respectively when compared to DBPRC. An enhancement of 13% and 27% is observed in the ductility of DBNFRC-4% and DBNFRC-5% respectively when compared to DBPRC. An enhancement of 51.66% and 80.94% is observed in the deflection of DBNFRC-4% and DBNFRC-5% respectively as compared to DBPRC. Study shows that nylon fiber with 5% has the potential to enhance the load carrying capacity (shear strength), ductility and crack control. However, it must be tested with different combination of design mixes, fiber content and lengths.

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Abbreviations

CE1	The Compressive Absorbed Energy up to First Crack (MPa)
CE2	The Compressive Energy from First Crack till End (MPa)
CoS	Compressive Strength (MPa)
CToE	Compressive Total Absorbed Energy (MPa)
CToI	The Compressive Toughness Index (-)
DBFE1	Deep Beam Absorbed Energy up-to First Crack (kN-mm)
DBFE2	Deep Beam Absorbed Energy after First Crack till End (kN-mm)
DBNFC-4%	4% Nylon Fiber Concrete Deep Beams
DBNFC-5%	5% Nylon Fiber Concrete Deep Beams
DBNFRC-4%	4% Nylon Fiber Reinforced Concrete Deep Beams with Rebars
DBNFRC-5%	5% Nylon Fiber Reinforced Concrete Deep Beams with Rebars
DBPRC	Plain Reinforced Concrete Deep Beam
DBTI	Deep Beam Toughness Index (-)
DBPC	Plain Concrete Deep Beam
DBTE	Deep Beam Total Absorbed Energy (kN-mm)
FE1	Flexural Absorbed Energy up to Initial Cracks (kN.mm)
FE2	Flexural Energy after Initial Cracks till Last Crack (kN.mm)
FoS	Factor of Safety
FRC	Fibers Reinforced Concrete
FToE	Flexural Total Absorbed Energy (kN.mm)
FToI	Flexural Toughness Index (-)
GFRC	Glass Fiber Reinforced Concrete
JFRC	Jute Fiber Reinforced Concrete
MoR	Modulus of Rupture (MPa)

NFRC	Nylon Fiber Reinforced Concrete
NFRC-4%	Nylon Fiber Reinforced Concrete with 4% Fiber Content
NFRC-5%	Nylon Fiber Reinforced Concrete with 5% Fiber Content
PCC	Plain Cement Concrete
PPFRC	Polypropylene Fiber Reinforced Concrete
PRC	Plain Reinforced Concrete
RCC	Reinforced Cement Concrete
SFRC	Steel Fiber Reinforced Concrete
SiFRC	Sisal Fiber Reinforced Concrete
SpE1	The Splitting Absorbed Energy up to the First Crack (kN.s)
SpE2	The Splitting Energy after First Crack till Last Crack (kN.s)
SpS	The Splitting-tensile Strength (MPa)
STM	Servo-hydraulic Testing Machine
SpToE	The Total Absorbed Energy of Splitting-tensile Strength (kN.s)
SpToI	The Splitting-tensile Toughness Index (-)

Symbols

Φs	Strength Reduction Factor in Shear
θ	Angle b/w Strut and Tie
βs	Strength Reduction Factor for Strut
βn	Strength Reduction Factor for Nodes
ϵ	Strain
Δo	Deflection

Chapter 1

Introduction

1.1 Background

Deep beams are mostly used in civil engineering projects. Reinforced cement concrete (RCC) deep beams are used to achieve its better functionality in tall buildings, concrete bridges, in footings, in pile caps and in floor diaphragms, etc. RCC deep beams are component of structures that have smaller shear spans. In these building components, shear failure is normally seen and special care is given to shear strength in deep beam design [1,2,3]. The actual stress distribution of a deep beam is non-linear [4].

In deep beams, due to their lesser span to depth ratio ($\leq$3), the strength is controlled by shear. Predictable shear stirrups dont have the capability to provide efficient resistance to cracks in case of earthquakes or any other accidental loading etc [5]. Due to this, brittle failure mechanism may occur in beep beams. Some researchers have already done the experimental work in past decades with addition of different fibers such as glass, steel, polypropylene and sisal in concrete to enhance shear strength and controlling the brittle failure of deep beams. Robert et al. [6] conducted experimental study of deep beams using steel fiber and observed improvement in shear strength and ductility. The presence of steel fiber increases the shear strength as well as toughness of deep beams. Steel fibers also have ability to significantly enhance the post-cracking in tensile property and enhance ductility of concrete. In addition, steel fibers are also effective to reduce and delay the emergence of micro-cracks [7]. Fibers ultimately decreases the crack width due to loadings [8].

Therefore, keeping in mind the above advantages of fibers, nylon fibers could be also one of the possible solution. The nylon fiber is strong, have better elastic behavior and very fast in drying when used in concrete [9]. Habib et al. [10] concluded that using 2% of nylon fiber in cement mortar the flexural strength was improved and the cracks formation was reduced. Cook et al. [11] stated that nylon fibers have better elastic recovery, good toughness, and effective tenacity. Subramanian et al. [12] carried out an experimental study on nylon fiber reinforced concrete. The nylon fiber properties were checked with mix design ratio of (1:1.5:3), concrete cubes and cylinders were casted for compressive strength and splitting strength of concrete respectively. Nylon fiber with four different percentages of 0%, 1%, 2% and 3% were used. After testing it was concluded that nylon fiber enhanced the concrete compressive and splitting-tensile strength. Nylon fiber showed better mechanical properties i.e, nylon fiber increased the compressive strength, splitting tensile strength, modulus of rupture and impact resistance of concrete by 12.4%, 17.1%, 5.9% and 19% respectively [13]. Nylon fiber have better resistance to a wide variety of organic and inorganic materials like strong alkalis. Nylon fiber does not affect the cement hydration and workability of concrete. Nylon fiber is cheap and easily available in the market [14]. The properties of nylon fiber are shown in the Table-1.1.

Table 1.1: Properties of nylon fibers

Fiber type	Diameter inch x 10^{-3}	Specific gravity	Tensile strength ksi	Elastic modulus, ksi	Ultimate elongation, percent	Temperature, degrees F	Water absorption per ASTM D 570, Percent by weight
Nylon	0.90	1.14	140	750	20	392-430	2.8-5.0

To the best of author's knowledge, no study has been conducted on nylon fiber reinforced concrete (NFRC) for enhancing shear strength in deep beams, therefore, nylon fibers needs to be investigated in perspective of enhancing of mechanical properties and shear strength of concrete deep beams.

1.2 Research Motivation and Problem Statement

Now a days, the demand for safety of high-rise building and heavy loaded structures against severe loading conditions like earthquake loads and other accidental loads is increasing. This requires manufacturing of high-performance materials with better flexural and shear properties. At the same time, the cost of structures should be in desired limit. So, achieving the desired properties, fibers are being used for enhancing and modifying the concretes properties to resist high flexure and shear loadings. The problem statement is:

"The structures that have better capability to support high earthquake and heavy loads are of high importance. It becomes a matter of great importance to safely design the important high-rise buildings, bridge beams, marine structures and pile caps of foundations. Concrete is core material used for the construction of all infrastructure, however, it is weak in tension. To resist the tensile and shear forces in concrete, steel rebars are provided in the concrete components. This may be costly or even impracticable in some cases such as shear and ductility of deep beams. For achieving low-cost as well as enhancing the mechanical properties of concrete, fibers are used. Madan et al. [15] found that addition of small steel fibers up-to 40mm length in the concrete deep beams has effectively enhanced the shear strength, cracks control and ductility. The addition of steel fibers in addition to conventional reinforcements may be uneconomical. Therefore, there is a need to explore an alternative cheap solution, such as use of cheap and abundantly available nylon fibers in concrete, for the enhancement of the mechanical properties of concrete, ductility and ultimate load carrying capacity property (shear strength) of deep beams".

1.3 Objective and Scope of Work

i. To experimentally evaluate the mechanical properties of NFRC (compressive strength, splitting tensile strength and flexure strength) likely to affect the design of deep beams.

ii. To experimentally compare load carrying capacity of plain concrete deep beam (DBPC), Nylon fiber concrete deep beams (DBNFC), Plain reinforced concrete deep beams (DBPRC) and Nylon fiber reinforced concrete deep beams (DBN-FRC).

Mechanical properties, which are to be determined for achieving above objectives, are flexural strength, compressive strength, splitting tensile strength, energy absorption, toughness index, Load-deflection curve, crack pattern and shear strength. Samples of deep beams 900mm x 300mm x 150mm, beam lets 450mm x 100mm x 100mm, and cylinders 100mm dia x 200 height are cast and tested for the above mentioned properties.

1.4 Methodology

In this experimental study, the mechanical properties of PCC, RCC and NFRC are determined. The mix design ratio selected is 1:2.5:3.5:0.6 (cement: sand: aggregate: water) which is normally used in the country of author's. Based on literature review [13,16], 25mm long nylon fibers with a fiber content of 4% and 5% by mass of cement have been used for preparing NFRC because smaller fiber effectively enhanced the concrete mechanical properties with 4 and 5% fiber content by mass of cement. The mix design for NFRC is the same as that of PCC. For carrying and placing the deep beam samples, hooks are provided in all samples [17]. The mixing process is done in different layers, first some portion of course and fine aggregate is filled in concrete mixer and then some portion of fiber is spread manually on concrete in the mixer and this process is repeated throughout the NFRC mixing process. The filling of molds is done in four layers horizontally avoiding honey combing. Molds are filled in layers of 25mm, 50mm, 50mm and then 25mm thickness [16]. After every layer proper compaction is made. To determine the compressive and splitting tensile strength, three cylinders each for PCC and NFRC having dimensions of 100mm diameter and 200mm height are casted. To determine modulus of rupture, three beam-lets each for PCC and NFRC having dimensions of 100mm x 100mm x 450mm are casted. The steel reinforcements have been calculated using strut and tie method of ACI-318 for an assumed applied load. The 12 deep beam specimens are cast and tested to determine the shear strength, energy absorption and toughness index.

1.5 Thesis Outline

There are six chapters in this thesis, which are as follows:

Chapter 1 consists of introduction section. Importance of shear strength in deep beam is explained in this chapter. It also consists of research motivation and problem statement, objective and scope of work, methodology and thesis outline.

Chapter 2 contains the literature review section. It consists of background, improvement in mechanical properties and in load carrying capacity of concrete by using fibers, improvement in mechanical properties of concrete by using nylon fibers, design of selected deep beam using ACI-Code, and summary.

Chapter 3 consists of detail of experimental program. It contains background, concrete components, preparation of nylon fibers, mix design and casting procedure, preparation of deep beam samples, concrete specimens, testing procedure of concrete specimens, testing for mechanical properties, (i.e. slump and density test, compressive strength test, splitting tensile strength test and flexure strength test), testing procedure of deep beams and summary.

Chapter 4 consists of experimental results evaluation. It contains background, results of mechanical properties (i.e. slump and density test, compressive behavior, compressive strength, compressive energies, compressive toughness index, splitting-tensile behavior, splitting-tensile strength, splitting-tensile energies absorption/total absorbed energies, splitting-tensile toughness index, flexural behavior, modulus of rupture, flexural absorbed energies/total absorbed energies and flexural toughness index), crack pattern and propagation, deflection, first and final crack loading capacity of PCC deep beams with and without fibers, modulus of rupture, ultimate strength, flexural absorbed energies/total absorbed energies and flexural toughness index of PCC deep beams with and without fibers, crack pattern and propagation, deflection, first and final crack loading capacity of PRC deep beams with and without fibers, modulus of rupture, ultimate strength, absorbed energies/total absorbed energies and toughness index of PRC deep beams with and without nylon fibers and summary.

Chapter 5 includes the discussion. It covers background, reason of difference between theoretical and experimental loading of deep beams, ductility of concrete deep beams, relationship between deep beams and material properties and failure mode/pattern of deep beams.

Chapter 6 includes conclusions and future works.

References are presented right after chapter 6.

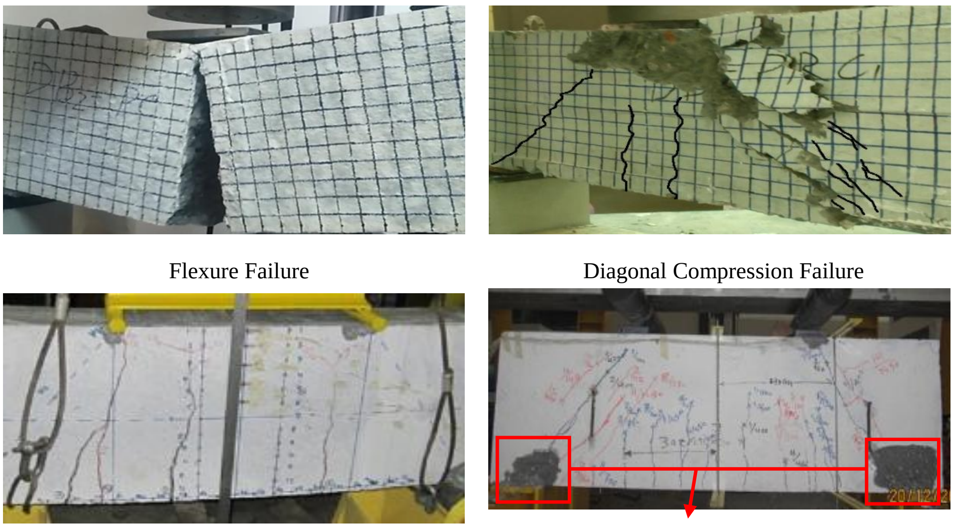
Chapter 2

Literature Review

2.1 Background

Reinforced cement concrete (RCC) deep beams are used as load transferring members in high-rise building and bridges etc [18]. According to ACI 318-14, deep beams are structural member with clear span equal or less than four times the overall depth. The load transferring mechanism of deep beams is totally different from that of slender beams, therefore, the design and detailing of deep beams need special care [5]. Due to geometry of deep beams, the strength is controlled by shear rather than by flexure [19]. Normal steel stirrups are not efficient to provide better resistance to crack formation and enhance ductility in case of earthquake or other accidental dynamic loading. Due to the small energy absorption after first crack and low shear strength, brittle failure mechanism may occur in RCC deep beams [5]. For controlling the crack propagation, enhancing the first crack loading capacity and ultimate loading capacity (shear strength) of deep beams, fibers have been tried by researchers in the recent past.

There are basically three types of failures in deep beams, i.e. flexural failure, diagonal failure and local failure. In flexural type of failure, the tie of deep beam starts yielding. This type of failure is normally occurred in the center at the bottom face of deep beam and progresses towards the top of deep beam. The diagonal type of failure is divided into farther two types; the first one is the diagonal compression failure, which is the failure of the strut of concrete deep beam in diagonal crushing. In this failure, the concrete particles are crushed and spalling of concrete is observed. The second type of diagonal failure is diagonal splitting failure, in which the concrete deep beam strut fails in diagonal splitting. In this failure, the concrete deep beam splits in two pieces along-with diagonal strut. The possible reason of this type of failure is reduced region of compression zone at the tip of inclined crack or by the fracture of the concrete along the inclined cracks. The local failure in deep beams includes the failure of deep beams at bearing plates or at anchorage points etc. The reason of these cracks is, low confinement of the concrete under high axial stresses. The details of all these types of failures are shown in figure 2.1 [18,20,21].



Flexure Failure

Diagonal Compression Failure

Diagonal Splitting Failure

Local Failure in Deep Beams

Figure 2.1: Types of failure of deep beams

The use of fibers reduces crack lengths, widths and their propagation in the concrete [14] because concrete mix behaves as an isotopic material. Many researchers carried out studies on Fibers reinforced concrete (FRC) such as (steel, glass, polypropylene, sisal and natural fibers etc) and concluded that fibers significantly enhance the shear strength of deep beams. The use of steel fibers in concrete enhances the highest load carrying capacity (shear strength) of deep beams upto 16%, enhances the load at first crack upto 36%, reduce crack formation and propagation, increase the energy absorption capacity of concrete and enhance the ductility of concrete [19].

The mechanical properties that contribute to the crack resistance of deep beams, and their performance in supporting heavy loads are compressive strength, splitting tensile strength and flexure strength. The flexural strength and splitting tensile strength act a key role in reducing cracks of deep beams [22]. It can be noted from ACI-318-14 that the compressive strength and steel yield strength are two main factors used for designing of deep beams. The design is controlled by bottom reinforcement yielding. However, experimental studies show that concrete deep beam failure is governed by brittle diagonal compression failure, which is brittle in nature. However, flexural cracks at mid, diagonal cracks and brittle failure can be a problem in deep beams. That is why factor of safety is kept more in deep beams. When principal stresses exceed the tensile strength of concrete, diagonal cracks appear which try to split the concrete [23]. The splitting tensile strength of concrete need to be enhanced to reduce diagonal cracks. Fibers can control cracks length and width propagation in concrete [14]. An addition of small percentage of fibers has the capability to enhance the impact resistance and mechanical properties of concrete [24]. Merta and Tschegg [25] conducted an experimental study to investigate cracking energy of concrete composites using natural fibers. The researcher concluded that cracking energy of concrete composites can be increased by using natural fibers. Joshi et al. [26] stated that natural fibers show better performance than glass fibers in many cases because natural fibers are environmental friendly. Wand et al. [27] considered three kinds of synthetic fibers i.e., nylon, acrylic, and aramid. The synthetic fiber behavior in concrete was studied by performing flexure, compression, and splitting tests. The mechanical properties of concrete were significantly improved with the use of synthetic fibers.

2.2 Improvement in Mechanical Properties and in Deep Beams Load Carrying Capacity by Using Fibers

Kulkarni et al. [5] carried out a research on hybrid fiber RCC deep beams (steel and glass) with mix design ratio of 1:1.98:3. The steel fiber by volume fraction of 0.5%, 0.7%, 0.9%, 1.1% and 1.3% with addition of glass fiber by 0.1%, 0.2% and 0.3% were used. An enhancement of 14.3% and 36.84% was observed in the compressive strength and highest load carrying capacity (shear strength) of deep beams respectively by optimum fiber content of steel and glass (1.3+0.3%). Sandeep et al. [28] conducted a research on steel FRC (SFRC) deep beams by using mix design ratio of 1:1.5:3 and steel fiber content of 0.75% and 1% by volume fraction. An enhancement of 6.6% and 47% was noted in the compressive strength and load carrying capacity (shear strength) of deep beams respectively with steel fiber of 1% fiber content. Sakthi et al. [29] carried out an experimental research using sisal FRC (SiFRC) deep beams. The sisal fiber content ratio of 0.5%, 1%, 1.5% and 2% was used by volume fraction with mix design ratio of 1:1.5:2.85. An enhancement of 20%, 31% and 10% was observed in the compressive strength, splitting tensile strength and highest load carrying capacity (shear strength) of deep beams respectively with fiber ratio of 1.5%. Robert et al. [6] conducted an experimental study on deep beams using SFRC with mix design ratio of 1:3:1.5. The steel fiber content of 3% and 4.5% by weight of cement was used. The steel fiber content of 4.5% gives better result and an enhancement of 22%, 78% and 53% was observed in the compressive strength, splitting tensile strength and the ultimate load carrying capacity (shear strength) of deep beams respectively. The researchers concluded that the failure mechanism of tested deep beams was ductile in nature and the shear strength was improved significantly. Shaikh et al. [30] carried out an experimental study on steel and polypropylene fiber by volume fraction. The steel fiber ratio of 0.5%, 0.7%, 0.9%, 1.1% and 1.3% with 0.1%, 0.2% and 0.3% of polypropylene fiber was used with each percentage of steel

TABLE 2.1: CoS, SpS, and Loading capacity of deep beams for PCC, by SFRC, GFRC, SiFRC, Previous Studies

Sr. No	Concrete type	Mix design	Fiber length	Fiber percentage	CoS % increase	SpS % increase	Loading capacity of deep beam % increase	References
1	PC	—	—	—	—	—	—	—
2	SFRC & GFRC	1:1.98:3	60mm	SFRC 0.5%^{a}, 0.7%^{a}, 0.9%^{a}, 1.1%^{a}, 1.3 %^{a} GFRC 0.1%^{a}, 0.2%^{a}, 0.3%^{a}	14.3	—	36.84	[5]
3	SFRC	1:1.5:3	—	0.75%^{a}, 1%^{a},	6.6	—	47	[28]
4	SiFRC	1:1.5:2.85	30mm	0.5%^{a}, 1%^{a}, 1.5%^{a}, 2%^{a},	20	31	10	[29]
5	SFRC	1:1.5:3	38mm	4%^{b}, 4.5%^{b}	22	78	53	[6]
6	SFRC & PPFRC	1:1.98:3.09	60mm	SFRC 0.5%^{a}, 0.7%^{a}, 0.9%^{a}, 1.1%^{a}, 1.3 %^{a} PPFRC 0.1%^{a}, 0.2%^{a}, 0.3%^{a}	16	—	67	[30]
7	SFRC	1:1.5:3	—	0.75%^{a}, 1%^{a}	—	—	31, 7	[19]

Note: ^{a} content by volume fraction of concrete and ^{b} content by mass of cement.

fiber. The mix design ratio of 1:1.98:3.09 was used for concrete preparation. An improvement of 16%, 25% and 67% was observed in the compressive strength, first crack loading capacity and in the ultimate load carrying capacity (shear strength) of deep beams respectively with fiber content of steel to polypropylene ratio of 1.3% and 0.3%. Vengatachalapathy et al. [19] carried out an experimental study on SFRC deep beams. The steel fiber of 0.75% and 1% by volume fraction were used in concrete mix ratio of 1:1.5:3. An enhancement of 36% and 31% was observed in first crack load and an improvement of 16% and 7% was observed in highest load carrying capacity (shear strength) of deep beams with the fiber content of 0.75% and 1% respectively. The shear strength of deep beams is related to the maximum load, it sustains before failure. The ultimate carrying capacity depends upon the compressive and splitting tensile strength of concrete. Thus, the ultimate load carried by beam is the shear strength capacity of deep beams, Kulkarni et al [5], Medan et al [15] and Shaikh et al [30]. The literature shows that, the cheap and abundantly available, synthetic nylon fibers have not been investigated yet in perspective of deep beam.

2.3 Improvement in Mechanical Properties of Concrete by Using Nylon Fibers

Nylon fibers can enhance the mechanical properties of the concrete. The benefits of nylon fibers are that they are not affected by corrosion, smaller in weight and highly elastic. Nylon Fibers Reinforced Concrete (NFRC) dries quickly, have better elastic behavior and are strong [9]. NFRC has the ability to enhance the serviceability of concrete structures, controls the permeability of water and other chemicals [14]. The experimental investigations conducted by few researchers in the past using NFRC for enhancing the mechanical properties of concrete are given below:

Hanif et al. [31] carried out an experimental study on nylon fiber reinforced mortar using fiber content of 0.5%, 1.5% and 2.5% by total weight of mortar. An enhancement of 19%, 12% and 1% was observed in the compressive, tensile and flexure strength of cement-based mortar respectively. Khan and Ali [32] conducted an experimental study on glass fiber reinforced concrete (GFRC) and NFRC with fiber length of 50mm and with 5% fiber content by mass of cement because from literature 5% fibers by mass can enhance the mechanical properties of concrete. The mix design ratio of 1:3.33:1.67 were used. An enhancement of 11% and 5.6% was observed with GFRC and improvement of 8.4% and 3% was observed with NFRC in the splitting and flexural strength respectively. A reduction of 2.8% and 5.8% was observed in the compressive strength using glass and nylon fiber respectively. Subramanian et al. [12] carried out an experimental research on NFRC. The mix design ratio of 1:1.5:3 were used with fiber content of 1%, 2% and 3% by mass of cement. An enhancement of 26% and 110% was observed in the compressive and splitting strength respectively with 1% nylon fiber content. Habib et al. [10] carried out an experimental study on polypropylene, nylon and glass fiber reinforced mortar. Standard specimens were cast using fiber length of 12mm, 25mm and 37mm with fiber content of 0.5%, 1% and 2% by weight of cement from each type of fiber. An enhancement of 57% and 62% was observed in the compressive strength of polypropylene and nylon fiber respectively and a reduction of 27% was observed in the compressive strength of glass fiber, with 25mm fiber length and 2% fibers content. An improvement of 146%, 148% and 106% was observed in the flexure strength of polypropylene, nylon and glass fiber respectively by 25mm fiber length and 2% fiber content. The tensile strength of nylon and polypropylene fiber was improved 27% and 21% and a little reduction of 13% was observed in the tensile strength of glass fiber mortar, with 25mm fiber length and 2% fiber content. Song et al. [13] conducted an experimental investigation on NFRC for evaluating the mechanical properties of concrete. The mix design of 1:2.8:3.5, with fiber content of 0.6 by volume fraction were used. An improvement of 12.4%, 17.1%, 5.9% and 19% was observed in the compressive strength, splitting tensile strength, modulus of rupture and in the impact resistance respectively. Jagannathan et al. [33] carried out an experimental research on NFRC. The mix design ratio of 1:1.22:2.8 with 45mm fiber were used. Standard specimens were casted with different fiber content ratio of 0.5%, 1% and 1.5% by volume fraction. An enhancement of 7.54%, 9.68% and 12.5% were noted in compressive strength, splitting tensile strength and in flexure strength respectively by 1% fiber content.

2.4 Design of Selected Deep Beam Using ACI-Code

The deep beam having 150 mm (width), 300 mm (height) and 900 mm (length) has been selected. The maximum load carrying capacity (shear strength) of the selected deep beam has been computed using shear strength equation of ACI [34].

The strut and tie method of [34] is used to calculate the longitudinal bottom steel. The selected diagonal strut and longitudinal tie truss model is shown in Figure 2.2. The force demand in the strut and tie is calculated using method of joints. All design parameters, force demand and area of longitudinal and stirrups steel to meet the demand is given in Table 2.2.

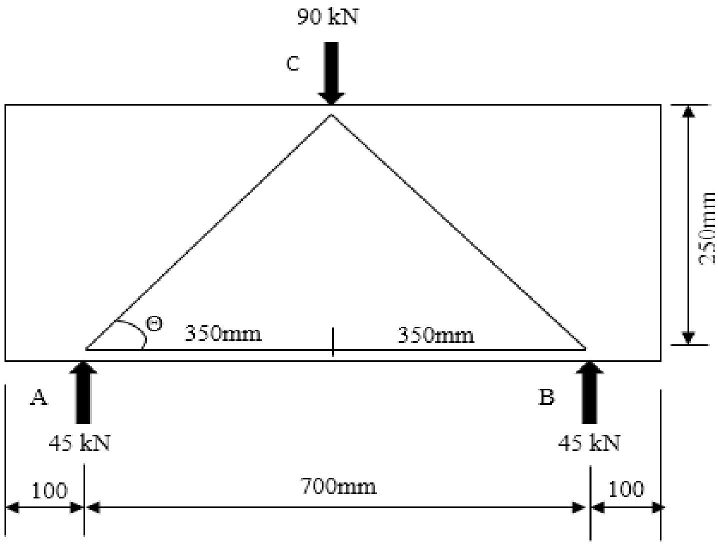


FIGURE 2.2: Truss of deep beam

The designed longitudinal steel reinforcement and stirrups for RCC, NFRC-4%, and NFRC-5% deep beam samples given in table 2.2 are shown in Figure 2.3.

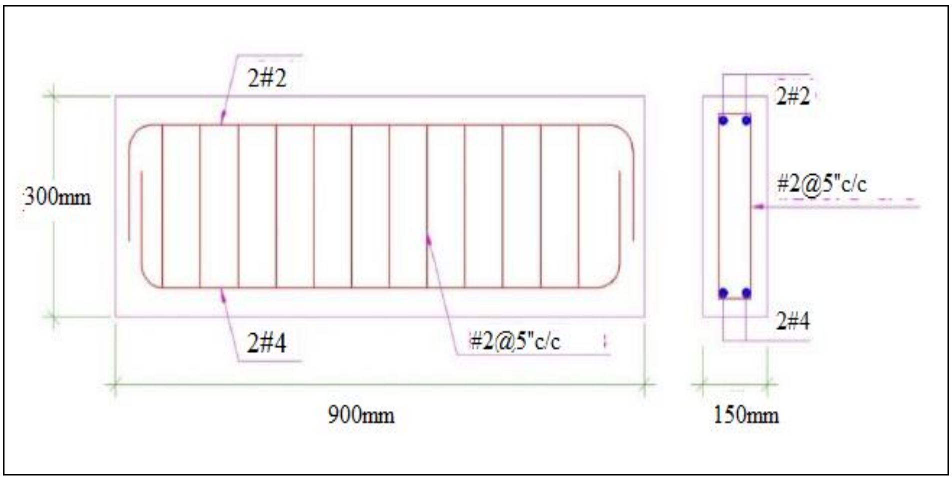


FIGURE 2.3: X-section and Longitudinal Section showing reinforcement Detail of deep beam

TABLE 2.2: Deep Beam Design Parameters

Deep Beam parameters	Descriptions	Values	Equations and Reference
b	Width of beam	150mm	—
d	Depth of beam	250mm	—
L	Length of beam	900mm	—
ϕs	Strength reduction factor in shear	0.75	—
fc'	Cylinder compressive strength at 28 days	16.5 MPa	Taking average of three tested cylinders
Vu	The maximum shear carrying capacity	97 kN	Vu $\leq \phi s$ *10*$\sqrt{fc'}$*b*d [34]
ϕb	Strength reduction factor in bending	0.9	[34]
θ	Angle b/w strut and tie	35.53^0	Calculated by tangent ratio of perpendicular/base of the strut and tie truss in Figure-2
βs	Strength reduction factor for strut	0.75	Taken from [34] Table 23.4.3
fy	Yield strength of steel	276 MPa	Grade-40 steel
Fnt	Force in tie	61.6 kN	Calculated by method of joint of truss.
Ast	Area of steel	2-#4 =226mm^2	[34], Fnt=Ast*fy i.e. Ast=Fnt/fy

fce	Effective compressive strength for strut	10.5 MPa	Calculated by [32] equation fce=0.85*βs*fc'
ws	Width of strut	135 mm	Calculated by [34] equation. ws=wt*cosθ+lb*sinθ, wt is the thichness of strut and lb is the width of bearing plate
Wb	Width of beam	150 mm	—
Acs	Area of trust	20250 mm^2	Calculated by [34] equation
Fns	Strength of strut	160 kN	Calculated by [34] equation. Fns=ϕ*fce*Acs
Anz	Area of node	22500mm^2	The bearing plate of size (150*150mm) was used as Anz
Fnn	Strength of node	193 kN CCT, 242 kN CCC node. Fnn=fce*Anz	[34] Load at CCT 45 kN $\leq$ 193 kN. ok Load at CCC 90 kN $\leq$ 242 kN. ok
βn	Strength reduction factor for nodes	βn=0.8 for CCT node, βn=1 for CCC node	Taken from table 23.9.2. of [34]
fce	Effective compressive strenght for nodes	11.25 MPa at CCT node, 14 MPa at CCC node	Calculated by Eq (fce= 0.85* βn*fc) of [34]

Stirrup Rienforcements	Equation $\Sigma(Asi/bs*si) *\sin\alpha \geq 0.003$. Asi is the Area of steel, bs is the width of strut (135mm), si is the selected spacing 125mm and sin is the angle 54.47^0	Ast =56.54 mm^2 Using 2 legged vertical stirrups #2, @25mm C/C were provided.	[34] clause 23.5.3. If fc $\leq$ 41.3 MPa then minimum stirrups will be provided.

2.5 Summary

It is known from the literature that fibers can be effectively used to improve the mechanical properties and the load carrying capacity (shear strength) of concrete deep beams. Most of the research studies are conducted on artificial fibers. Among all artificial fibers only steel and glass fibers are investigated for possible shear strength enhancement of deep beams [5,30]. Synthetic fibers have better properties to absorb more energy in case of earthquake.

To the best of the author's knowledge, nylon fiber has not been investigated yet for shear strength enhancement of deep beams. The performance of nylon fibers in concrete deep beams for shear strength and ductility enhancement need to be investigated. Due to better mechanical properties and ductile behavior, the nylon fiber is investigated in this research program for possible enhancement of shear strength and ductility of deep beams. The nylon fibers are cheap and abundantly availability in the market. For controlling the crack propagation in mechanical properties and in deep beams, the crack width of approximately 5mm were considered to be controlled by 25mm fiber. Therefore, the present research, focuses on the experimental evaluation of NFRC deep beams with mix design ratio of 1:2.5:3.5 (cement, sand and aggregate). Due to limited scope of work, the most common design mix ratio being used in the country of author in structural components, has been selected in this preliminary and relative research investigation. Lot of work still needs to be done to arrive at the practical solution. Therefore, it has been recommended in the thesis recommendation section to use different high strength concrete mixes with varying fiber percentages far an optimum result.

Studying the literature, it was found that the smaller length of fiber, enhances the concrete compressive strength and other mechanical properties [12,13]. Some previous studies [12,13] used 19mm nylon fiber which enhances the concrete mechanical properties. Zia and Ali [16] and Khan and Ali [32] used nylon fiber with 50mm length in which the concrete compressive strength was reduced up-to 6 and 31% respectively. Habib et al. [10] used nylon, polypropylene and glass

Table 2.3: CoS, SpS, and MoR of PC, by GFRC, JFRC, NFRC, and PPFRC Previous Studies

Sr. No	Concrete type	Mix design	Fiber length	Fiber percentage	CoS % increase	SpS % increase	MoR % increase	References
1	PC	—	—	—	—	—	—	—
2	NFR Morter	1:3	38mm	0.5%[c], 1.5%[c], 2.5%[c]	19	12	1	[31]
3	NFRC & GFRC	1:3.33:1.67	50mm	5%[b]	-5.8, -2.8	8.4, 11	3, 5.6	[32]
4	NFRC	1:1.5:3	19mm	1%[b], 2%[b], 3%[b]	26	110	—	[12]
5	PPFRC Mortar, GFRC mortar, NFRC mortar	1:1.5	12mm, 25mm, 38mm	0.5%[b], 1%[b], 2%[b]	75.13, 75,10	21, 21, -1.9	148, 150, 112	[10]
6	NFRC	1:2.8:3.5	19mm	0.6%[a]	12.4	17.1	5.9	[13]
7	NFRC	1:1.22:2.8	45mm	0.5%[a], 1%[a], 1.5%[a]	7.45	9.68	12.5	[33]
8	JFRC, NFRC, PPFRC	1:3:1.5	50mm	5%[b]	-36, -31, 1	-21, -11, 5	8, 10, 34	[16]

Note: [a] content by volume fraction of concrete, [b] content by mass of cement and [c] content by total mass of concrete.

fiber successfully with 25mm fiber length which also enhances the mortar mechanical properties. Since we are not using nylon fiber exclusively as an alternate to reinforcing bars in spanning member. Our aim was to enhance the mechanical properties, such as compressive strength and splitting tensile strength, which contributes to enhancement of shear strength. Nylon fibers with 45mm or greater length will be better to use in spanning members. However, small length of fiber needs to be explored. Just to start with, 25mm length of fiber (which is near to 19mm) has been selected based on literature given in the table 2.3. It can be seen from table that desired mechanical properties have been increased using the relatively small fiber length (19mm). Therefore it is recommended to use different fibers lengths in future for optimum result. First, the basic mechanical properties of PCC, NFRC-4% and NFRC-5% were determined by casting and testing concrete cylinders and beamlets. The prototype concrete deep beam samples were then cast and tested with PCC, NFRC-4% and NFRC-5% to evaluate the load carrying capacity at first flexure and diagonal cracks and at ultimate failure, the cracking behavior, deflection and ductility of deep beams.

Chapter 3

Experimental Program

3.1 Background

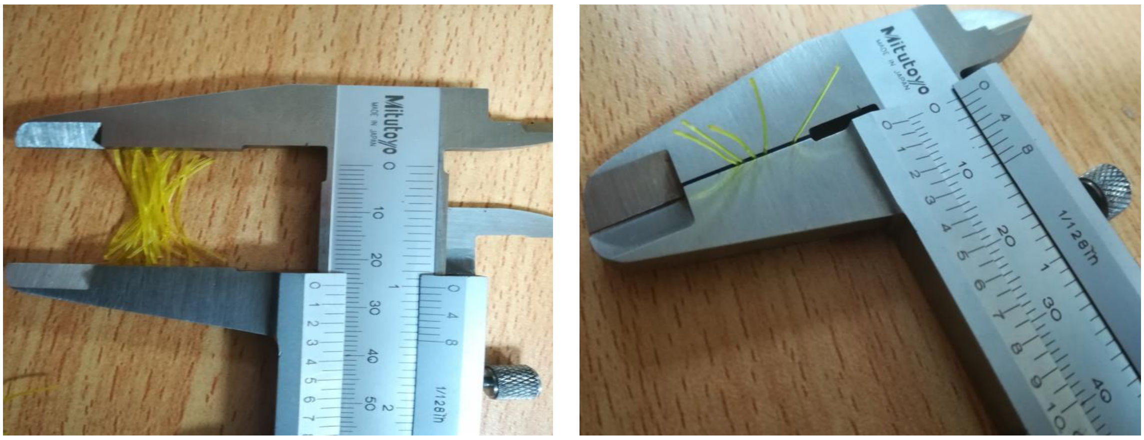
The demand of fibers has been increasing in todays era for improving the mechanical properties of concrete. Fiber reinforced concrete (FRC) mainly enhances the splitting strength, energy absorption, toughness index and flexural strength. In this study, efficiency of nylon fiber for improving the mechanical properties of concrete and shear strength of concrete deep beams is investigated in detail by experimental testing. In following chapter, concrete components, preparation of nylon fibers, mix design and costing procedure, preparation of deep beam samples, concrete specimens and testing procedure of concrete specimens are explained in detail.

3.2 Concrete Components

In concrete ingredients, locally accessible best quality cement, fine aggregate, course aggregates and tap water were used for casting of PCC samples. For the preparation of NFRC-4% and NFRC-5% samples, 4% and 5% of nylon fiber were added in PCC respectively. The maximum size of coarse aggregate was 20 mm.

3.3 Preparation of Nylon Fibers

Locally available nylon fibers are usually in the form of long ropes, hence, acquirement of fiber in the desired size (i.e. 25mm) is a difficult task. For preparation of fibers, all the fibers were first separated from the rope and then cut into the required specific length of 25 mm [10]. All fibers were then washed and cleaned with water. The diameter of nylon fiber was 0.21 mm. Nylon fibers cut into specific length are shown in Figure 3.1a and 3.1b.



(a) (b)

FIGURE 3.1: (a) Nylon fiber of 25mm length and (b) 0.21mm diameter

3.4 Mix Design and Casting Procedure

The mix design ratio for (PCC) was 1:2.5:3.5 for cement, fine aggregate and well graded course aggregates, respectively. Water cement ratio of 0.60 was used to ensure proper work-ability of concrete [18]. The mix design for NFRC was similar to that of PCC with the addition of 25 mm long nylon fibers by content of 4% and 5% according to the mass of cement. The electric concrete mixer was used for mixing. All ingredients of concrete were placed in the mixer pan in three layers. In first layer, course aggregates were placed, then fiber ware dispersed manually above them, followed by fine aggregates and finally cement was added. This laying procedure was repeated for the 2nd and 3rd layer.

The concrete mixer was run for three and half minutes. Then about 1/3rd portion of the total required water was added to the mixer, and the concrete mixer was run for three and half minutes again. The mixing process was observed carefully to avoid balling of fibers and segregation of concrete ingredients. During the mixing, some balls were formed in the concrete mix, they were dispersed and the mixer was again rotated for more than two minutes. After this procedure, the concrete mix was observed to be in good condition as shown in Figure 3.2, which shows the top view of the NFRC mix. Slump test for each sample was conducted before pouring into molds.

Figure 3.2: NFRC mix

The slump of PCC, NFRC-4% and NFRC-5% was found to be 25mm, 16mm and 6mm respectively, however, the NFRC samples were in workable condition despite of low slump. All the samples, were poured into molds in three layers and each layer was tempted 25 times and then the molds were lifted up-to 150mm height and dropped for self-compaction, in-order to avoid air voids. All concrete samples were kept in water for 28 days.

3.5 Mix Design and Casting Procedure of Deep Beams

In order to determine the behavior of deep beams with the Nylon Fiber Reinforced Concrete (NFRC), deep beam specimens of PCC, RCC, NFRC-4% and NFRC-5% with and without reinforcement were casted using the locally available cement, sand, aggregate, drinking water, and nylon fibers.

The same design mix, which was used for the preparation of basic mechanical properties evaluation samples, was used for the preparation of deep beams. 25 mm nylon fibers with 4% and 5% by mass of cement were also added in NFRC. The mixing process was same as adopted for basic mechanical properties of concrete.

3.6 Concrete Specimens

Concrete cylinders, having diameter and height of 100 mm and 200 mm, respectively, and beam-lets 100 mm wide, 100 mm height and 450 mm long, respectively were casted for PCC and NFRC samples. A set of three samples for each specimen (PCC and NFRC) were casted. A total of 18 cylinders (6 each for PCC, NFRC-4% and NFRC-5%) and 9 beams (3 each for PCC, NFRC-4% and NFRC-5%) were prepared. All samples were labeled accordingly as PCC and NFRC. Figure 3.3 shows the detail of different concrete cylinders and beam specimens. In addition the prototype concrete deep beam samples having size of 150 mm width, 300 mm depth and 900 mm, length were casted for PCC, RCC, NFRC-4% and NFRC-5% respectively. Wooden molds were prepared and used for the preparation of deep beam samples.

Total 12 deep beams, two specimens each for PCC, RCC, NFRC-4% and NFRC-5% were casted with and without steel reinforcement respectively. Two steel bars of 12mm diameter were placed at bottom, two steel bars of 6mm diameter were placed at top and for stirrups reinforcement 6mm diameter bar at 125mm c/c were

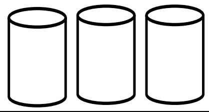
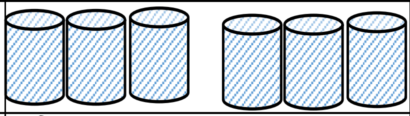
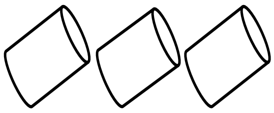
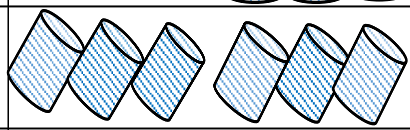
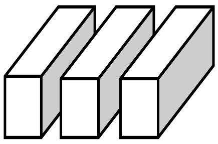
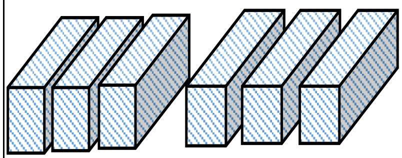
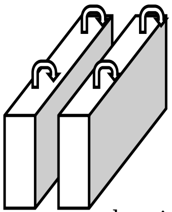
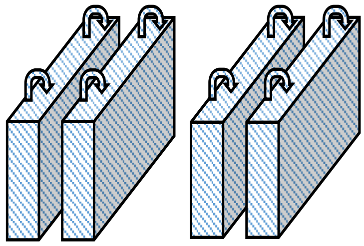
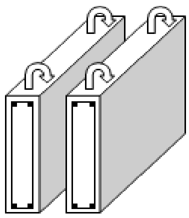
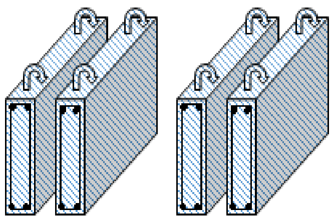
PCC 1:2.5:3.5:0.6 Samples dimensions 100mm dia and 200mm height	NFRC 1:2.5:3.5:0.6 with 4% & 5% fiber content	Proposed property to be determined
		➢ Compressive strength ➢ CE_{max}, CE_{total}, CTI ➢ Cracking behavior
		➢ Split tensile strength ➢ SE_{max}, SE_{total}, STI ➢ Split cracking behavior
Dimensions 100mm X 100mm X 450mm 		➢ Flexure strength ➢ FE_{max}, FE_{total}, FTI ➢ Load-deflection curve ➢ Cracking behavior
PCC 1:2.5:3.5:0.6 Samples dimensions 900mm X 300 X 150mm ln/d=2.33	**NFRC** 1:2.5:3.5:0.6 with 4% & 5% fiber content	**Proposed properties to be determined**
 The deep beam sample without steel reinforcement is already casted by A.K Sachan & Rao (1990).		➢ Shear strength ➢ FE_{max}, $FE_{total,}$ FTI ➢ Load-deflection curve ➢ Cracking behavior
		➢ Shear strength ➢ FE_{max}, $FE_{total,}$ FTI ➢ Load-deflection curve ➢ Cracking behavior

FIGURE 3.3: Detail of Concrete Specimens

provided in RCC, NFRC-4% and NFRC-5% deep beams samples. All specimens were poured in three layers and each layer were tempted properly with rods. After 24 hours, all the specimens were demolded and placed in water tank for curing up-to 28 days and tested for determination of deep beam properties according to ASTM standards.

3.7 Testing Procedure of Concrete Specimens

Compressive behavior, compressive strength and energy absorption, splitting behavior, splitting strength and energy absorption, flexural behavior, flexural strength and energy absorption are determined. Shear strength of deep beams, the load capacity at first flexure and diagonal crack and toughness index are determined.

3.7.1 Testing for Mechanical Properties

3.7.1.1 Slump and Density Test

Slump cone tests were conducted to find out and to compare the workability of PCC with NFRC. Standard slump cone test was conducted as per ASTM standard [35]. PCC and NFRC were tested for density as per ASTM [36].

3.7.1.2 Compressive Strength Test

The compressive strength and compressive behavior of standard specimens were tested in the STM according to ASTM standard [37] with a loading rate of 0.30 MPa/s. Standard specimens were properly caped with plaster of paris for uniform distribution of load. The stress strain curve, energy absorption and toughness index were calculated from the test results.

3.7.1.3 Splitting Tensile Strength Test

Standard specimens were tested for splitting-tensile strength, splitting-tensile behavior and energy absorption etc. All the specimens of PCC and NFRC were tested in STM as per ASTM standard [38] by a loading rate of 1.2 MPa/m.

3.7.1.4 Flexure Strength Test

Flexure strength test of beam-lets samples was conducted in STM as per ASTM standard [39] with a loading rate of 1.2 MPa/m. In flexure strength test, modulus of rupture (MoR), toughness index, energy absorption and flexure behavior were determined.

3.7.2 Testing Procedure of Deep Beams

After 28 days of curing, deep beam samples were properly dried in sun for at least one day and were cleaned from the dust. The grids with 25mm x 25mm mesh were marked on both side faces of deep beam samples for clear observation/marking of shear and flexure cracks. The loading plane on deep beams was properly leveled with plaster of paris to equally distribute the load. The casted deep beam samples were tested by a loading rate of 1.2 MPa/m, in STM according to ASTM standard [39]. Hooks were provided in deep beam for lifting and proper placing of deep beam samples in STM. For samples shifting, a small weight lifter was used. The deep beam samples were placed 1 by 1 on the weight lifter and then shifted to STM lab. The detail, can be seen from figure 3.6a. The deep beam samples have approximately 105 Kg weight, so placing of these samples manually was also a difficult task. For proper placing of samples and preventing STM from damage, special care was taken. For placing purposes, a small-scale hydraulic crane was used. Before lifting samples with hydraulic crane, first ropes were attached in deep beam hooks and then these samples were accurately lifted and placed in STM. The safety of lab personnel was insured using proper, lab safety gear. The detail can be seen from figure 3.6b. The steel bearing plates of size 150x150x10 mm were used at the top center point and at the supports to prevent local failure. The center point load was applied. The deep beam sample ready for testing is shown in Figure 3.6d. The quasi-static load at the rate of 1.2 MPa/m as per ASTM [39] was applied till the complete failure of the beam. The cracking behavior was recorded with the on camera. The load-deflection curve and load-time curve, generated by the machine, were obtained.

FIGURE 3.4: a) Weight lifter, b) Small-scale hydraulic crane, c) STM, d) Placed Sample in STM

From the load-deflection curve, stress-strain curve, first flexure and diagonal crack loading capacity, ultimate load carrying capacity (shear strength), deflection, toughness index, energy absorption were determined for all deep beam samples.

3.8 Summary

PCC specimens were casted with a mix design ratio of 1:2.5:3.5:0.6. The nylon fibers with 4% and 5% by mass of cement were added in concrete to prepare NFRC by using same mix design ratio. The steel bars of diameter 6mm and 12mm were used as top and bottom reinforcement respectively in concrete deep beams. For stirrups 6mm steel bar at 125mm c/c were used in concrete deep beams. Total 12 deep beams samples, 18 cylinders and 9 beam-lets samples were tested to determine the load carrying capacity (shear strength) of deep beams and to determine the compressive, splitting and flexural strength of concrete.

Chapter 4

Experimental Results Evaluation

4.1 Background

The chapter comprises of the evaluation of experimental results based on mechanical properties and shear strength properties of deep beams. For the preparation of concrete mix, mix design ratio of (1:2.5:3.5:0.6) was used for PCC and NFRC samples. All the ingredients were same in concrete mix, only nylon fibers were added with a ratio of 4% and 5% for the preparation of NFRC mixes. For reference, PCC was used. For determining the compressive, splitting, and flexural properties, an average of three values were taken according to ASTM standards for PCC and NFRC samples. The observed crack pattern of deep beam and load-deflection curve, the deflection at mid span and loads was presented in detail in this chapter for deep beam samples with and without reinforcements. It may be noted that the quantity of sand was taken more in the mix design to properly mix the fiber in the concrete and to achieve proper workability because fiber reduce the workability of concrete. The second reason of using more sand was to grab fiber in concrete mix. Special care was taken in concrete mixing; fibers were manually dispersed in concrete. Experimental results of mechanical properties of concrete and the results of deep beam samples are discussed in detail in this chapter.

4.2 Testing of Mechanical Properties

4.2.1 Slump and Density Test

The slump cone test was conducted for fresh concrete. In the 3rd column of Table 4.1 the slump test values for PCC and NFRC samples are shown. It was observed that the workability of PCC was more than NFRC using same W/C ratio of 0.6. This might be due to the reason that fiber tends to hold and retain the concrete ingredients. As compared to PCC, the slump was reduced by a value of 9 mm and 19 mm for NFRC-4% and NFRC-5%, respectively. The reduction was 36% and 76% respectively when compared to PCC using same W/C ratio. The reduction of workability trend with NFRC was similar to that reported in literature.

Standard test method was adopted for calculation of densities according to ASTM standard [36]. The volume were taken physically for the samples of PCC and NFRC. Values are shown in the 4th column of Table 4.1. The addition of fibers in NFRC increased the densities of NFRCs when compared to PCC.

The reason of this increase was better mixing and compaction of NFRC samples. The densities of PCC, NFRC-4% and NFRC-5% were 2377.4 kg/m^3, 2395.8 kg/m^3 and 2426.5 kg/m^3, respectively. An increase of 18.4 kg/m^3 and 49.1 kg/m^3 was noted in densities of NFRC-4% and NFRC-5% respectively. The densities of NFRC-4% and NFRC-5% were increased by 0.76% and 2% respectively when compared to PCC.

Table 4.1: Water-cement ratio, slump, and density of PCC, NFRC-4%, and NFRC-5%

Concrete type	Water cement ratio	Slump (mm)	Density (kg/m^3)
PC	0.6	25	2377.4
NFRC-4%	0.6	16	2395.8
NFRC-5%	0.6	6	2426.5

4.2.2 Compressive Behavior

During testing, compressive behavior of PCC, NFRC-4% and NFRC-5% specimens were observed. Figure 4.1 shows initial cracks, peak load cracks and rupture/ultimate load cracks for PCC, NFRC-4% and NFRC-5%. Following have been noted; (i) position and size of initial cracks, (ii) number, position and size of cracks at maximum load, (iii) position, size and number of cracks at the rupture/ultimate load. The initial cracks in the samples of PCC, NFRC-4% and NFRC-5% were noted at 89%, 93% and 95%, respectively of the peak load. Cracks of NFRC samples were smaller than that of PCC. The length and size of initial cracks in the PCC, NFRC-4% and NFRC-5% were nearly 30 mm, 25 mm and 20 mm, respectively. The cracks numbers, lengths and widths at the maximum load were much smaller in case of NFRC in comparison to PCC. At the maximum load, sizes of cracks were observed length-wise and were observed as 75 mm, 65 mm and 60 mm for PCC, NFRC-4% and NFRC-5% specimens, respectively. During rupture/ultimate loading, the sizes of cracks in the samples of PCC, NFRC-4% and NFRC-5% were increased up-to 90 mm, 80 mm and 75 mm in length, respectively. During the testing, it was noted that PCC samples were broken in two pieces, whereas the samples of NFRC were observed to be ductile and tough. The use of nylon fibers reduces crack length, width and effectively controls deformation. Additionally, use of fibers also controls spalling of the concrete. In PCC samples, large cracks were observed where weak particles were present but in case of NFRC specimens, this phenomenon was not observed because the fibers control and distribute cracks in specimens. At rupture/ultimate loading, the fibers were observed to be pulled-out from their position, but not broken. In case of NFRC-4%, the fiber breaking to pull-out ratio was almost 20:80 and in NFRC-5%, this ratio was nearly 15:85. From these observations, it can be concluded that nylon fibers can be effectively used in concrete and only enhancement in their bonding with concrete mix is needed. This bonding effect of fibers can be controlled by using additives and surface treatment of fibers.

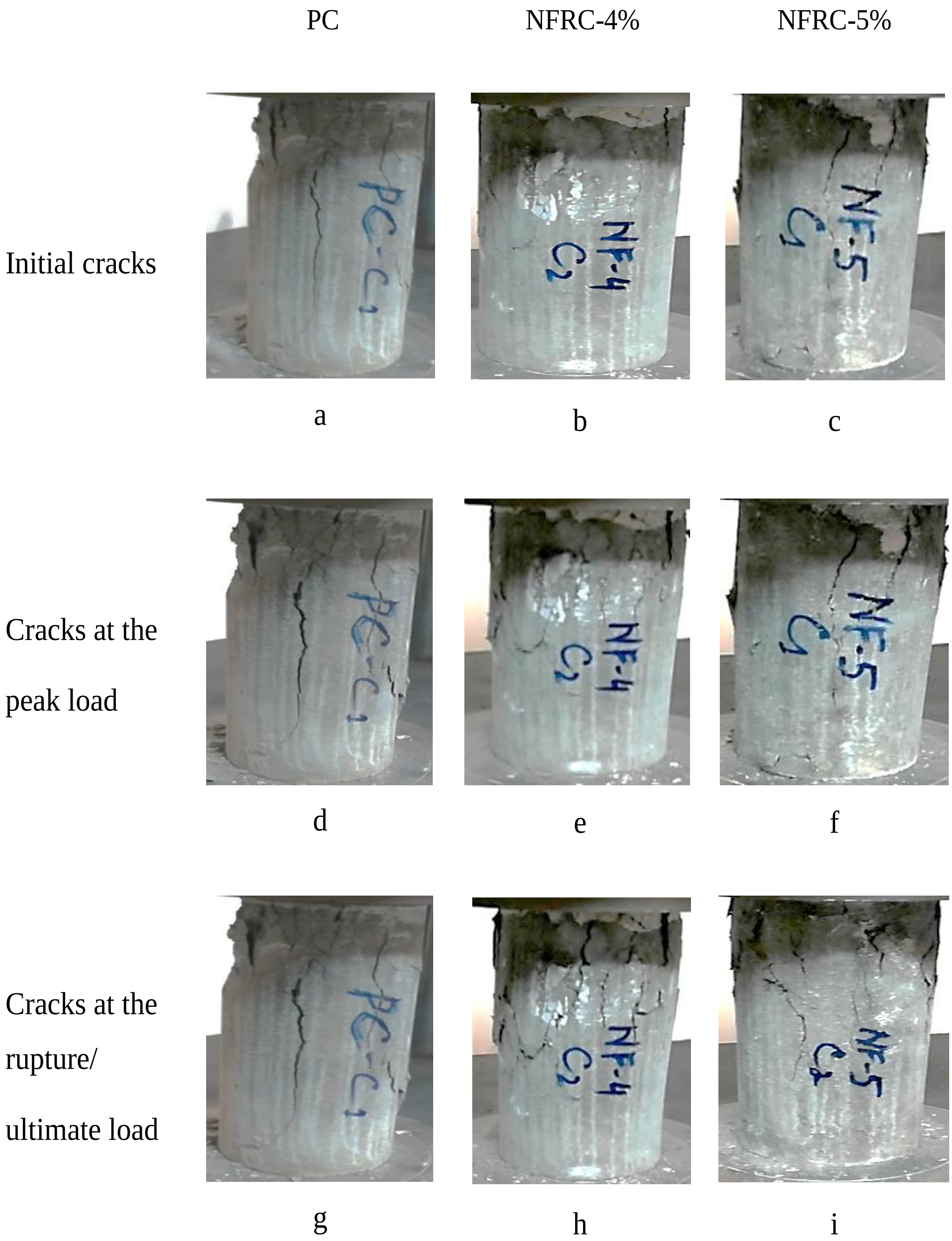


Figure 4.1: Cracks formation in the samples of PC, NFRC-4% and NFRC-5% under compressive load

4.2.2.1 Compressive Strength, Compressive Energies and Compressive Toughness Index

Figure 4.2 shows the compressive stress-strain curves of PCC, NFRC-4% and NFRC-5%. The compressive strength (CoS) is the peak value of stress-strain curve.

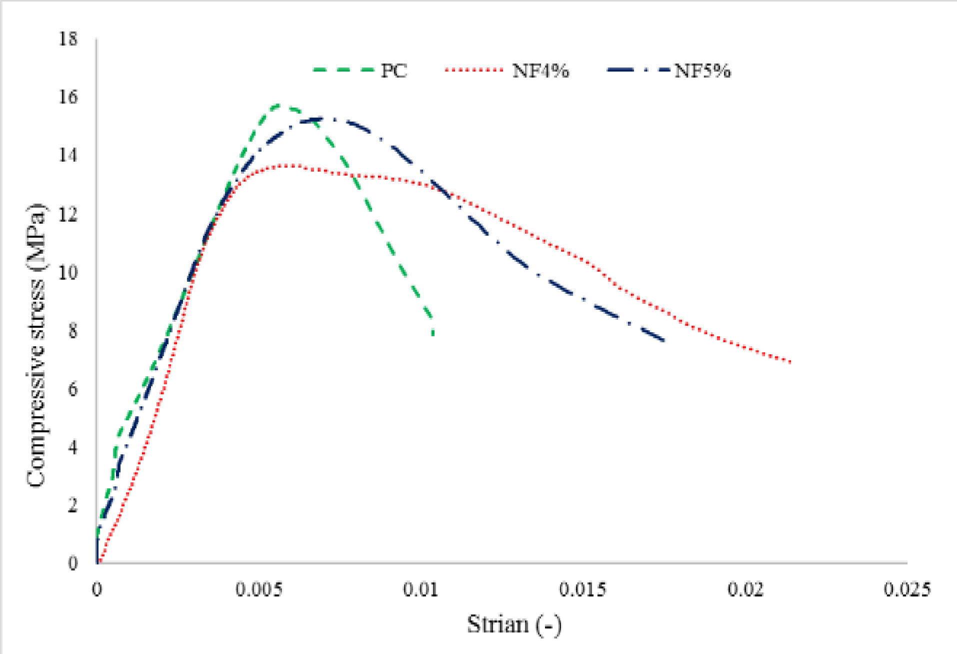


FIGURE 4.2: Stress-strain curve of PCC and NFRC-4% and NFRC-5% from compressive strength tests

The energy absorbed up-to first crack (CE1) was calculated by measuring area under the stress-strain curve up-to first crack load. The energy absorbed from first crack till end of cracks is considered (CE2) and calculated from the area under stress strain curve from first crack load to the rupture/ultimate load. The total energy absorbed from starting point till end point of stress-strain curve was considered as compressive total absorbed energy (CToE). The compressive toughness index (CToI) was calculated from the total compressive energy/energy absorbed up-to the first crack. Table 4.2 shows CoS, Strain (ϵo), CE1, CE2, CToE and CToI of PCC, NFRC-4% and NFRC-5%. The CoS of PCC, NFRC-4% and NFRC-5% were 15.71 MPa, 13.63 MPa and 15.24 MPa, respectively. The CoS of NFRC-4% and NFRC-5% decreased by 2.08 MPa and 0.47 MPa (13.23% and 2.99%) respectively, as compared to PCC. The nylon fibers which fill the gap between aggregates having low compressive strength could be reason of less compressive strength in case of nylon fibers concrete. Nylon fibers being low-density material imparts in heterogeneousness of concrete mix design up-to some extent, this may be the reason for low compressive strength. Third possible reason is that due to addition of nylon fibers, cement percentage in the mix design is relatively less, which may cause a low compressive strength value. Strain (ϵo) at the highest stress was 0.0056, 0.0060 and 0.0070 for PCC, NFRC-4% and NFRC-5%, respectively. The value of strain was increased by 7.14% and 25% in case of NFRC-4% and NFRC-5%, respectively in comparison to PCC. The enhancement of strain in NFRC show that nylon fibers have better elongation ability. This elongation can reduce the spalling of concrete and hold concrete particles from falling down in case of failure and thus precious lives can be saved before the conversion of a potent condition/hazard to a disaster.

The values of CE1 were 0.042 MPa, 0.028 MPa and 0.052 MPa for PCC, NFRC-4% and NFRC-5%, respectively. The values of CE1 was reduced by 0.014 MPa in case of NFRC-4% and increased by 0.01 MPa in case of NFRC-5% as compared to PCC. The CE2 were 0.076 MPa, 0.19 MPa and 0.14 MPa of PCC, NFRC-4% and NFRC-5%, respectively. By comparing the values of CE2 with PCC, an enhancement of 0.114 MPa and 0.063 MPa was noted in NFRC-4% and NFRC-5%, respectively. The CToE were 0.118 MPa, 0.217 MPa and 0.191 MPa of PCC,

Table 4.2: CoS, ϵo, CE1, CE2, CToE, and CToI of PCC, NFRC-4%, and NFRC-5%

Parameters	Concrete type		
	PCC	NFRC-4%	NFRC-5%
CoS (MPa)	15.71	13.63	15.24
ϵo (-)	0.0056	0.0060	0.0070
CE1	0.042	0.028	0.052
CE2	0.076	0.19	0.14
CToE	0.118	0.217	0.191
CToI	2.8	7.8	3.6

NFRC-4% and NFRC-5%, respectively. Comparing the CToE values with PCC, an enhancement of 0.099 MPa and 0.073 MPa was noted in case of NFRC-4% and NFRC-5%, respectively. This enhancement is due to fibers, that increase the energy absorption ability of concrete. The CToI were 2.8, 7.8 and 3.6 of PCC, NFRC-4% and NFRC-5%, respectively. These details are provided in Table 4.2.

After comparing the CToI with PCC, an enhancement of 5 and 0.8 in NFRC-4% and NFRC-5% was observed, respectively.

The size of cracks has been reduced due to fibers. The probable cause of high CToI is the presence of fibers which provided resistance to cracks and enhanced the CToI, energy absorption and ductility of concrete. The results of CoS, CE1, CToE and CToI for PCC, NFRC- 4% and NFRC-5% are shown in Figure 4.3. A reduction of 33.3% was observed in CE1 of NFRC-4% and an enhancement of 23.8% was noticed in the CE1 of NFRC-5% respectively as compared to PCC. An enhancement of 150% and 82.8% was noted in CE2 of NFRC-4% and NFRC-5%, respectively in comparison to PCC. An enhancement of 83.8% and 61.8% was noted in CToE of both NFRC-4% and NFRC-5%, respectively in comparison to PCC.

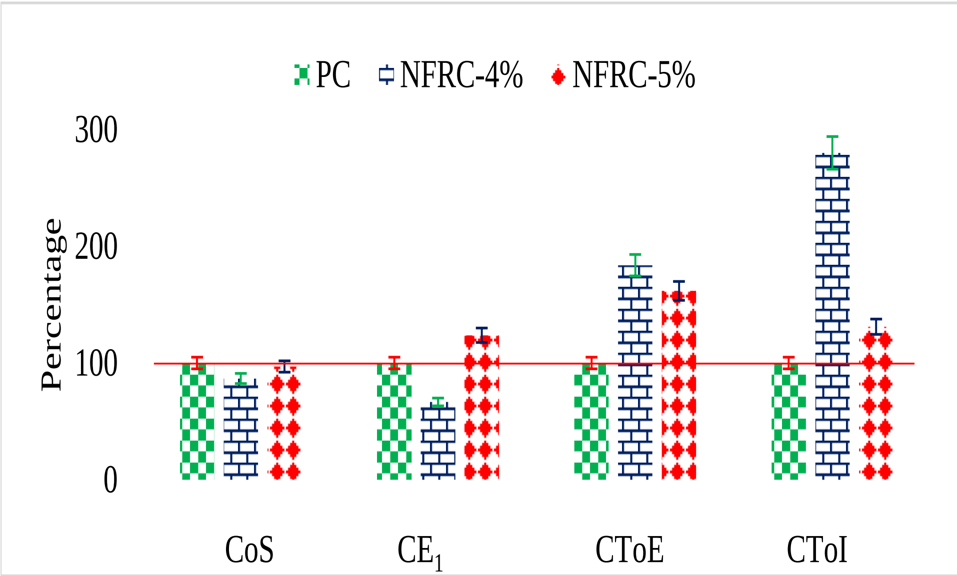


FIGURE 4.3: Comparison of CoS, CE1, CToE and CToI, of PCC, NFRC-4% and NFRC-5%

The values of CToI in case of NFRC-4% and NFRC-5% were increased up-to 180% and 31.1%, respectively as compared to PCC. An enhanced value of CE1, CE2, CToE and CToI were observed in case of NFRC-5%. This shows that nylon fibers have the capability to increase the shear resistance, reduce cracks, improve ductility and load carrying capacity (shear strength) of concrete, when used in concrete deep beams.

4.2.3 Splitting-tensile Behavior

The cracks observed during the splitting-tensile test under initial load, peak load and rupture/ultimate load are shown in Figure 4.4 for PCC, NFRC-4% and NFRC-5%. During the testing of PCC, NFRC-4% and NFRC-5% samples, the behavior was critically observed. Figure 4.4 (a) - Figure 4.4 (c) show the initial cracks in the samples of PCC, NFRC-4% and NFRC-5%. The initial cracks were observed at 100%, 94% and 96% of the peak load for PCC, NFRC-4% and NFRC-5% samples respectively.

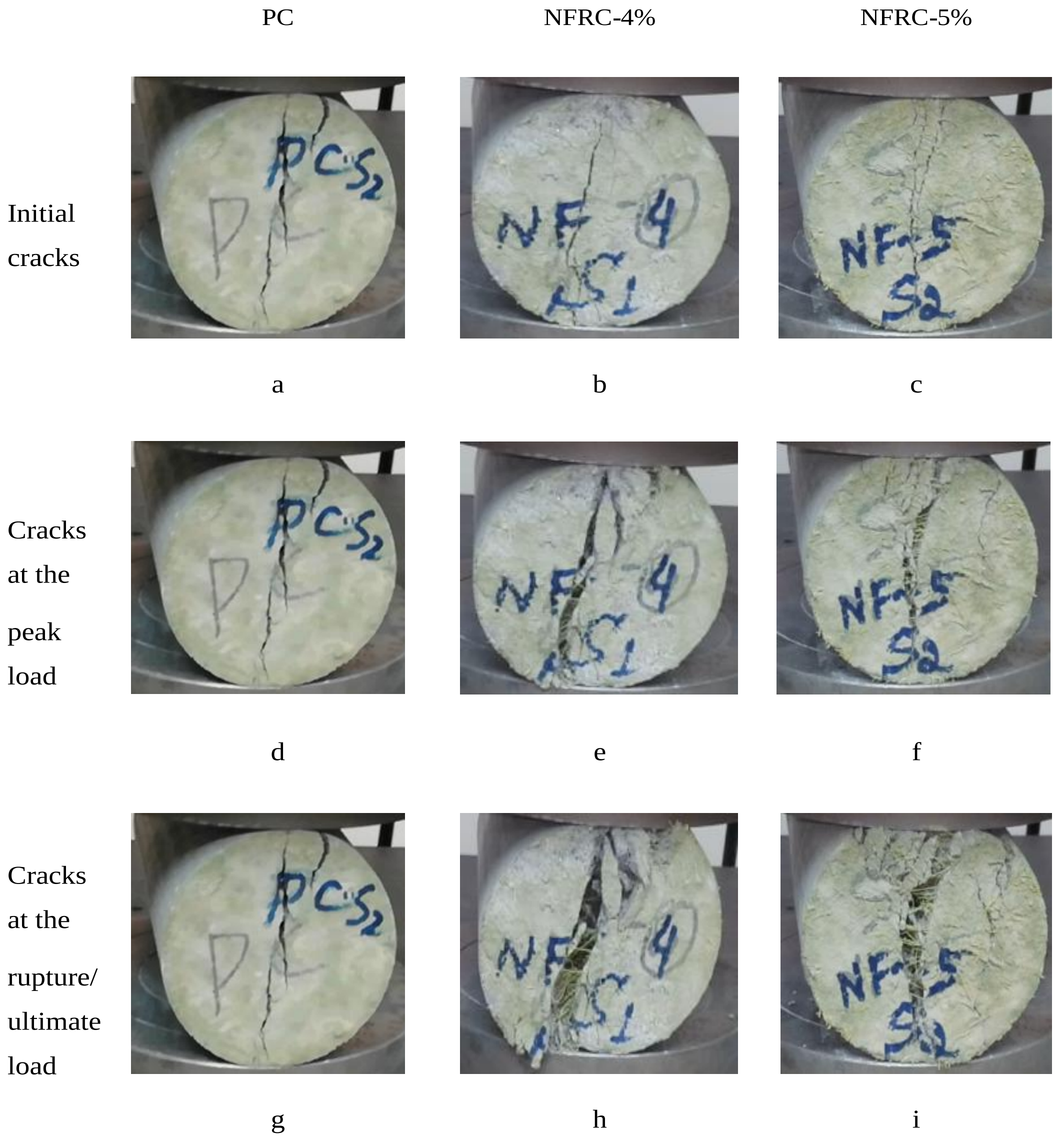


FIGURE 4.4: Cracks formation under splitting-tensile test in the samples of PCC, NFRC-4% and NFRC-5%.

This means that the PCC samples were broken in two pieces suddenly, whereas the NFRC samples show resistance to cracks and remained intact after initial cracks. At the maximum load, however, the crack sizes were increased in the specimens of NFRC-4% and NFRC-5%. This can be observed from the Figure 4.4 (d) - Figure 4.4 (f). The crack sizes were 65 mm and 75 mm in specimens of NFRC-4% and NFRC-5%, respectively at this stage. At the rupture/ultimate loading, the cracks sizes were increased to 75 mm and 85mm in the specimens of NFRC-4% and NFRC-5%, respectively. This cracking behavior can be observed from the Figure 4.4 (g) - Figure 4.4 (i). The cracks in PCC samples were observed to be large and suddenly appeared, thus samples of PCC were broken suddenly within half of a second. The cracks in the specimens of NFRC were observed to be small and equally distributed over the specimen surface. This behavior explains that the use of fibers in concrete reduce cracks formation and their propagation. The fibers also reduce the brittle behavior of concrete and increase the toughness of concrete. Furthermore, the samples were not broken into two pieces. After detailed visual examination, it was observed that the fibers were mostly pulled-out. The ratio between the fiber breaking and pull-out was approximately 25:75 in the NFRC samples. The fibers bond strength can be increased by using some admixtures or treatment of fibers.

4.2.3.1 Splitting-tensile Strength, Splitting-tensile Energy Absorption and Toughness Index

Splitting-tensile load-time curve is shown in Figure 4.5. The splitting-tensile strength (SpS) was observed as the peak value in load-time histories. The splitting-tensile energy (SpE1) absorbed up-to the first crack was calculated by area under the load-time curve. The splitting-tensile energy absorbed (SpE2) after first crack till rupture/ultimate load was also calculated by area under the curve.

The initial load crack and the peak load crack was observed at the same time in case of PCC samples. PCC samples were fully broken in two pieces. The total absorbed energy of splitting-tensile strength (SpToE) was calculated from the total

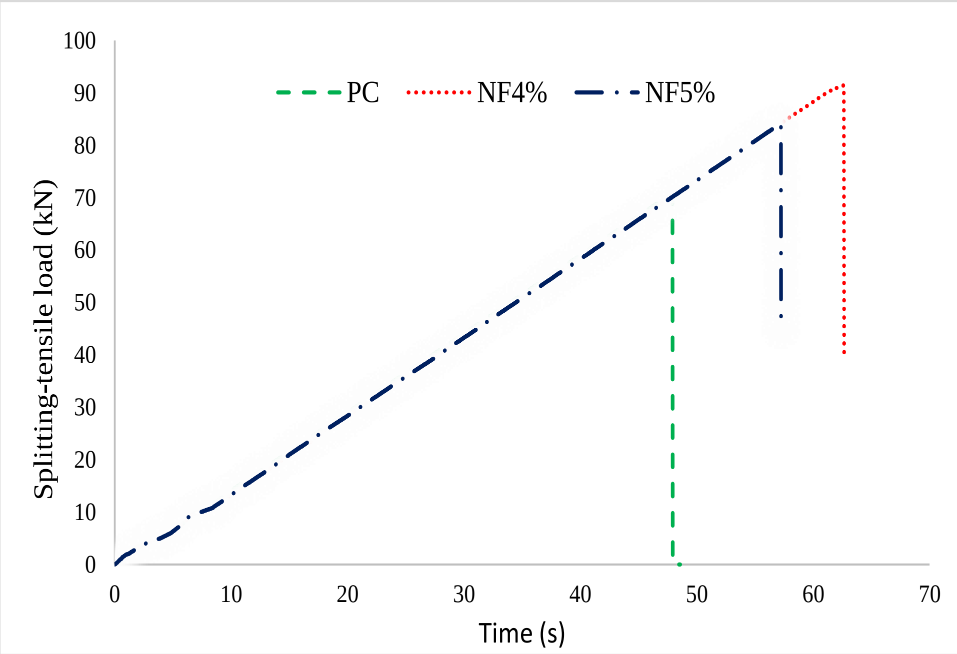


FIGURE 4.5: Load-time curve of PCC, NFRC-4%, and NFRC-5% of splitting-tensile test

area under the load time curve. The splitting-tensile toughness index (SpToI) was calculated from the ratio of total energy absorbed and the energy absorbed up-to initial cracks (SpToE/SpE1). Table 4.3 shows the results of SpS, SpE1, SpE2, SpToE and SpToI for PCC, NFRC-4% and NFRC-5%. The SpS of PCC, NFRC-4% and NFRC-5% were 2.18 MPa, 2.84 MPa and 2.61 MPa, respectively. The increase of 0.66 MPa and 0.43 MPa were noted in SpS for the specimens of NFRC-4% and NFRC-5%, respectively in comparison to PCC. The results of SpE1 are 1678.91 kN-s, 2230.01 kN-s and 1838.25 kN-s for PCC, NFRC-4% and NFRC-5% respectively. By comparing the results of PCC and NFRC, an enhancement of 551.1 kN-s and 159.34 kN-s in the SpE1 of NFRC-4% and NFRC-5% was observed, respectively. The detail is provided in Table 4.3.

Fibers enhanced the SpE1 of NFRC-4% and NFRC-5%. In case of NFRC-4%, the initial energy absorption capacity, resistance to cracks formation and propagation was more than PCC and NFRC-5%. The results of SpE2 for PCC, NFRC-4% and NFRC-5% were 00 kN-s, 623.65 kN-s and 535.09 kN-s, respectively. Comparing the results SpE2 of PCC to NFRC specimens, it was observed that the enhancement was more than 100 times in case of NFRC samples. This enhanced value of SpE2

Table 4.3: SpS, SpE1, SpE2, SpToE, and SpToI of PCC, NFRC-4%, and NFRC-5%

	Concrete type		
Parameters	PCC	NFRC-4%	NFRC-5%
SpS (MPa)	2.18	2.84	2.61
SpE1 (kN.s)	1678.91	2230.01	1838.25
SpE2 (kN.s)	00	623.65	535.09
SpToE (kN.s)	1678.91	2853.65	2373.34
SpToI (-)	1.0	1.28	1.29

for NFRC sample shows that fibers absorbed energy after first crack, and show better resistance to cracks formation. This better behavior of fibers increase the load carrying capacity (shear strength) of deep beams and change brittle behavior to ductile behavior. The results of SpToE are 1678.91 kN-s, 2853.65 kN-s and 2373.34 kN-s for PCC, NFRC-4% and NFRC-5%, respectively. The comparison of the results of SpToE of PCC to NFRC samples, show an enhancement of 1174.74 kN-s and 694.43 kN-s for NFRC-4% and NFRC-5%, respectively. The results of SpToI for specimens of PCC, NFRC-4% and NFRC-5% were 1.0, 1.28 and 1.29, respectively. An enhancement of 0.28 and 0.29 was observed in case of NFRC-4% and NFRC-5%, respectively as compared to PCC. NFRC has increased SpToI due to its high crack resistance capability and consequently the ductility. Figure 4.6 shows the results of SpS, SpE1, SpToE and SpToI for PCC, NFRC-4% and NFRC-5%, respectively. As compared to PCC, an enhancement of 30.27% and 19.72% was noted in the SpS of NFRC-4% and NFRC-5%, respectively. Comparing the results of SpE1 of PCC to NFRC samples, an increase of 32.82% and 9.49% was noted in case of NFRC-4% and NFRC-5%, respectively. Comparing the values of SpE2 of PCC to NFRC, an increase of 623.65% and 535.09% in case of NFRC-4% and NFRC-5% was observed, respectively. Comparing the results of SpToE of PCC to NFRC samples, an increase of 69.96% and 41.36% was noted in case of NFRC-4% and NFRC-5%, respectively. Comparing the results SpToI to PCC, an enhancement of 28% and 29% was noted in case of NFRC-4% and NFRC-5%, respectively. After analyzing all the results of NFRC samples, it can be concluded that NFRC samples increased the energy absorption, toughness indexes, and reduced the brittle characteristics of concrete due to the presence of fibers. Comparing the results of NFRC 4% and NFRC 5%, it can be noted that NFRC-4% can offer better resistance to crack formation and can effectively enhance the shear resistance capability of deep beams. Figure 4.6 shows the results of SpS, SpE1, SpToE and SpToI for PCC, NFRC-4% and NFRC-5%, respectively. As compared to PCC, an enhancement of 30.27% and 19.72% was noted in the SpS of NFRC-4% and NFRC-5%, respectively. Comparing the results of SpE1 of PCC to NFRC samples, an increase of 32.82% and 9.49% was noted in case of NFRC-4% and NFRC-5%, respectively. Comparing the values of SpE2 of PCC to NFRC, an increase of 623.65% and 535.09% in case of NFRC-4% and NFRC-5% was observed, respectively. Comparing the results of SpToE of PCC to NFRC samples,

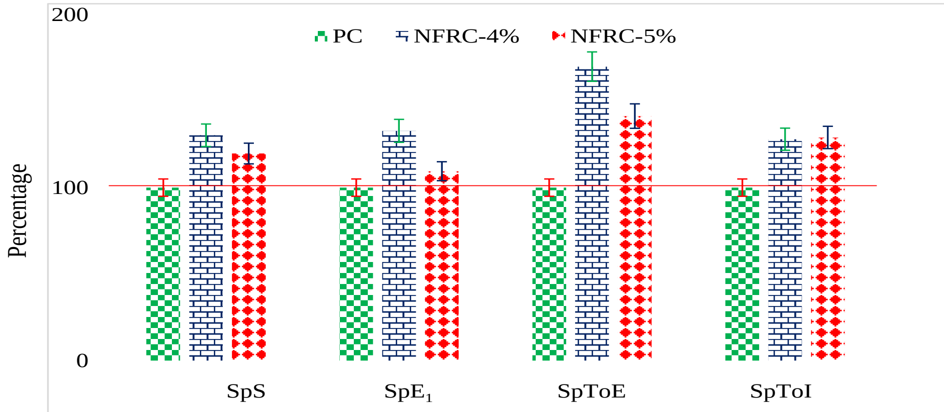


FIGURE 4.6: Comparison of SpS, SpE1, SpToE and SpToI, of PCC, NFRC-4% and NFRC-5%

an increase of 69.96% and 41.36% was noted in case of NFRC-4% and NFRC-5%, respectively. Comparing the results SpToI to PCC, an enhancement of 28% and 29% was noted in case of NFRC-4% and NFRC-5%, respectively. After analyzing all the results of NFRC samples, it can be concluded that NFRC samples increased the energy absorption, toughness indexes, and reduced the brittle characteristics of concrete due to the presence of fibers. Comparing the results of NFRC 4% and NFRC 5%, it can be noted that NFRC-5% can offer better resistance to crack formation and can effectively enhance the shear resistance capability of deep beams.

4.2.4 Flexural Behavior

Figure 4.7 shows the behavior and formation of cracks at initial load, peak load, and at rupture/ultimate load in the small beam samples of PCC, NFRC-4% and NFRC-5%. Figure 4.7 (a) - Figure 4.7 (c) show the behavior of beam samples at initial cracks of PCC, NFRC-4% and NFRC-5%. The initial cracks appeared approximately at the 100%, 94% and 92% of the peak load in the samples of PCC, NFRC-4% and NFRC-5%, respectively. The cracks sizes were critically observed and found 12mm, 9mm and 7mm in the samples of PCC, NFRC-4% and NFRC-5%, respectively. Visual observation pointed out that the PCC beam samples were fully broken in two parts, whereas the NFRC beam samples were not broken into parts and remained intact due to the effect of nylon fibers. When load was further increased, the sizes of cracks were also enlarged in NFRC-4% and NFRC-5%. At peak load, the observed cracks lengths in the samples of NFRC-4% and NFRC-5% were 85 mm and 79 mm, respectively. Figure 4.7 (e) and

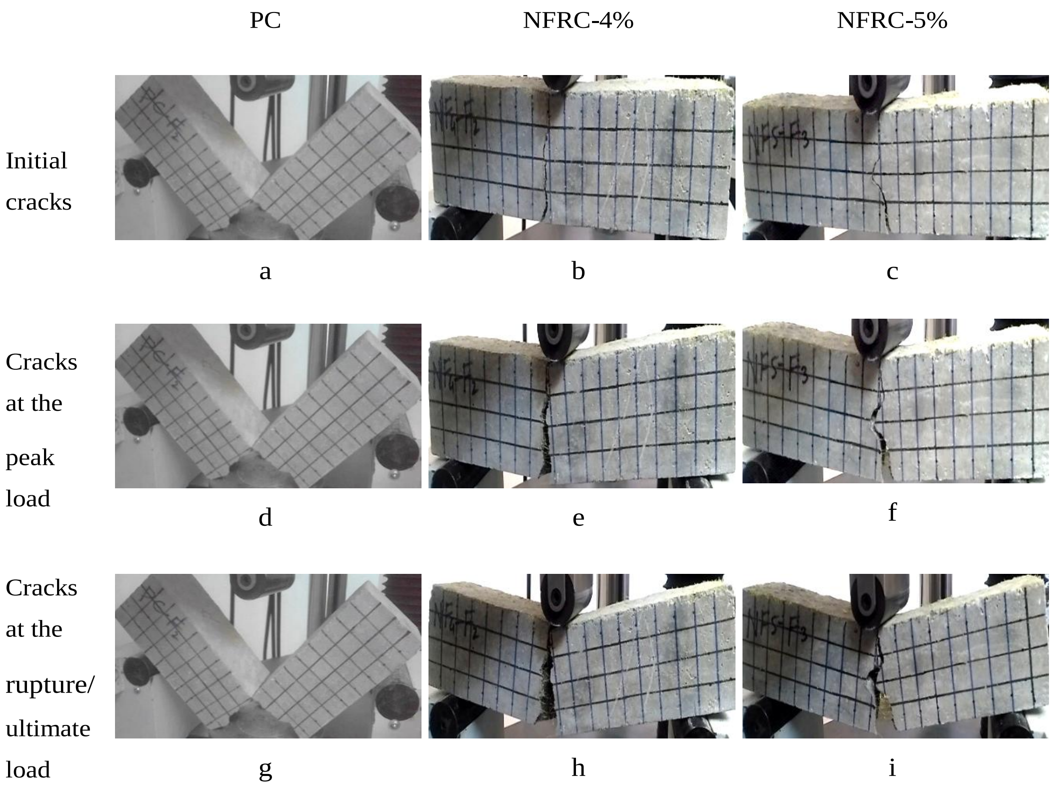


Figure 4.7: Cracks formation under flexural test in the samples of PCC, NFRC-4% and NFRC-5%

Figure 4.7 (f) show cracks in the samples of NFRC-4% and NFRC-5%. Near the rupture/ultimate load, cracks lengths were nearly 91mm and 87mm in NFRC-4% and NFRC-5%, respectively. The detail is shown in Figure 4.7 (h) and Figure 4.7 (i). For the observation of fibers failure, the specimens were critically observed visually. During assessment of fiber fracture and pull-out in the NFRC samples, it was found that fiber pull-out ratio was nearly at 35:65. It can be concluded that nylon fibers were well distributed and show better result under flexure test. The fiber pull-out mechanism can be minimized by surface treatment and using some admixture in FRC.

4.2.4.1 Modulus of Rupture, Total Absorbed Energies and Toughness Index

The load-deflection curves of flexure strength test are shown in Figure 4.8. For calculating the modulus of rupture (MoR), the first crack load value in the load-deflection of flexural test was used. For calculating the flexural absorbed energy up-to initial crack (FE1), the area under load-deflection curve up-to initial crack was used. It was noticed during flexural testing that PCC samples were fully broken in two pieces at initial cracks.

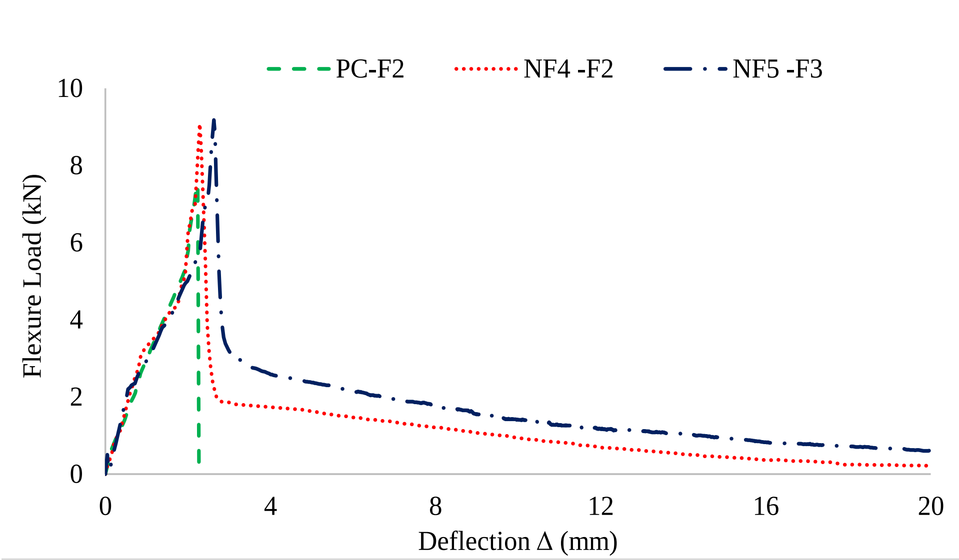


FIGURE 4.8: Flexure load-deflection curves of PCC, NFRC-4% and NFRC-5% from flexural test

For calculating the energy after initial cracks till rupture/ultimate loading (FE2), the area under load-deflection curve from initial cracks till rupture/ultimate load was used. For calculating the flexural total absorbed energy (FToE), the area under load-deflection curve from staring point till end was used. The flexural toughness index (FToI) was calculated from flexural total absorbed energy divided by flexure energy absorbed up-to flexural first cracks (FToE/FE1). Table 4.4 shows the results of MoR, FE1, FE2, FToE and FToI for PCC, NFRC-4% and NFRC-5%. The MoR of PCC, NFRC-4% and NFRC-5% were 3.88 MPa, 4.37 MPa and 4.61 MPa, respectively. The MoR of NFRC-4% and NFRC-5% were enhanced by 0.49 MPa and 0.73 MPa, respectively, as compared to PCC. The deflection (Δo) was noted down at the maximum load in PCC, NFRC-4% and NFRC-5%. The deflections were 2.23 mm, 2.28 mm and 2.63 mm for PCC, NFRC-4% and NFRC-5%, respectively. The greater value of Δo was noted in case of NFRC-5% when compared to the other concretes. The first reason behind the greater Δo is the equal dispersion of fibers and fibers pull-out in case of NFRC-5%. The second reason is higher percentage of nylon fibers in case of NFRC-5% than other concretes. The values of FE1 were 7.36 kN-mm, 7.64 kN-mm and 9.47 kN-mm in the samples of PCC, NFRC-4% and NFRC-5%, respectively. The FE1 was compared to PCC and an enhancement of 0.28 kN-mm and 2.11 kN-mm was noted in case of NFRC-4% and NFRC-5%, respectively. The detail is shown in Table 4.4.

TABLE 4.4: MoR, Δo, FE1, FE2, FToE, and FToI of PCC, NFRC-4%, and NFRC-5%

	Concrete type		
Parameters	PCC	NFRC-4%	NFRC-5%
MoR (MPa)	3.88	4.37	4.61
Δo (mm)	2.23	2.28	2.63
FE1 (kN.mm)	7.36	7.64	9.47
FE2 (kN.mm)	00	17.41	26.23
FToE (kN.mm)	7.36	25.05	35.7
FToI (-)	1	3.27	3.76

The reason behind the enhanced value in FE1 was the better random dispersion of fibers that reduces and resists the crack formation and propagation and enhances the load carrying capacity of beam-lets. The FE2 were 0 kN-mm, 17.41 kN-mm and 26.23 kN-mm, for PCC, NFRC-4% and NFRC-5%, respectively. The FToE were 7.36 kN-mm, 25.05 kN-mm and 35.7 kN-mm in the samples of PCC, NFRC-4% and NFRC-5%, respectively. The FToE of NFRC-4% and NFRC-5% was enhanced by 17.69 kN-mm and 28.34 kN-mm respectively in comparison to PCC. The FToI of PCC, NFRC-4% and NFRC-5% were 1, 3.27 and 3.76, respectively. The FToI were enhanced by 2.27 and 2.76, respectively for NFRC-4% and NFRC-5% as compared to PCC. Enhanced energy absorption up-to first crack were observed in FRC samples. The nylon fibers reduce the cracks formation and enhance the toughness index and ductility of concrete. Figure 4.9 shows the comparison of MoR, FE1, FToE and FToI for PCC, NFRC-4% and NFRC-5%. The MoR of NFRC-4% and NFRC-5% were increased by 12.62% and 18.81%, respectively to PCC.

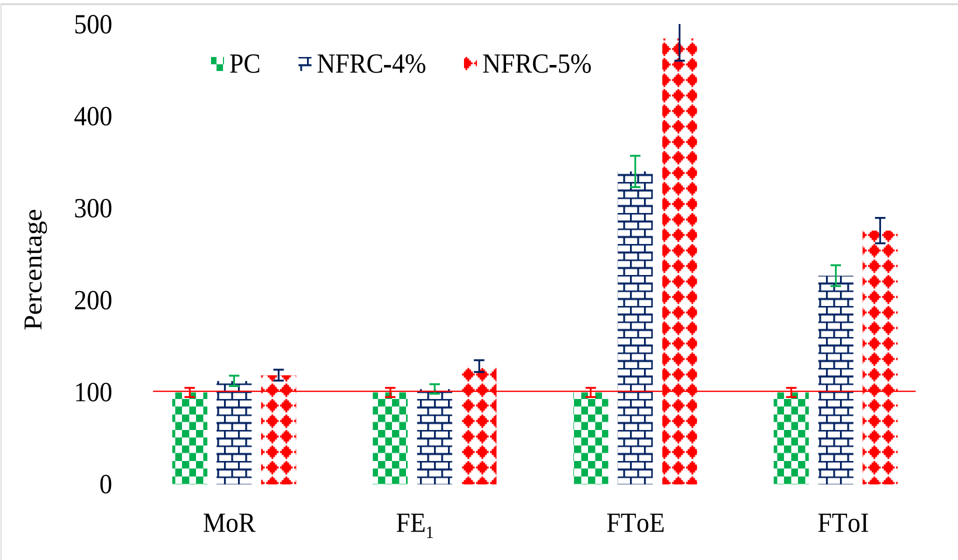


FIGURE 4.9: Comparison of MoR, FE1, FToE, and FToI, of PCC, NFRC-4% and NFRC-5%.

The results of FE1 was also compared with PCC and an improvement of 3.8% and 28.66% was noted in NFRC-4% and NFRC-5%, respectively. The FToE was found to be increased by 240.35% and 385% in NFRC-4% and NFRC-5%, respectively. The FToI of NFRC-4% and NFRC-5% were increased by 227% and 276%, respectively. In conclusion, both the NFRC-4% and NFRC-5% increase the MoR, FE1, FToE and FToI, but the result of NFRC-5% was better than NFRC-4%. Now considering the enhanced flexural properties of NFRC-5%, fibers can be effectively used in concrete deep beams for enhancing the load carrying capacity (shear strength), reducing shearing cracks and reducing brittle behavior of deep beams.

4.3 Crack Pattern and Propagation, Deflection, Energy Absorption, First and Final Crack Loading Capacity of PCC Deep Beams With and Without Fibers

The crack propagation in each sample of PCC deep beam (DBPC), NFRC deep beams with 4% fiber (DBNFC-4%) and NFRC deep beams with 5% fiber (DBNFC-5%) was carefully recorded during the testing using high resolution camera. The first flexural crack in DBPC, DBNFC-4% and DBNFC-5% specimens was appeared at 42.17 kN, 56.2 kN and 44.47 kN load respectively. The length of the crack was initially 200 mm, 180 mm, and 160 mm respectively in DBPC, DBNFC-4% and DBNFC-5% specimens. This crack propagated towards the mid loading point with increase in load. The DBPC samples were broken in two pieces suddenly after appearance of first flexure crack, whereas NFRC samples took some time after first crack and were remained intact even when sample stop taking further load. An improvement of 33.27% and 5.45% was observed in the load carrying capacity of deep beam for DBNFC-4% and DBNFC-5% respectively as compared to DBPC. Better random dispersion of nylon fibers was believed to resist the crack formation and enhance the load carrying capacity (shear strength) of deep beam. The deflection (Δo) at first crack loading points in deep beams are 1.3 mm, 1.9 mm and 2.4 mm for DBPC, DBNFC-4% and DBNFC-5% respectively. Improvement of 47.7% and 84.6% was observed in the deflection at first loading crack, for the specimens of DBNFC-4% and DBNFC-5% respectively when compared to DBPC.

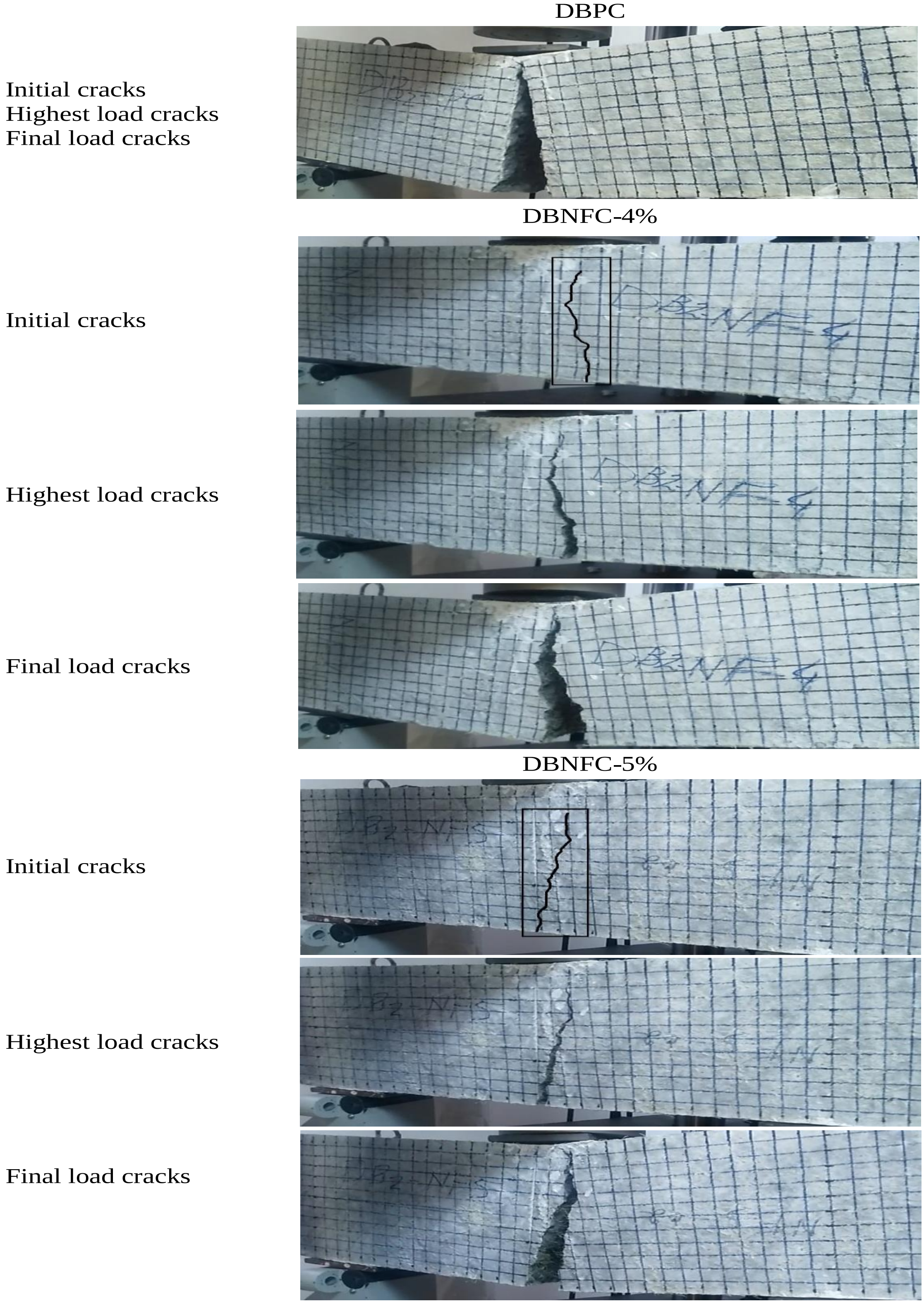


FIGURE 4.10: Initial cracks, highest load cracks and final load cracks in DBPC, DBNFC-4% and DBNFC-5%

The deflection enhancement of deep beam samples shows that the NFRC can change the brittle behavior of concrete to ductile behavior and increase the shear strength. Nylon fibers delayed the formation and propagation of cracks in deep beam samples. The details of initial cracks, highest load cracks and final load cracks are shown in Figure 4.10.

4.3.1 Ultimate Strength, Shear Absorbed Energies/Total Absorbed Energies and Shear Toughness Index of PCC Deep Beams With and Without Fibers

The load-deflection behavior of DBPC, DBNFC-4% and DBNFC-5% are shown in Figure 4.11. The ultimate load carrying capacity (shear strength) of deep beam samples were 42.17 kN, 56.2 kN and 44.47 kN for DBPC, DBNFC-4% and DBNFC-5% respectively. An enhancement of 33% and 5.4% was observed in the ultimate load carrying capacity (shear strength) of DBNFC-4% and DBNFC-5% respectively when compared to DBPC. The load at first crack in load-deflection curve was used for MoR calculation. The MoR was calculated to be 4.18 MPa, 5.53 MPa and 4.35 MPa for DBPC, DBNFC-4% and DBNFC-5% respectively.

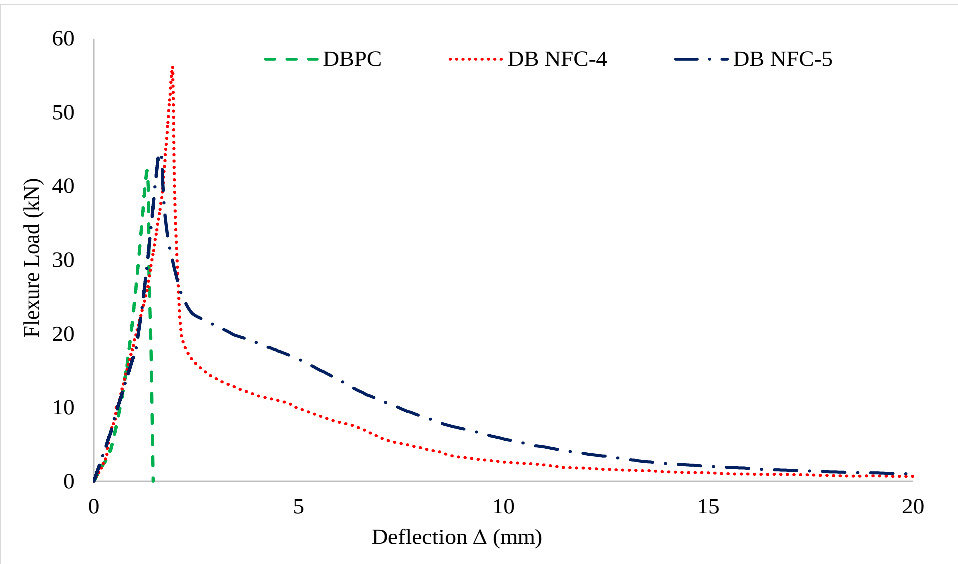


FIGURE 4.11: load-deflection behavior of DBPC, DBNFC-4% and DBNFC-5%

An improvement of 32.29% and 4.06 was noted in the MoR of DBNFC-4% and DBNFC-5% respectively as compared to that of DBPC. The deep beam absorbed energy up-to first crack (DBFE1) were 18.56 kN-mm, 38.62 kN-mm and 25.3 kN-mm for DBPC, DBNFC-4% and DBNFC-5% respectively. An enhancement of 108% and 36.3% was observed in the DBFE1 for DBNFC-4% and DBNFC-5% respectively. The reason of enhancement of DBFE1 is the better random dispersion of fiber. The energy absorbed in deep beams after first crack till last crack (DBFE2) are 0 kN-mm, 85.75 kN-mm and 152.2 kN-mm for DBPC, DBNFC-4% and DBNFC-5%, respectively. An improvement of 8575% and 15220% is observed in the DBFE2 for DBNFC-4% and DBNFC-5% respectively as compared to DBPC. A greater improvement of DBFE2 in case of fibers indicates highly ductile nature of NFRC in flexure. The deep beam total absorbed energy (DBTE) was calculated using total area under the load-deflection curve. The deep beam toughness index (DBTI) was calculated by total absorbed energy/energy absorbed up-to first crack. Table 4.5 shows the details of result. The DBTE were 18.56 kN-mm, 124.37 kN-mm and 177.5 kN-mm for DBPC, DBNFC-4% and DBNFC-5%, respectively. The DBTE of DBNFC-4% and DBNFC-5% was enhanced by 570% and 856%

TABLE 4.5: Ultimate load, Δo, MoR, DBFE1, DBFE2, DBTE, and DBTI of DBPC, DBNFC-4%, and DBNFC-5%

Parameters	Concrete type				
	DBPC	DBNFC-4%	Percentage increase in comparison to DBPC	DBNFC-5%	Percentage increase in comparison to DBPC
Maximum Load (kN)	42.17	56.2	33.2	44.47	5.4
Δo (mm)	1.3	1.92	47.6	2.4	84.6
MoR (MPa)	4.18	5.53	32.29	4.35	4.06
DBFE1 (kN.mm)	18.75	38.62	108	25.3	36.3
DBFE2 (kN.mm)	00	85.75	8575	152.2	15220
DBTE (kN.mm)	18.56	124.37	570	177.5	856
DBTI (-)	1	3.22	222	7.02	602

respectively in comparison to that of DBPC. The DBTI of DBPC, DBNFC-4% and DBNFC-5% were 1, 3.22 and 7.02 respectively. The DBTI were enhanced by

222% and 602% for DBNFC-4% and DBNFC-5% respectively when compared to DBPC. Significant improvement in DBFE1, DBFE2, DBTE, DBTI, deflection and the ultimate load carrying capacity was observed in case NFRC deep beams. The percentage enhancement is graphically shown in Figure 4.12. The enhancement in the above-mentioned properties shows that nylon fibers can be effectively used in Reinforced cement concrete (RCC) deep beam to enhance their shear strength capacity, ductility and serviceability.

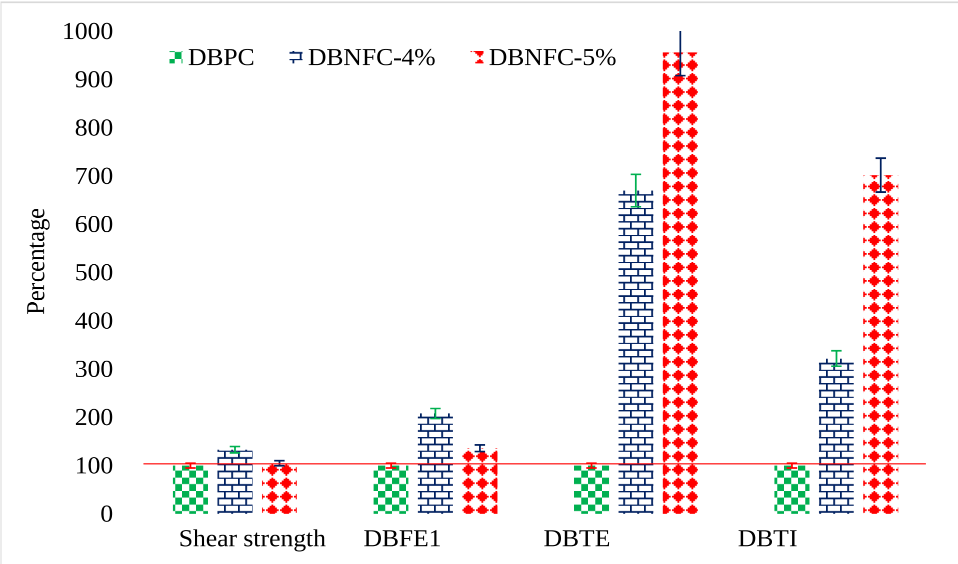


FIGURE 4.12: Comparison of PCC, DBFE1, DBTE, and DBTI, of DBPC, DBNFC-4% and DBNFC-5%.

4.4 Crack Pattern and Propagation, Deflection, Energy Absorption, First and Final Crack Loading Capacity of PRC Deep Beams With and Without Fibers

The crack propagation in each samples of plain reinforced concrete (PRC) deep beams (DBPRC), DBNFRC-4% and DBNFRC-5% was carefully observed during testing. The first flexural and diagonal crack in DBPRC was appeared at a load of 125.4 kN and 150.8 kN respectively. The first flexure crack propagated towards the support with the increase in load. The length of this crack was initially 150 mm which was further increased with the increase in load. The first flexure and diagonal crack in DBNFRC-4% was observed at a load of 158.8 kN and 185.4 kN respectively. The length of initial diagonal (shear) crack was 130 mm, started from the right bottom support of deep beam sample and propagated towards mid-point load with further increase in the load. The first flexure crack in the specimens of DBNFRC-5% was observed at a load of 127.9 kN. The first initial shear cracks in the specimens of DBNFRC-5% was observed at a load of 168 kN. The length of this shear crack was initially 110 mm, started from top loading point and progressed towards right support with further increase of the load. An improvement of 22.94% and 11.25% was observed in the first diagonal crack loading capacity of deep beams for DBNFRC-4% and DBNFRC-5% respectively as compared to DBPRC. The deflection at first diagonal cracks at loading point of deep beam samples were observed to be 3.31 mm, 3.94 mm and 6.51 mm for DBPRC, DBNFRC-4% and DBNFRC-5% respectively. Improvement of 19% and 96.6% was observed in the deflection at first diagonal loading crack for the specimens of DBNFRC-4% and DBNFRC-5% respectively when compared to DBPRC. This enhancement in the deflection show that DBNFRC can significantly enhance the ductile behavior of DBPRC to more ductile behavior. Nylon fibers were also observed to reduce the cracks formation and propagation. At failure, PRC sample got crushed under loading point, whereas nylon fiber reinforced samples remained intact even when it stopped taking further load. Nylon fibers dissipate and distribute (because in FRC the cracks sizes were reduced and energy absorption was enhanced) the energy from one point to the other and act as a crack arrester in concrete. Due to this, tensile strength of concrete and ductility of NFRC was increased. The detail of initial cracks, highest load cracks and final load cracks are shown in Figure 4.13 and 4.14.

DBPRC

First flexural
Crack
Time 95 sec
Load 125.46 kN

Initial diagonal
cracks Time, 114 s
Load, 150.8 kN

Highest load
Cracks

Final load
Cracks

DBNFRC-4%

First flexural Cracks
Time, 120 s
Load 158.8 kN

Initial diagonal Cracks
Time, 140 s
Load, 185.4 kN

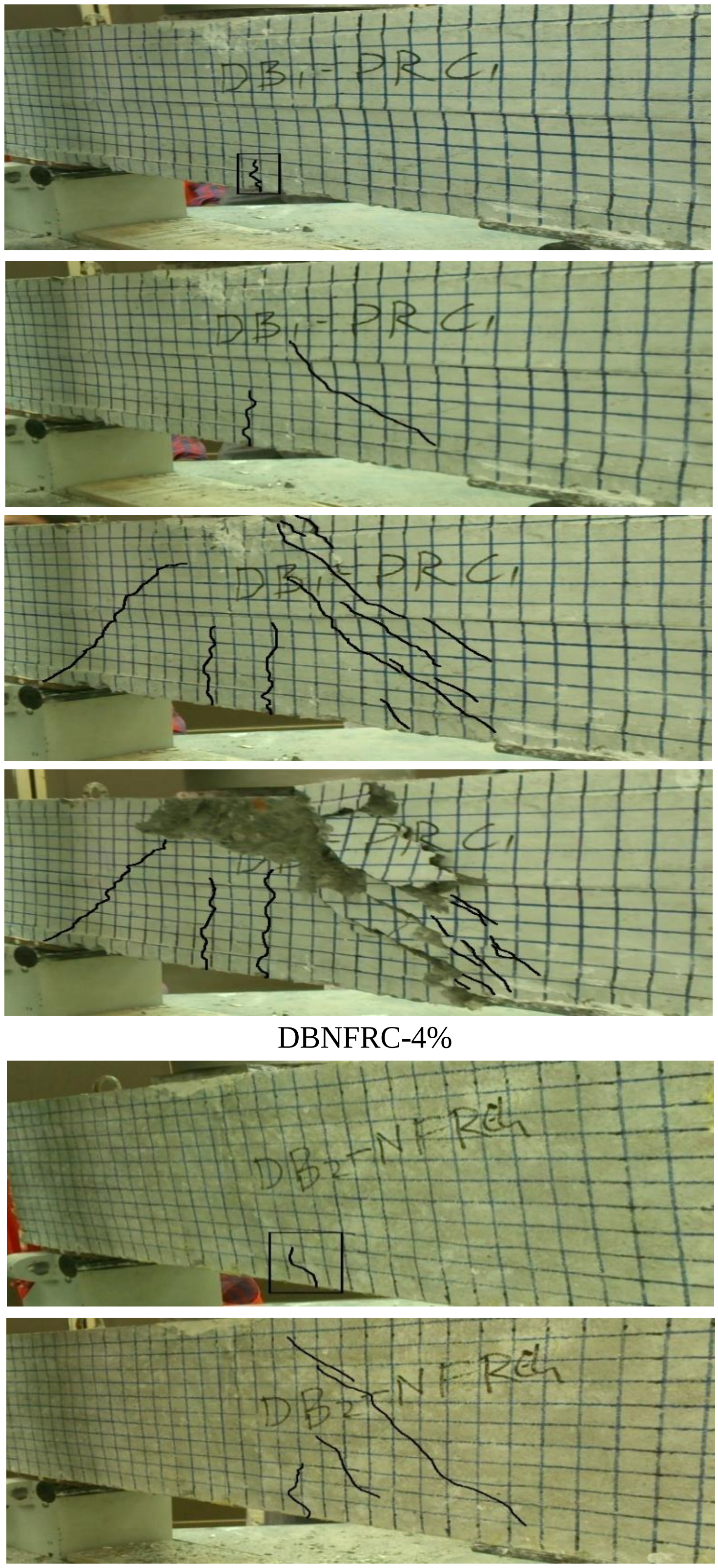
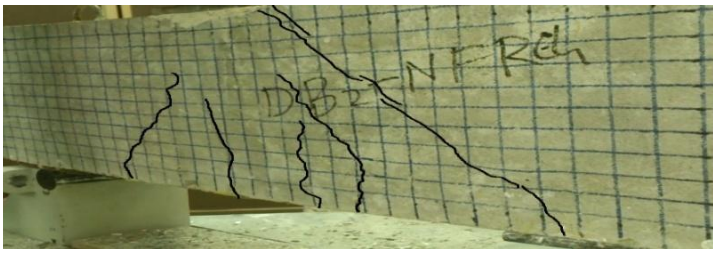


FIGURE 4.13: Initial cracks, highest load cracks and final load cracks in DBPRC, DBNFRC-4% and DBNFRC-5%

DBNFRC-4%

Highest load

Cracks



Final load

Cracks

DBNFRC-5%

First flexural
Crack
Time, 145 s

Load, 127.9 kN

Initial diagonal Cracks
Time, 190 s

Load, 167.9 kN

Highest load

Cracks

Final load

Cracks

FIGURE 4.14: Initial cracks, highest load cracks and final load cracks in DBPRC, DBNFRC-4% and DBNFRC-5%

4.4.1 Ultimate Strength and Total Absorbed Energies of PRC Deep Beams With and Without Nylon Fibers

The load-deflection behavior of DBPRC, DBNFRC-4% and DBNFRC-5% are shown in Figure 4.15. First crack load in load-deflection curve was used for MoR calculation. The MoR was calculated to be 12.44 MPa, 15.75 MPa and 12.68 MPa for DBPRC, DBNFRC-4% and DBNFRC-5% respectively. An enhancement of 26.6% and 1.92% was observed in MoR of DBNFRC-4% and DBNFRC-5% respectively as compared to that of DBPRC.

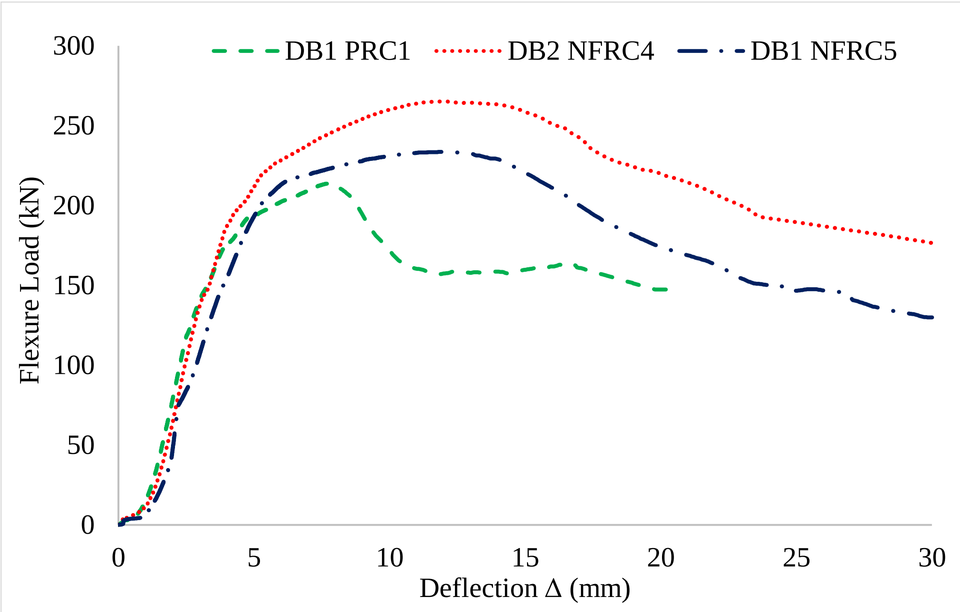


FIGURE 4.15: load-deflection behavior of PRC, DBNFRC-4% and DBNFRC-5%

The absorbed energies were calculated using area under load deflection curve at first crack (DBFE1), first crack to last crack (DBFE2), and total area under the curve (DBTE) shown in Figure 4.14. The deflection at the highest load points were noted as 7.82 mm, 11.86 mm and 14.15mm for DBPRC, DBNFRC-4% and DBNFRC-5% respectively. An improvement of 51.6% and 80.9% was observed in the deflection of DBNFRC-4% and DBNFRC-5% respectively as compared to DBPRC. The absorbed energy up-to first crack (DBFE1) were calculated to be 119.6 kN-mm, 213.37 kN-mm and 153.71 kN-mm for DBPRC, DBNFRC-4% and

DBNFRC-5% respectively. An enhancement of 78.4% and 28.52% was observed in the DBFE1 for DBNFRC-4% and DBNFRC-5% respectively.

TABLE 4.6: Δo, First flexure crack load, First diagonal crack load, Ultimate load of deep beam, MoR, DBFE1, DBFE2, DBTE, and DBTI of DBPRC, DBNFRC-4%, and DBNFRC-5%

Parameters	Concrete type				
	DBPRC	DBNFRC-4%	Percentage increase in comparison to DBPRC	DBNFRC-5%	Percentage increase in comparison to DBPRC
First flexure crack load (kN)	125.4	158.8	26.63	127.9	2
First flexure crack load Δo (mm)	2.6	3.4	30.76	5.5	111.5
First diagonal crack load (kN)	150.8	185.4	22.94	167.9	11.34
First diagonal crack load Δo	3.3	3.9	18.18	6.5	96.96
Maximum Load (kN)	213.92	265.2	23.98	233.6	9.2
Maximum load Δo	7.82	11.86	51.66	14.15	80.94
MoR (MPa)	12.44	15.75	26.6	12.68	1.9
DBFE1 (kN.mm)	119.6	213.37	78.4	153.71	28.52
DBFE2 (kN.mm)	3010.37	6101.13	102.67	4990.55	65.77
DBTE (kN.mm)	3129.98	6314.51	101.74	5144.27	64.35
DBTI (-)	26.16	29.59	13.11	33.46	27.9

The deep beam energy absorption after first crack till last crack (DBFE2) were calculated to be 3010.37 kN-mm, 6101.13 kN-mm and 4990.55 kN-mm for DBPRC, DBNFRC-4% and DBNFRC-5% respectively. An improvement of 102.6% and 65.7% was observed in the DBFE2 for DBNFRC-4% and DBNFRC-5% respectively as compared to DBPRC. The deep beam total absorbed energy (DBTE) was calculated using total area under the load-deflection curve. The deep beam toughness index (DBTI) was calculated by total absorbed energy/energy absorbed up-to first crack. Table 4.6 shows the PRC deep beam details for first flexural crack load, first diagonal crack load, ultimate load carrying capacity (shear strength) of deep beam, deflection, DBFE1, DBFE2, DBTE and DBTI for DBPRC, DBNFRC-4% and DBNFRC-5%. It can be inferred that the NFRC deep beams shall behave in ductile manner for low strain rate loading due to increase in DBFE2, whereas they will also behave well for impact type of loading due to increased DBTI. The ultimate load carrying capacity (shear strength) of deep beam samples were 213.92 kN, 265.2 kN and 233.6 kN for DBPRC, DBNFRC-4% and DBNFRC-5% respectively. An enhancement of 23.9% and 9.2% was observed in the ultimate load carrying capacity (shear strength) of DBNFRC-4% and DBNFRC-5% respectively when compared to DBPRC.

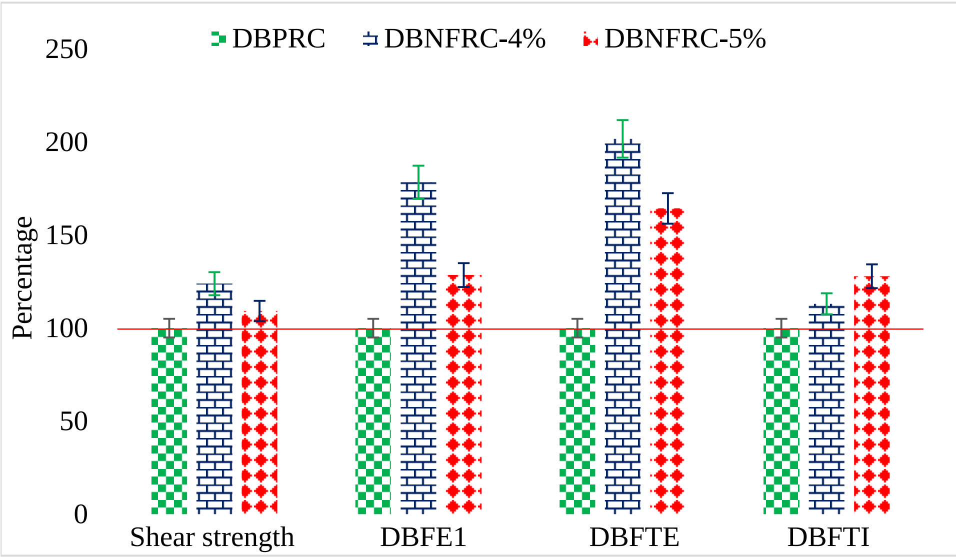


FIGURE 4.16: Comparison of Shear strength, DBFE1, DBTE, and DBTI, of DBPRC, DBNFRC-4% and DBNFRC-5%.

Improved results of DBFE1, DBFE2, DBTE, DBTI, deflection and the ultimate load carrying capacity was observed in case of nylon fiber beams. The percentage enhancement is shown graphically in Figure 4.16. The enhanced results in the above-mentioned properties suggests that the nylon fibers can be effectively used in concrete deep beams to enhance the ultimate shear strength carrying capacity, ductility, reduction of cracks in terms of numbers and formation.

4.5 Summary

The mechanical properties, the load carrying capacity at first flexure crack of deep beam, the load carrying capacity at first diagonal crack of deep beam and the load carrying capacity at highest load of deep beam were determined for PCC, NFRC-4% and NFRC-5%. Improvement of 0.7% and 2% was noted in the density of NFRC-4% and NFRC-5% respectively when compared to PCC. An enhancement of 30.23% and 19.72% was seen in the splitting tensile strength for NFRC-4% and NFRC-5% respectively when compared to PCC. An enhancement of 20.87% and 22.16 was noted in the flexure strength of beamlets samples for NFRC-4% and NFRC-5% respectively when compared to PCC. A small reduction was observed in slump and compressive strength of NFRC when compared to PCC. An improvement of 33.2% and 5.4% was noted in the ultimate load carrying capacity (shear strength) for DBNFC-4% and DBNFC-5% respectively when compared to DBPC. An enhancement of 26.6% and 2% was observed in the first flexure crack loading capacity of DBNFRC-4% and DBNFRC-5% respectively when compared to DBPRC. An improvement of 22.9% and 11.3% was observed in the first diagonal crack loading capacity of DBNFRC-4% and DBNFRC-5% respectively when compared to DBPRC. An enhancement of 23.9% and 9.2% was observed in the ultimate load carrying capacity (shear strength) of DBNFRC-4% and DBNFRC-5% respectively when compared to DBPRC.

Chapter 5

Discussion

5.1 Background

The results of experimental testing for compressive strength, splitting tensile strength, flexural strength, in the load carrying capacity (shear strength) of deep beams with and without reinforcement are discussed in detail in chapter 4. Significant enhancement in the splitting tensile strength, flexure strength, in the load carrying capacity (shear strength) of deep beams with and without reinforcements and in the energy absorption capacity was observed when compared to PCC. The relationship between material properties and deep beams are discussed in this chapter. The design strength of deep beam and experimental loading strength of deep beam are discussed in this chapter. The ductility and failure crack patterns of concrete deep beams are discussed in this chapter.

5.2 Relationship in Deep Beams and Material Properties

The concrete mechanical properties play an important role in enhancing the concrete strength in flexure and in shear. The shear behavior of concrete deep beams could be related to diagonal cracks. When the diagonal tension stresses reach the tensile strength of concrete, a diagonal crack appears [23]. Concrete compressive strength is used for code-based design of deep beams [34]. The tensile strength and compressive strength of concrete can be increased by using fiber [40]. Using fibers, the energy absorption and ductility can be enhanced [5]. The shear cracks of concrete deep beams can be controlled if the tensile strength of concrete is enhanced [19]. Thus, tensile strength plays an effective role in controlling shear cracks of the deep beams. The heavy loads and other earthquake loads can cause bending stresses in concrete members. The cracks due to this kind of loading can be controlled by enhancing their pre-crack energy absorption capacity [18]. The energy absorption capability can be enhanced by using fibers. The brittle behavior of concrete structure is also one of the reason of cracks. For controlling this effect, the concrete toughness index and energy absorption should be enhanced [41]. It is evident from literature that fibers can be effective in enhancing the basic properties and consequently the member strengths.

In light of above points, the concrete mechanical properties are tested with incorporation of nylon fibers. The inclusion of nylon fibers enhanced the concrete compressive energy absorption and splitting tensile strength which ultimately enhanced the load carrying capacity (shear strength) of deep beam. As the mode of failure in the strut of deep beam is diagonal compression and tension, therefore, the nylon fibers can enhance load carrying capacity of deep beam strut towards diagonal compression and tension failure. The inclusion of nylon fibers in concrete controlled the crack propagation as compared to that of PCC which in turn enhanced the capacity of deep beam strut towards the cracks propagation and sizes. The flexure strength of beam-let samples has increased with inclusion of nylon fibers, which ultimately improved the load carrying capacity of deep beam. The use of nylon fibers in concrete also changed the behavior of concrete from brittle failure to ductile failure, hence the brittle failure of deep beam can be controlled. The detail of enhanced basic mechanical properties is shown in table 5.1.

Table 5.1: Improved material properties with inclusion of nylon fibers

S.No.	Description	Related basic mechanical property	Percentage increase or decrease in this study
1	Diagonal cracks [23]	Tensile strength of concrete [SpS]	Increased by 30.2% and 19.7% with NFRC-4% and NFRC-5% respectively
2	Design of deep beam [34]	Compressive strength [CoS]	Decreased by 13.2% and 2.99% with NFRC-4% and NFRC-5% respectively
3	Bending/flexural cracks [18]	MoR	Increased by 12.6% and 18.8% with NFRC-4% and NFRC-5% respectively
4	Diagonal cracks [diagonal compression and diagonal tension] [23]	Pre-crack energy absorption	The CE1 decrease by 33.3% with NFRC-4% and increase by 23.85% with NFRC-5%. The SpE1 increased by 32.82% and 9.49% with NFRC-4% and NFRC-5%, respectively. The FE1 increased by 3.8% and 28.66% with NFRC-4% and NFRC-5%, respectively
5	Brittle behavior [41]	Ductility/Toughness index	The CtoI increased by 180% and 31.1 with NFRC-4% and NFRC-5%, respectively. The SpToI increased by 28% and 29% with NFRC-4% and NFRC-5%, respectively. The FToI increased by 227% and 276% with NFRC-4% and NFRC-5%, respectively

5.3 Ductility of Concrete Deep Beams

Shear failure is the probable mode of failure in deep beams due to the dominancy of shear deformation. The strength of structural elements below the flexural capacity is reduced due to shear failure, therefore, this type of failure is normally considered undesirable. It also reduces the ductility considerably. Because of the allowance for stress redistribution and provision of early warning before the brittle failure, ductility is considered a desirable structural property. Ductility is defined as the failure that is started due to yield in steel bars and large deformation without any decrease in load bearing capacity. As in deep beams, normally shear failure occurs which is brittle in nature and gives no warning before failure. In order to avoid such type of failure, ductility of deep beams need to be enhanced [21].

Table 5.2: Toughness index of material properties and deep beams.

Parameters	Concrete type				
	PC	NFRC-4%	Percentage enhancement	NFRC-5%	Percentage enhancement
CToI	2.8	7.8	180	3.6	31.1
SpToI	1	1.28	28	1.29	29
FToI	1	3.27	227	3.76	276
DBPC-TI	1	3.22	222	7.02	602
DBPRC-TI	26.16	29.59	13.11	33.46	27.9

Ductility is measured in terms of energy absorption which is the area under load deflection curve [21]. Ductility is basically toughness index of concrete. For enhancing the ductility of concrete, nylon fibers have been used in this study. An improvement of 180% and 31.11% is noted in compressive toughness index of NFRC-4% and NFRC-5% respectively when compared to PCC. By comparing the splitting tensile toughness index for PCC and NFRC, an improvement of 28% and 29% is noted in of NFRC-4% and NFRC-5%, respectively. An improvement of 227% and 276% is noted in the flexure toughness index of NFRC-4% and NFRC-5% respectively when compared to that of PCC. An improvement of 295% and 621% was observed in the deep beam toughness index of DBNFC-4% and DBNFC-5% respectively when compared to DBPC. An enhancement of 13.11% and 27.9% in the deep beam toughness index of DBNFRC-4% and DBNFRC-5% respectively as compared to DBPRC. The detail is shown in table 5.2.

5.4 Reason of Difference b/w Theoretical and Experimental Loading of Deep Beams

Deep beams are normally used in transfer girders in high-rise building and bridges etc. The failure of these building components is brittle in nature and more catastrophic, that's why the Factor of Safety (FoS) is kept higher in deep beam design by ACI Code. The design of deep beam is governed by design of tie. However in experimental studies, it observed that failure is governed by crushing/splitting of strut compression member, and concrete is stronger in compression that's why the experimental load of deep beam is greater than the theoretical load. If we observe the value of strength reduction factor (ϕ) in strut and tie model of deep beam, that is 0.75 (ACI Table 21.2), this is also a reason of higher experimental load. In accordance with ACI clause 23.5.3 minimum stirrups reinforcement should be provided if fc $<$ 6000psi. These stirrups may have contributed to enhancement of experimentally load carrying capacity [42].

Table 5.3: Load comparison of NFRC, SFRC+GFRC, SFRC+PPFRC deep beams.

Concrete Type	Parameters					
	Design load kN	First flexure crack load (kN)	First diagonal crack load (kN)	Maximum Load (kN)	% increase in comparison to PC	References
DBPRC	90	125.4	150.8	213.9	—	Current study
DBNFRC-4%	90	158.8	185.4	265.2	23.9	Current study
DBNFRC-5%	90	127.9	167.9	233.6	9.2	Current study
DBPRC	75	—	340	380	—	Kulkarni et al [5]
SFRC+GFRC 1.3%+0.3%	75	—	450	520	36.8	Kulkarni et al [5]
DBPRC	75	—	300	415	—	Shaikh et al [30]
SFRC+PPFRC 1.3%+0.3%	75	—	375	695	67	Shaikh et al [30]

As shown in table 5.3, the maximum load carrying capacity (shear strength) has been increased by 23.9% and 9.2% for DBNFRC-4% and DBNFRC-5% respectively as compared to that of DBPRC. Kulkarni et al. [5] used steel and glass fibers in combination for enhancing the concrete deep beam shear strength and an enhancement of 32.3% in first crack, 36.8% in ultimate load carrying capacity(shear strength) was observed. Shaikh et al. [30] used steel and polypropylene in concrete deep beam for enhancing the shear strength and an enhancement of 25% in first crack, 67% in ultimate load carrying capacity was observed. Although, enhancement in load carrying capacity (shear strength) with nylon fiber is low as compared to steel with glass fiber, steel with polypropylene fiber, but the nylon fiber is cheaper than steel, glass and polypropylene fiber.

5.5 Failure Mode/pattern of Deep Beams

All the beams were tested under one-point loading. The failure occurred in flexure and diagonal shear. Typical cracks pattern and modes of failure are shown in Figure 5.1. In all deep beam samples with and without reinforcement, cracks started as flexural cracks, at the middle bottom of deep beams. The first flexural crack was appeared at highest load in DBPC, thats started from bottom portion and propagate towards upper portion in deep beam. In this case, the deep beam was suddenly broken in two pieces due to brittle failure. The nylon fibers enhanced the load carrying capacity (shear strength) and changed the behavior from brittle to ductile failure. The nylon fibers enhanced the flexure load carrying capacity of deep beams up-to 33% and 5.4% with DBNFC-4% and DBNFC-5%, respectively, and 26% and 2% in flexure with DBNFRC-4% and DBNFRC-5%, respectively. But in this case the cracks length and width were smaller than DBPC samples. The cracks were propagated upward when load increased. The DBNFRC was not broken in two pieces because the fibers keep intact the concrete, and changed the nature of failure from brittle to ductile.

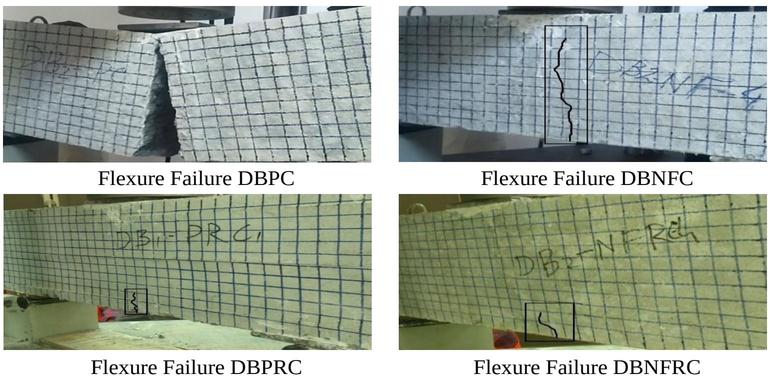


FIGURE 5.1: Cracks patterns of deep beam nylon fiber samples with and without reinforcements.

In the DBPRC samples, initial diagonal cracks appeared when load was further increased, the numbers and sizes of diagonal cracks were increased with the increase in load. The failure type was diagonal compression, that was appeared at middle point between right support and top loading point. The initial cracks in the DBNFRC samples were smaller in size and numbers. The fibers enhanced the initial diagonal load carrying capacity of deep beams up-to, 22% and 11% with DBNFRC-4% and DBNFRC-5%, respectively. When the load was further increased, new diagonal cracks were appeared at the same region of DBNFRC samples but in both sides of strut. In these samples, the type of cracks was diagonal tension. The fibers enhanced the diagonal tension load carrying capacity of deep beams up-to, 23% and 9% with DBNFRC-4% and DBNFRC-5%, respectively. Fibers reduced cracks propagation and sizes. Fibers enhanced the highest

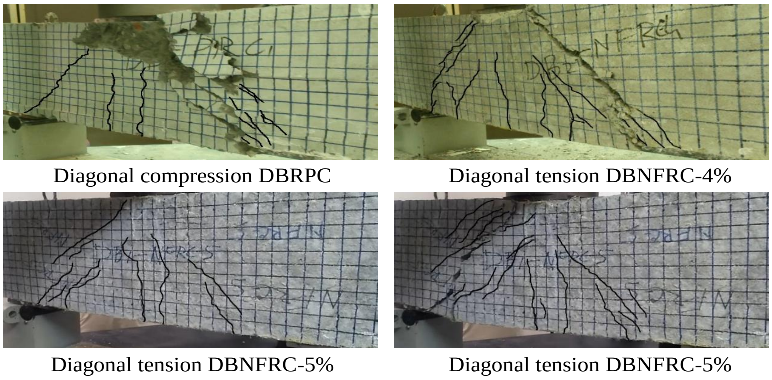


FIGURE 5.2: Cracks patterns of deep beam with nylon fiber samples with and without reinforcements

loading capacity of deep beams and changed the brittle failure mode to ductile failure, as shown in figure 5.2, that no spalling of concrete was present in DBNFRC samples. Shaikh et al. [30] conducted the experimental study with steel and polypropylene fiber. The first crack loading capacity was increased with addition of hybrid fibers percentages. The shear cracks were appeared at bottom face near the support of deep beam and propagate towards loading point, as load was increased. Fibers controlled cracks sizes and stopped their propagation. When the load was increased, new diagonal cracks were produced but shorter in length as compared to conventional deep beam. All the beams were failed in shear and considerable enhancement were observed with addition of hybrid fiber percentage in the first (38%) and ultimate (67%) loading capacity of concrete deep beam. The failure type was more ductile in nature as compared to convention concrete deep beam.

Chapter 6

Conclusion and Future Work

6.1 Conclusions

The different types of FRC are being used nowadays that have the potential to enhance the mechanical properties of concrete in terms of low shear cracks, enhance ductility of concrete and enhance load carrying capacity (shear strength) of deep beams. The use of fibers for improving the mechanical properties of concrete is in use since long time. Natural and artificial fibers have the capability to enhance the concrete mechanical properties. In current research study, nylon fiber is experimentally investigated for evaluating their performance in terms of reducing shear cracks, increasing ductility and enhancing the load carrying capacity (shear strength) in perspective of deep beams. The evaluation of material properties includes compressive strength, splitting-tensile strength, and flexure strength. For reference, PCC samples were used. For the preparation of NFRC, 4% & 5% nylon fiber was used. The fiber length was 25 mm and a mix design ratio of 1:2.5:3.5 was used for PCC and NFRC. During experimental investigation, following results have been observed.

- In comparison of NFRC to PCC for the same water cement ratio, the densities of NFRC-4% and NFRC-5% are improved by 0.76% and 2.06%, respectively. In comparison of NFRC to PCC, the slump of NFRC-4% and NFRC-5% is reduced by 36% and 76%, respectively.

- A reduction of 13.23% and 2.99% in the compressive strength of NFRC-4% and NFRC-5% is observed, respectively to that of PCC. Comparing the result of SpS of NFRC-4% and NFRC-5%, an enhancement of 30.27% and 19.72% is observed, respectively in comparison to PCC. By comparing the results of NFRC to PCC, an enhancement of 12.62% and 18.81% is noted in the MoR of NFRC-4% and NFRC-5%, respectively.

- By comparing the results of NFRC to PCC, an enhancement of 83.8%, and 61.8% is noted in the total compressive absorbed energy of NFRC-4% and NFRC-5%, respectively. By comparing the results of total absorbed energy in splitting-tensile for PCC and NFRC, an enhancement of 69.96% and 41.36% is noted for NFRC-4% and NFRC-5%, respectively. By comparing the results of NFRC to PCC an enhancement of 240.3% and 385% is noted in the total absorbed energy in flexure for NFRC-4% and NFRC-5%, respectively.

- An improvement of 178% and 28.5% is noted in compressive toughness index of NFRC-4% and NFRC-5%, respectively, when compared to PCC. By comparing the splitting tensile toughness index for PCC and NFRC, an improvement of 28% and 29% is noted in of NFRC-4% and NFRC-5%, respectively. An improvement of 227% and 276% is noted in the flexure toughness index of NFRC-4% and NFRC-5%, respectively when compared to that of PCC.

- There was significant increase in MoR of NFRC-4% and NFRC-5% samples. An improvement of 32.29% and 4.06% is observed in the MoR of DBNFC-4% and DBNFC-5% respectively when compared to DBPC. An improvement of 26.6% and 1.9% is noted in the MoR of DBNFRC-4% and DBNFRC-5% respectively when compared to DBPRC.

- An improvement of 222% and 602% is observed in the toughness index of DBNFC-4% and DBNFC-5% respectively when compared to DBPC. An enhancement of 13.11% and 27.9% is observed in the toughness index of DBNFRC-4% and DBNFRC-5% respectively as compared to DBPRC.

- An enhancement of 26.63% and 2% is noted in first crack loading capacity of DBNFRC-4% and DBNFRC-5% respectively as compared to DBPRC. An enhancement of 22.9% and 11.3% is observed in the first diagonal crack of DBNFRC-4% and DBNFRC-5% respectively as compared to DBPRC. An improvement of 23.9% and 9.2% is observed in the ultimate loading capacity (shear strength) of DBNFRC-4% and DBNFRC-5% respectively when compared to DBPRC.

- An improvement of 108% and 36% is observed in DBFE1 of DBNFC-4% and DBNFC-5% respectively when compared to DBPC. An enhancement of 78.4% and 28.52% is observed in DBFE1 of DBNFRC-4% and DBNFRC-5% respectively as compared to DBPRC.

- An enhancement of 570% and 856% is observed in total absorbed energy of DBNFC-4% and DBNFC-5% respectively when compared to DBPC. An enhancement of 101.7% and 64.3% is noted in the total absorbed energy of DBNFRC-4% and DBNFRC-5% respectively when compared to DBPRC.

- An enhancement of 47.6% and 84.6% is noted in the deflection of DBNFC-4% and DBNFC-5% respectively when compared to DBPC. An increase of 30.76% and 111.5% is observed in the deflection at first flexure crack of DBNFRC-4% and DBNFRC-5% respectively as compared to that of DBPRC. An enhancement of 18.18% and 96.96% is noted in the deflection at first diagonal crack of DBNFRC-4% and DBNFRC-5% respectively as compared to that of DBPRC. An enhancement of 51.6% and 80.9% is observed in the deflection at ultimate crack of DBNFRC-4% and DBNFRC-5% respectively as compared to DBPRC.

High pre-crack energy absorption capacity in splitting and flexure strength can control cracks in deep beams as well as enhance its shear strength characteristics. Comparing these properties for NFRC-4% and NFRC-5%, the NFRC-5% seems to have more potential to control shear cracks and enhance the load carrying capacity (shear strength) of deep beams because of the better observed properties.

The use of nylon fibers in concrete results in a significant increase in first crack loading capacity, ultimate loading capacity (shear strength), energy absorption and ductility of deep beams. The nylon fibers reduced the crack sizes, spalling of concrete and changed the brittle behavior to ductile behavior. Due to improved results and behaviors of DBNFRC especially, NFRC can be effectively used in concrete to enhance the first crack loading capacity and the ultimate load carrying capacity (shear strength) of deep beams. Due to high pre-crack energy absorption capacity in deep beams samples, it can control crack propagation in deep beams. Higher toughness index in case of NFRC deep beam makes them more suitable in seismically effected area to absorb more energy and to resist earthquake forces effectively. (As toughness index is basically the ductility of concrete that controls the spalling of concrete particles in case of failure and increase, the energy absorption of concrete up-to first crack).

6.2 Future Work

Following are the recommendations for future work:

- Nylon fibers need to be investigated with various lengths, percentages and with different high strength design mixes, for optimum results.
- The durability of nylon fiber in concrete needs to be explored.
- Nylon fiber should be investigated with addition of different types of admixtures.

Bibliography

[1] K. H. Yang, H. S. Chung, E. T. Lee, and H. C. Eun, Shear characteristics of high-strength concrete deep beams without shear reinforcements, Engineering structures, vol. 25, pp. 1343-1352, 2003.

[2] Z. Zhang, C. T. T. Hsu, and J. Moren, Shear strengthening of reinforced concrete deep beams using carbon fiber reinforced polymer laminates, Journal of Composites for Construction, vol. 8, pp. 403-414, 2004.

[3] Nawy, and G. Edward, Reinforced Concrete- A Fundamental approach (5th Edition), Upper Saddle River Prentice Hall, vol. 10, pp. 171-183, 2005.

[4] M. N. Hassoun, and A. Al-Manaseer, Structural Concrete theory and design, Jhon Wiley and Sons, pp. 1-530, 2008.

[5] S. K. Kulkarni, G. A. Kekade, and S. A. Halkude, Experimental study on hybrid fiber reinforced concrete deep beams, International Journal of Civil Engineering (SSRG-IJCE) vol. 4(2), pp. 33-39, 2017.

[6] T. M. Roberts, and N. L. Ho, Shear failure of deep fiber reinforced concrete beams, International Journal of Cement Composites and Lightweight Concrete, vol. 4(3), pp. 145-152, 1982.

[7] G. L. Balazs, and I. Kovacs, Effect of steel fibres on the cracking behaviour of RC members, In 6th International RILEM Symposium on Fibre Reinforced Concretes, vol. 90, pp. 1007-1016, 2004.

[8] P. Casanova, and P. Rossi, High-strength concrete beams submitted to shear: steel fibers versus stirrups, Special Publication, vol. 182, pp. 53-68, 1999.

[9] K. Thamizharasan, S. R. Srinivasan, P. Varutharaju and V. Sathishkumar, Study on characteristics of textile fiber reinforced concrete, International Journal of Applied Sciences, vol. 8, pp. 41-57, 2016.

[10] A. Habib, R. Begum and M. M. Alam, Mechanical properties of synthetic fibers reinforced mortars, International Journal of Scientific and Engineering Research, vol. 4(4), pp. 923-927, 2013.

[11] J. G. Cook, Handbook of Textile Fibers, Morrow Publishing Company Ltd, Durham, England, pp. 261-283, 1984.

[12] E. S. Subramanian, V. R. Vaishnave, and V. T. S. Vignesh, Experimental Investigation of Concrete Composite Using Nylon Fiber, International Journal of Engineering Science and Research Technology (IJESRT) vol. 4 pp. 107-112, 2016.

[13] P. S. Song, S. Hwang, and B. C. Sheu, Strength properties of nylon-and polypropylene-fiber-reinforced concretes, Cement and Concrete Research, vol. 35(8), pp. 1546-1550, 2005.

[14] American Concrete Institute, State-of-the Art Report on Fiber Reinforced Concrete: Reported by ACI Committee 544, vol. 544(1), pp. 841-907, 1986.

[15] S. K. Madan, K. G. Rajesh, and s. p. Singh, Steel fibers as replacement of web reinforcement for RCC deep beams in shear, Asian Journal of Civil Engineering (Building and Housing), vol. 8(5), pp. 479-489, 2007.

[16] A. Zia, and M. Ali, Behavior of fiber reinforced concrete for controlling the rate of cracking in canal-lining, Construction and Building Materials, vol. 155, pp. 726-739, 2017.

[17] T. E. Maaddawy, and S. Sherif, FRP composites for shear strengthening of reinforced concrete deep beams with openings, Composite Structures, vol. 89(1), pp. 60-69, 2009.

[18] D. R. Sahoo, C. A. Flores, and S. H. Chao, Behavior of Steel Fiber-Reinforced Concrete Deep Beams with Large Opening, ACI Structural Journal, vol. 109(2), pp. 193-204, 2012.

[19] V. Vengatachalapathy, and R. Ilangovan, A study on steel fiber reinforced concrete deep beams with and without openings, International Journal of Civil and Structural Engineering, vol. 1(3), pp. 509-517, 2010.

[20] M. K. Dhahir, Shear strength of FRP reinforced deep beams without web reinforcement, Composite Structures, vol. 165, pp. 223-232, 2017.

[21] M. Mohammadhassani, M. Z. Jumaat, M. Jameel, H. Badiee, and A. M. Arumugam, Ductility and performance assessment of high strength self-compacting concrete (HSSCC) deep beams: An experimental investigation, Nuclear Engineering and Design, vol. 250, pp. 116-124, 2012.

[22] A. K. Sachan, and C. K. Rao, Behavior of fiber reinforced concrete deep beams, Cement and Concrete Composites, vol. 12(3), pp. 211-218, 1990.

[23] F. K. Kong, and R. H. Evans, Reinforced and Prestressed Concrete, CRC Press Book, (2nd Edition), pp. 162-168, 1980.

[24] S. K. Al-Oraimi, and A. C. Seibi, Mechanical characterization and impact behavior of concrete reinforced with natural fibers, Composite Structures, vol. 32(1-4), pp. 165-171, 1995.

[25] I. Merta, and E. K. Tschegg, Fracture energy of natural fiber reinforced concrete, Construction and Building Materials, vol. 40, pp. 991-997, 2013.

[26] S. V. Joshi, L. T. Drzal, A. K. Mohanty, and S. Arora, Are natural fiber composites environmentally superior to glass fiber reinforced composites, Composites Part A: Applied Science and Manufacturing, vol. 35(3), pp. 371-376, 2004.

[27] Y. Wang, S. Backer, and V. C. Li, An experimental study of synthetic fiber reinforced cementitious composites, Journal of Materials Science, vol. 22(12), pp. 4281-4291, 1987.

[28] M. S. Sandeep, P. Nagarajan, A. P. Shashikala, and S. A. Habeeb, Determination of strut efficiency factor for concrete deep beams with and without fiber, Advances in Computational Design, vol. 1(3), pp. 253-264, 2016.

[29] P. Sakthi, and S. Nishanthi, Study on sisal fiber reinforced concrete beam with and without openings, International Journal of Research in Science and Technology, vol. 6, pp. 152-159, 2016.

[30] Suhail shaikh, S. K. Kulkarni, S. S. Patil, and S. A. Halkude, Effect of hybrid fiber reinforcement in concrete deep beams, Imperial Journal of Interdisciplinary Research (IJIR), vol. 3(1), pp. 238-247, 2017.

[31] I. M. Hanif, M. R. Noor Syuhaili, M. F. Hasmori, and S. M. Shahmi, Effect of nylon fiber on mechanical properties of cement based mortar, Materials Science and Engineering, vol. 271, pp. 768-776, 2017.

[32] M. Khan, and M. Ali, Use of glass and nylon fibers in concrete for controlling early age micro cracking in bridge decks, Construction and Building Materials, vol. 125, pp. 800-808, 2016.

[33] S. Jagannathan, S. Rangasamy, and K. Kumarasamy, An experimental investigation on nylon fiber (Textile Waste) reinforced concrete, International Journal of Recent Research and Applied Studies, vol. 3(1), pp. 69-74, 2016.

[34] ACI Committee 318, Building Code Requirements for Structural Concrete (ACI 318-14): An ACI Standard: Commentary on Building Code Requirements for Structural Concrete, (ACI 318R-14), Farmington Hills, MI: American Concrete Institute, pp. 1-520, 2014.

[35] ASTM C143/C143M-15a, Standard Test Method for Slump of HydraulicCement Concrete, West Conshohocken, PA: ASTM International, pp.1-6, 2015.

[36] ASTM C642-13, Standard Test Method for Density, Absorption, and Voids in Hardened Concrete, ASTM International, West Conshohocken, PA, pp. 1-5, 2013.

[37] ASTM C39/C39M-17, Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens, ASTM International, West Conshohocken, PA, pp. 1-7, 2017.

[38] ASTM C496 / C496M-11, Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens, ASTM International, West Conshohocken, PA, pp. 1-5, 2004.

[39] ASTM C293/C293M-16, Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Center-Point Loading), ASTM International, West Conshohocken, PA, pp. 1-3, 2016.

[40] J. Liu, Z. Ou, W. Peng, T. Guo, W. Deng, and Y. Chen, Literature review of coral concrete, Arabian Journal for Science and Engineering, vol. 43(4), pp. 1529-1541, 2018.

[41] V. S. Vairagade, and K. S. Kene, Introduction to steel fiber reinforced concrete on engineering performance of concrete, International Journal of Scientific and Technology Research, vol. 1(4), pp. 139-146, 2012.

[42] A. Demir, N. Caglar, and H. Ozturk, Parameters affecting diagonal cracking behavior of reinforced concrete deep beams, Engineering Structures, vol. 184, pp. 217-231, 2019.