STUDY ON INFLUENCE OF FIBER HYBRIDIZATION ON STRENGTH AND CONSTITUTIVE STRESS-STRAIN BEHAVIOUR OF CONCRETE

Submitted in partial fulfilment of the requirements
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by

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CERTIFICATE

This is to certify that the thesis entitled "**STUDY ON INFLUENCE OF FIBER HYBRIDIZATION ON STRENGTH AND CONSTITUTIVE STRESS-STRAIN BEHAVIOUR OF CONCRETE"** being submitted by **Mr. SRIKANTH KONIKI** for the award of the degree of **DOCTOR OF PHILOSOPHY** to the Faculty of Engineering and Technology of **NATIONAL INSTITUTE OF TECHNOLOGY, WARANGAL** is a record of bonafide research work carried out by him under my supervision and it has not been submitted elsewhere for award of any degree.

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APPROVAL SHEET

This Thesis entitled "**STUDY ON INFLUENCE OF FIBER HYBRIDIZATION ON STRENGTH AND CONSTITUTIVE STRESS-STRAIN BEHAVIOUR OF CONCRETE**" by **Mr. SRIKANTH KONIKI** is approved for the degree of Doctor of Philosophy.

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DECLARATION

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ABSTRACT

Concrete is a widely used construction material all over the world. Since the problems associated with concrete such as low tensile strength and low ductility is limiting the usage in all practical applications. Short randomly discrete fibers used in concrete to control cracking in fresh and harden state of the concrete. But the improvement in mechanical properties with the addition of fiber is limited in extent as the fracture in concrete is gradual and multi scale process. This necessitates the addition of two or more different kind of fibers to improve the wide range of concrete properties such as shrinkage resistant, tensile strength and toughness.

This research was under taken with an objective to evaluate the mechanical properties and constitutive stress-strain behaviour of hybrid fiber reinforced concrete. Effect of fiber hybridization on different grades of concrete i.e., 30 MPa (low strength), 50 MPa (medium strength) and 70 MPa (high strength) concretes was studied. Fibers used in the present investigation were hooked end steel, polyester and polypropylene. Entire experimental programme was carried out in four different phases.

First stage of the investigation is carried out on mechanical properties and constitutive stress-strain behaviour mono-FRC. Compressive strength, direct tensile strength, flexural strength of mono-FRC are determined. The stress-strain behaviour of mono-FRC under uni-axial compression and tension are also assessed. Fiber dosages of polyester and polypropylene are varied from 0.0, 0.05, 0.1, 0.15 and 0.2% and the fiber dosage of steel fiber is varied from 0.0, 0.5, 0.75, 1 and 1.25%. From the results it is observed that there is no significant improvement in compressive strength with the addition of fibers, but tensile strength and flexure strength of the concrete increased with the addition of fibers. It is also noticed that concrete containing non-metallic fibers dose not significantly enhanced the both pre-peak and post-peak behaviour

of concrete under uni-axial stresses, whereas addition of steel fibers enhanced the post-peak toughness but the tensile strength of the concrete is not significantly improved. Results obtained from the phase I gave an idea about mono-fiber behaviour in concrete and paved the way for developing the HFRC in the further investigation.

The second phase of the investigation is carried out to develop and study the mechanical properties of non-metallic HFRC. The non-metallic HFRC aims to counteract the plastic shrinkage cracks forming at early stages of concrete and also to bridge the micro-cracks forming at low-stress levels of harden concrete. Even though Young's modulus of both polyester and polypropylene fibers are nearer, due to the variation in tensile strength and aspect ratios of the fibers, the tensile strength of the concrete improved without compromising the plastic shrinkage cracks. Three types of hybrid combinations are considered i.e. PP 25% + PO 75%, PP 50% + PO 50% and PP 75% + PO25% at a total fiber volume fractions of 0.1, 0.15, 0.2 and 0.25%. From the experimental results it is observed that the optimum hybrid combination achieved at all fiber dosages is 75% PO + 25% PP. It is also observed that concrete reinforced with PO and PP hybrid fibers enhanced the tensile strength and toughness of the composite compared to mono-FRC for the same fiber volume fraction. The positive synergy between the non-metallic fibers drives to develop metallic and non-metallic HFRC.

The third phase of the investigation is carried out to develop the metallic and non-metallic HFRC with an aim to assess the strength properties and constitutive stress-strain behaviour. The developed HFRC can counteract the fracture process of concrete and achieve the overall performance of concrete in terms of strength, ductility and toughness. From the phase 2 experimental results, it is observed that non-metallic HFRC improved the tensile strength of the concrete but the improvement in toughness at post crack region is marginal. To increase the tensile strength and toughness at post-crack region, fiber hybridization is done using metallic and non-metallic fibers. Compressive strength, direct tensile strength, flexural strength and stress-strain behaviour under uni-axial stresses are studied. It is observed that Synergy effect was found to be more with the addition of metallic and non-metallic fibers due to inhibition of crack control at different stress levels. Results from the phase 3 have shown significant improvement on parameters like strength, ductility and toughness.

The fourth phase of the investigation consist of modelling of HFRC using ATENA software. Small prism of size 200 x 100 x 100 mm is modelled in ATEN to get the stress-strain curve analytically. The results obtained from the ATENA model are compared with the experimental values. The results shown good agreement with the experimental values within 15% variation. Later with the inputs from 200 x 100 x 100 model, flexure specimen of 500 x 100 x 100 model has been generated and analysed in ATENA. Results obtained from the flexure model are validated with experimental results. Experimental results and values obtained by the ATENA model is within 10% variation.

Overall the present study indicates that hybridisation of metallic and non-metallic fibers improved the properties of concrete with respect to tensile strength, flexural strength and toughness of the composite compared to mono-FRC and control mix for the same fiber volume fraction. Hence HFRC proven to be effective in resisting the cracks developed in concrete at all stress levels.

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Notations

FRC	Fiber Reinforced Concrete
HFRC	Hybrid Fiber Reinforced Concrete
PP	Polypropylene Fiber
PO	Polyester Fiber
HS	Hooked-end Steel Fiber
OPC	Ordinary Portland Cement
f_{ck}	Compressive Strength
f_{dt}	Direct Tensile Strength
f_{ft}	Flexural Strength
σ^c_u	Peak Stress
ε^c_u	Strain at peak stress
E_s	young's modulus
D_f	Ductility factor
EA^c	Energy absorption capacity of concrete in compression
T_f	Toughness Factor
"c"	Represents the values in compression
σ^t_f	Stress at inflection point
ε^t_f	Strain at inflection point
σ^t_u	Stress at ultimate point
ε^t_b	Strain at break point
EA^t	Energy absorption capacity
"t"	values in tension
NM-HFRC	Non-Metallic Hybrid Fiber Reinforced Concrete
M	Metallic
M-NM HFRC	Metallic and Non-metallic Hybrid Fiber Reinforced Concrete
ATENA	Advanced Tool for Non-linear Analysis
GID	Graphic Interface Devise

CHAPTER 1

INTRODUCTION

1.1 General

Concrete is a widely used construction material all over the world, because of several advantages like good compressive strength, lower life-cycle cost and mouldability. With the superior advantage compared to other construction material concrete also has some limitations to utilize as a construction material i.e., concrete is brittle in nature and almost having no ductility. Strategically placing rebar's in the concrete can eliminate the brittleness to some extent, but the concrete remains as a weak material with respect to tension. Also reinforcement in concrete shares a substantial part of the total cost of construction.

Addition of short random discrete fibers in concrete can address some of the concerns related to the concrete brittleness and low tensile strength, commonly known as fiber reinforced concrete (FRC). Fibres used as reinforcement can effectively arrest the cracks both at micro and macro-levels. FRC can sustain tensile loads even deflection exceeds the limiting value of plane concrete. But the fracture in concrete is gradual and multi-scale process [Van Mier J.G.M et al. 1997], i.e., plastic shrinkage cracks prior to the loading lead to micro-cracks during the loading, which further leads to macro-cracks and then fracture. Since the fracture in concrete is multi-scale process, using a single type of fiber in concrete can improve the properties to their scale level only.

More research is going on, to improve the properties of concrete, and to arrest the multi-scale cracks forming at various stress-levels in concrete, if two or more number of fibers are rationally combined to produce a cement concrete composite that derives the benefits from each of the individual fibers and exhibits a synergic response, the composite obtained is called as hybrid fiber reinforce concrete (HFRC).

1.2 Necessity of Hybrid fibers in concrete

Fiber effect on concrete mainly depends on the fiber properties like fiber volume, fiber aspect-ratio, fiber geometry, and Young's modulus. Fibers which are having low Young's modulus such as polyester, polypropylene, and nylon, etc., having low density and high aspect-ratio numerous fibers available throughout the matrix. Can effectively controls the shrinkage and micro-cracks forming at low-stress levels. With the use of low modulus fibers load carrying capacity at high stress-levels is not good [Hsie et al. 2008].

High Young's modulus fiber like steel fibers which can control the propagation of macro-cracks at higher stress levels and improves the load carrying capacity at failure regions thereby improves the toughness of concrete. Hence, catastrophic failures can be avoided, but the problems with plastic-shrinkage cracks and micro-cracks are not justified owing to its low reinforcing efficiency [Sivakumar A et al. 2007].

Hence, the problems of brittleness, early age shrinkage cracks and multi-scale cracks forming at various stress levels in concrete are not arrested by using by just one type of fiber, but rather by the addition of two different types of fibers (hybrid fibers). The large and strong fibers can control large cracks, the small and fine fibers can control crack initiation and propagation of small cracks. Successful HFRC composite comprises properties as good as sum of the individual fibers, this phenomenon is termed as "synergy". [N Banthia et al. 2004].

1.3 Types of hybridization

Extensive research work is being carried out to develop HFRC. There are many combinations and trials have been carried out by different researchers to address the issues related to multi-scale cracks developed in concrete during its service. Based on the combination of the fibers, they are grouped into three main categories as follows;

1.3.1 Hybrids based on fiber constitutive response

Here the fiber stiffness is the key parameter. Lower Young’s modulus fibers because of their high reinforcing efficiency control the plastic shrinkage-cracks and micro-cracks thereby improves the tensile strength of the concrete considerably. While the high Young's modulus fibers effective in high-stress levels by controlling the propagation of macro-cracks thereby improves the toughness of the cement composite.

1.3.2 *Hybrids based on fiber dimension and anchorage mechanism*

Here the key parameter is fiber length termed as micro-fiber and macro-fiber. Micro-fibers arrest the coalescence of cracks and improves the first-crack stress and ultimate-strength. While the macro-fibers intended to arrest the propagation of macro-cracks, therefore, substantial improvement in fracture toughness of the composite.

1.3.3 Hybrids based on fiber function

Here, one type of fiber enhances the early stages of concrete and the other one should improve the mechanical properties of hardened concrete by control the formation of cracks growth.

1.4 Mechanism of hybrid fibers in concrete

In order to develop a successful HFRC, it is necessary to understand the basic mechanism of individual fibers as shown in figure 1.1. The matrix contains short and fine fibers owing to its high reinforcing efficiency, these fibers can effectively control the shrinkage and micro-cracks thereby the tensile strength of cement matrix increases. At higher stress-levels the short and fine fibers in concrete cannot withstand the load and they undergo fracture or pull-out from the concrete. At this stage all the micro-cracks are interconnected and forms as macro-cracks hence stresses are being transferred from short fibers to long fibers. Long fibers prevent the propagation of macro-cracks thereby toughness of the composite increases.

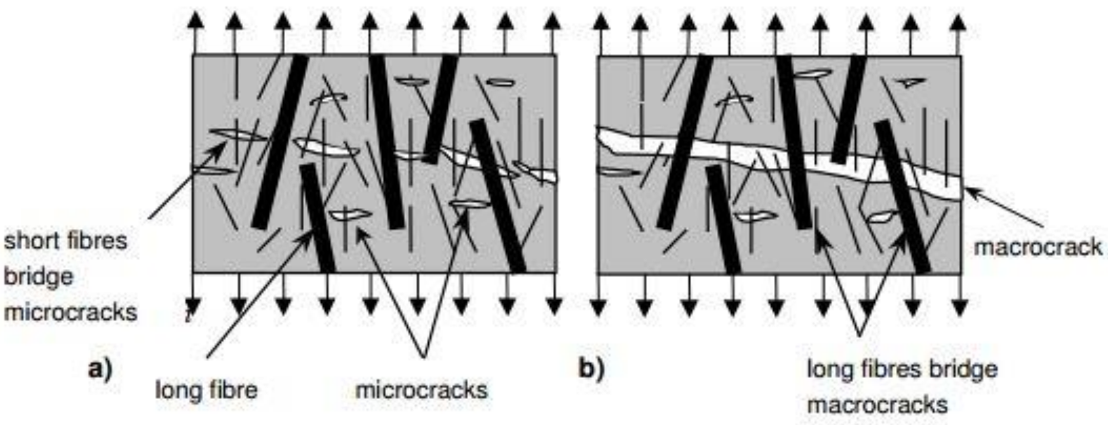


Figure 1.1 Mechanism of hybrid fibers in concrete [Ivan Markovic et al. 2006]

1.5 Analytical modelling

Recent advances in numerical methods and meterial science as well, increased the numerical simulations for the verification of practical design. ATENA-GID is a software based on finite element analysis specially designed for non-linear analysis of concrete structures. for the material models of ordinary reinforced concrete, ATENA offers special numerical models accounting inclusion of fibers into the concrete. ATENA calculates material properties based on the cube strength with equations from *Model Code 2010*. Another great advantage with ATENA it is specially designed for concrete. It is possible to simulate the real behavior of concrete and reinforced concrete structures including concrete cracking, crushing and reinforcement yielding using the software.

ATENA 3D program is designed for 3D nonlinear analysis of solids with special tools for reinforced concrete structures. However, structures from other materials, such as soils, metals etc. can be treated as well. The program has three main functions:

1. *Pre-processing* - The input of geometrical objects (concrete, reinforcement, interfaces, etc.), loading and boundary conditions, meshing and solution parameters.

2. *Analysis* - It makes possible real-time monitoring of results during calculations.

3. *Post-processing* - Access to a wide range of graphical and numerical results. ATENA 3D is limited to stress analysis. It does not include other types of analysis, such as creep and transport of heat and humidity.

1.6 Thesis organization

The present thesis organized in the following way

Chapter 1 Starts with the introduction to concrete along with its advantages and disadvantages. Followed by introduction to the fiber reinforced concrete and its limitations, and the need of hybrid fiber reinforced concrete. In addition, finite element based non-linear based software discussed in present chapter.

Chapter 2 The second chapter includes the collection of literature on mono-fiber reinforced concrete and hybrid fiber reinforced concrete and summary of literature presented.

Chapter 3 represents the scope and objectives of the research work.

Chapter 4 consists the detailed discussion on materials used for the preparation of concrete and methods used to test the concrete specimens.

Chapter 5 deals with mechanical behavior of mono-fiber reinforced concrete and its detailed discussion.

Chapter 6 This chapter focused on the mechanical behavior of non-metallic hybrid fiber reinforced concrete development and its behaviour.

Chapter 7 Presents the detailed discussion on mechanical behavior of metallic – non-metallic hybrid fiber reinforced concrete development and its behaviour.

Chapter 8 This chapter includes the validation of results obtained experimentally with the values through modelling of specimens using ATENA.

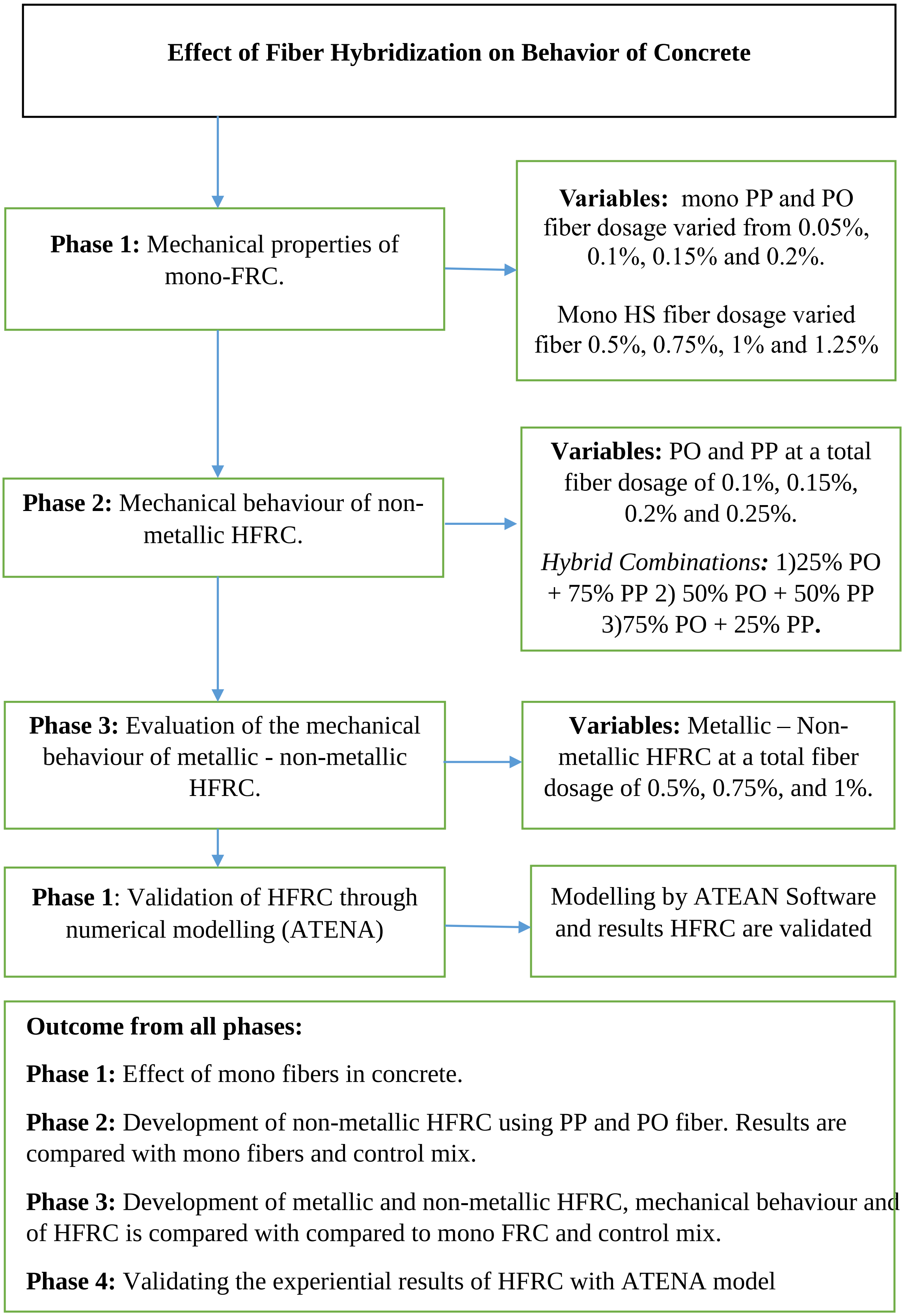
Chapter 9 This chapter presents the overall conclusions drawn from the research work. The scope for further research and references are also presented

1.7 Research methodology

- Reference concrete of 30 MPa, 50 MPa and 70 MPa was designed according to IS 10262.
- Steel, polyester and polypropylene fibers were added to concrete individually at varied fiber dosages to develop mono-FRC and assessed the mechanical behaviour of mono fibers in concrete.
- Later polypropylene and polyester fibers were combined in various volume proportions to develop non-metallic HFRC. Optimum hybrid combinations of these fibers was obtained.

- Obtained optimized non-metallic hybrid dosages are added to the hooked end steel fiber at varied fiber volume fractions to develop metallic - non-metallic HFRC.
- Mechanical properties of concrete (compressive strength, direct tensile strength and flexure strength) were determined. For the metallic and non-metallic HFRC
- Stress-strain behaviour of concrete under uniaxial stress (compression and tension) were obtained.
- Validated the experimental results with the results obtained by modelling the specimens using ATENA software.

1.8 Outline of the thesis



CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter presents a comprehensive review of the research studies conducted on the potential use of various kinds of fibers like metallic and non-metallic fibers to adders the shortcomings of concrete. The review also focuses on recent studies on hybrid fiber reinforced concrete.

2.2 Need of fibers in concrete: mono-fiber reinforced concrete.

Plain concrete is brittle in nature and having very less strain capacity both in tension and compression (Dubey and Banthia, 1998). Traditional use of fibers to strengthen the tension week materials are goes back to the ancient time, the oldest written account of the composite material is clay bricks reinforced with straw. Short random discrete fibers bridge the cracks forming at both low and high-stress levels and increases the strength and ductility of the concrete (Arnon Bentur and Sidney Mindess, 2014). In addition to this, fibers are known to control early age shrinkage-crack formation, thereby leading to better crack resistance at low-stress levels (Soroushian et al., 1993). Although the mechanism of fiber action and factors controlling fiber performance in concrete are well understood, a brief review of the fiber material used in the study and its influence on the concrete properties are provided for its relevance to the current research study.

2.2.1 *Literature on steel fiber reinforced concrete*

M.C. Natarajan et al. (1999), studied the stress-strain behaviour of steel-fiber reinforced concrete under uni-axial compression, the strength of the concrete ranging from 30 MPa to 50

MPa was considered in this investigation. Crimped steel fibers of two aspect ratios (55 and 82) and three volume fractions were used. The major conclusions from the study are, an increase in toughness is directly proportional to the reinforcement index and the percentage increase in toughness is lower for a higher grade of concrete. In this investigation an equation to predict the stress-strain curve of crimped steel fiber was developed based on β values and strain corresponding to peak compressive stress for crimped steel fibers; this equation provides a good correlation with experimental results.

M. A. Mansur et al. (1999), investigated the stress-strain relationship of high-strength fiber concrete ranging from 70 to 120 MPa concrete. The uni-axial test was carried out on both prismatic and cylindrical specimens to get the stress-strain curves. Steel fiber of 30mm length and 0.5mm diameter at a fiber dosage of 1% by volume was used in this investigation. To study the specimen shape effect on stress-strain curve three specimens of 100mm diameter and 200mm length cast vertically and 100mm x 100mm x 200mm prismatic specimens cast both in vertical and horizontal direction. From the experimental study, it has been concluded that there is no significant variation in initial tangent modulus with the change in shape of specimen. Specimens which were caste vertically shown marginal improvement in strength compared to the horizontally cast specimens. It has also been observed that cylinders have shown better post-peak performance compared to horizontally cast specimens.

Julie Rapoport et al. (2002), investigated the permeability of cracked steel fiber-reinforced concrete. Also investigated the relationship between crack width and permeability of steel fiber reinforced concrete at a fiber dosage of 0.5% and 1%. From the experimental study, it has been concluded that at larger crack widths concrete containing macro-steel fibers reduced permeability compared to micro-fibers at higher fiber dosages. And crack width below 100 μm macro-steel fibers are insignificant to reduce the permeability of concrete.

P.S. Song et al. (2004), investigated the mechanical properties of high-strength steel fiber-reinforced concrete. Experimental investigation consists compressive strength, splitting tensile strength and flexural strength conducted at a fiber dosage varied from 0.0% to 2.0% (0.5, 1, 1.5 and 2%). Hooked-end steel fibers made of mild carbon of length 35mm and diameter 0.55mm used in this study. From the experimental investigation, it has been concluded that the compressive strength of high-strength concrete (85 MPa) with the addition of fiber was maximum at 1.5% fiber volume fraction. The percentage increase in splitting tensile strength and modulus of rupture increased with the increase in steel fiber content, splitting tensile strength increased around 19.0% to 98.3% and percentage improvement in modulus of rupture was 28.1% to 126.6%.

R. D. Neves et al. (2005), studied the effect of fiber diameter, i.e., 0.38mm and 0.55mm and fiber content, i.e., 0.38%, 0.75%, 1.13% and 1.50% on the compressive stress-strain behaviour of SFRC. In this investigation, the compressive strength of concrete 35Mpa and 60MPa were considered. From the experimental investigation, it has been concluded that Addition of small diameter fibers enhances the pre-peak strength of concrete whereas large diameter fibers are exhibiting post peak deformation of concrete. And it has also been concluded that as the volume of the fiber increased to 0.38% to 1.50%, the strain at peak stress and toughness of the concrete significantly increased.

N. Banthia et al. (2007), investigated the toughness enhancement in steel fiber reinforced concrete through fiber hybridization. The main aim of the study is to enhance the toughness of the concrete using the combinations of large diameter steel fiber with a smaller diameter of steel fiber and to maintain the good workability, lower cost and good fiber dispersibility. Crimped steel fibers of 30mm length of varying diameters of 0.80, 0.45 and 0.4mm were taken. It has been concluded that combination of large and small diameter steel fibers can enhance the toughness of the composite with stain hardening behaviour which is generally not seen in FRC using only large diameter fibers. It has also been concluded that hybridization of large diameter with small diameter fibers may not always guaranty a better performance.

Francesco Bencardino et al. (2008), studied the stress-strain behaviour of steel fiber reinforced concrete in compression. Steel fiber of length of 22mm and an aspect ratio of 40 was used in the investigation. The cylindrical specimen were loaded in uni-axial compression (150 mm diameter and 300mm length) at a fiber volume fractions of 1%, 1.5% and 3%. It has been concluded that the compressive strength of FRC with the addition of fibers was not varied significantly. But the increase in fiber content in concrete increased the post-peak behaviour of concrete. It has also been observed that the ultimate strain of FRC is achieved at 0.01 at the residual strength of 75% corresponding to peak stress. The ultimate strain values reached five times higher compared to current guidelines.

Yu-Chen Ou et al. (2012), Assessed the compressive behaviour of steel-fiber reinforced concrete with a high reinforcing index on 40 MPa concrete. The objective of the investigation is to study the effect of steel fiber reinforced concrete with a reinforcing index up to 1.7 by volume fraction. The most important conclusions in this study are, there is a significant improvement in toughness and strain at peak stress observed with the addition of steel fibers up a volume fraction of 0.2% and there is only a marginal improvement in compressive strength and modulus of elasticity observed with the addition of fibers. It has also been noticed that steel fibers of longer in length and smaller aspect ratio, i.e. 10/60 (0.1mm diameter and 60mm length) shown better performance regarding flexural response.

Job Thomas et al. (2017), in this paper an experimental programme and an analytical assessment of the influence of steel fiber on mechanical properties of normal, medium and high strength concrete was investigated. Compressive strength, split tensile strength, flexural strength and stress-strain behaviour of steel fiber reinforced concrete were conducted. In this experimental work, glued hooked-end steel fiber of 30mm length and aspect ratio of 55 was used, at a fiber volume fractions varied from 0.0, 0.5, 1.0 and 1.5%. And also developed an analytical model and the results were compared with available predicted models from the literature. From the experimental findings, it has been concluded that there is no significant improvement in compressive strength observed with the addition of fibers, unlike the concrete in compression tensile strength of the concrete enhanced around 40% in all grades of concrete and peak stress and strain at peak stress enhanced with the addition of fibers. It is also noticed that strength effectivness of steel fiber in tension increasesd with increase in grade of concrete.

2.2.2 *Literature on polypropylene fiber reinforced concrete.*

AM. Alhozaimy et al. (1995), investigated the mechanical properties of Polypropylene fiber reinforced concrete. Fibrillated polypropylene at low volume fractions of 0.3% used in this study. Compressive strength, flexural strength and impact resistance of PP FRC was investigated. From the experimental results, it has been concluded that there is no significant effect on compressive strength and flexural strength observed with the addition of polypropylene fibers. But the flexural toughness increased 387% at 0.3% volume fraction compared to control mix. It has also been noticed that the addition of polypropylene fibers increased the first crack strength.

H. Toutanji et al. (1998), studied the impact resistance and chloride permeability of polypropylene fiber reinforced concrete. Polypropylene of length 12 mm and 19mm at a fiber volume fractions of 0, 0.1, 0.3 and 0.5% used in the investigation. The major conclusions from the study are permeability of the concrete increased with the addition of polypropylene fiber containing no silica fume, and the addition of silica fume reduced the concrete permeability.

It has also been concluded that concrete containing shorter polypropylene fibers reduced the permeability compared to longer length fibers.

Bing Chen et al. (2003), investigated the residual strength of the hybrid fiber reinforced high strength concrete after exposure to high temperatures. In this investigation, specimens are heated up in an electric oven to 20, 200, 400, 600 and 800 ^{o}C at the heating rate of 10 ^{o}C/min, and the peak temperature was maintained at 3 hours. From the experimental study, it has been concluded that there is an explosive problem for high strength concrete when exposed to higher temperature, it has been worse with the increase in temperature. It has been noticed that HFRC is mixing with polypropylene fiber shown better performance compared to mono FRC due to the melting of PP fiber under high temperatures micro-channels release inner moisture of concrete.

Nemkumar Banthia et al. (2006), studied the Influence of polypropylene fiber geometry on plastic shrinkage cracking in concrete. The investigation carried out to study the exact influence of fiber diameter, length and geometry. Volume fractions of the PP fibers varied from 0.1% to 0.3%. From the experimental results, it has been concluded that PP fibers are highly effective in controlling the plastic shrinkage cracks and long fine fibers are effective compared to short dancer fibers. It has also been concluded that fibrillated fiber is shown better performance compared to monofilament fibers.

Okan Karahan et al. (2010), studied the durability properties of polypropylene fiber reinforced concrete. flyash used in the mix proportions varied at a rate of 0, 15, and 30% and fiber volume fractions varied from 0, 0.05, 0.1 and 0.2%. From the test results it has been noticed that workability of the concrete improved with increase in flyash content and decreased with addition of fibers. Durability properties are increased with increase in flyash and polypropylene content. It is also concluded that positive interaction between polypropylene and flyash decrease the drying shrinkage cracks of concrete.

G.M. Sadiqul Islam et al. (2016), studied the shrinkage and permeability of polypropylene fiber reinforced concrete. Polypropylene fiber of aspect ratio 300 used at a volume fractions of 0 to 0.3%. Compressive strength, tensile strength, shrinkage and permeability tests were conducted. It has been concluded that there is a negative effect on compressive strength observed with the addition of polypropylene fiber. The optimum fiber content is achieved at 0.1% volume fraction and the strength reduction was 2%. Tensile strength increment of 39% achieved at an optimum dosage of 0.1%. It has also been concluded that addition of PP fiber reduced the crack width around 50 - 99% at 0.1 – 0.3% fiber dosage and crack width reduced with the increase in PP fiber content.

2.2.3 *Literature on polyester fiber reinforced concrete*

A. Sivakumar et al. (2007), investigated the plastic shrinkage cracking in high strength hybrid fiber reinforced concrete. The investigation is carried out to control the shrinkage cracks by adding fibers at low fiber volume fractions (0.5%). Influence of steel fibers and hybrid combinations of steel fibers with non-metallic fibers like polyester, polypropylene and glass fibers studied. From the experimental investigation, it has been concluded that a combination of polyester with steel fiber reduced the cracks up to 99% compared to the control mix.

Saroj Gupta et al. (2008), investigated the mechanical properties and durability properties of polyester fiber reinforced concrete. From the experimental investigation, it has been concluded that compressive strength and flexural strength of concrete improved significantly with the addition of polyester fiber and there is no change observed in compressive strength after 24 months to those 28 days concrete. It has also been concluded that drying shrinkage of concrete reduced. Author from the experimental study, is polyester fiber reinforced concrete can be used for concrete pavements.

Indrajit Patel et al. (2011), investigated the effect of polyester fibers on engineering properties of high volume flyash concrete. Polyester fiber of length 12mm and triangular-Trilobal cross-sectioned fibers were used as a supplementary reinforcing material. From the experimental investigation, it has been concluded that with the addition of polyester fiber significantly increased the strength properties and ductility at 28 and 56 days of curing time.

Slosarczyk A. et al. (2015) the research showed that polyester fibers, when added to concrete (2% of volume), improved its fracture resistance. However, the effectiveness of the fibres depended greatly on the strength class of the concrete. Much better co-operation of the fibres with the cement matrix was observed in the case of C 25/30 class concrete. The application of higher class concretes (C 35/45) results in decreased ability of the fiber to transfer loads after the cement matrix cracks. The addition of fibers seems to be positive in terms of the compressive strength. Depending on the concrete formula, for composites with polyester fibers, a 6 to 15% increase in compressive strength was observed, as well as a decrease in abrasibility by 20-50%.

U Bhavitha et al. (2016), studied the strength properties of polyester fiber reinforced concrete. Strength properties such as compressive strength, split tensile strength and flexure strength were obtained. Fiber dosages of 0.25, 0.5, 0.75 and 1% by weight of the cement were added to the plain concrete. The major conclusions of the study were strength properties of the concrete with significantly improved at an optimum fiber dosage of 0.75%.

2.3 Literature on hybrid fiber reinforced concrete (HFRC).

N. Banthia et al. (1995), Studied the stress-strain behaviour of micro-fibre reinforced composite with carbon (diameter: length, 0.018mm: 3mm), steel (0.025mm: 3mm), and polypropylene (0.004mm: 6mm) fibers under uniaxial tension. Major conclusions from the study are, cement matrix with steel fibers showed higher improvement in ultimate tensile strength compared to carbon and polypropylene (PP) fibers. Composite with carbon fibers provided better ductility than that of other fibers, on the other hand, PP fibers exhibiting better toughening at large crack openings. Hybridization of carbon and steel fibers provided a considerable increase in both pre-peak tensile strength and post-peak ductility compared to other combinations.

Wu Yao et al. (2002), investigated the mechanical properties of hybrid fiber reinforced concrete at low fiber volume fraction. The main objective of the investigation is to study the basic characteristics of three different hybrid combinations, i.e., steel – polypropylene, polypropylene – carbon and steel - carbon in terms of compressive strength, split tensile strength and flexural strength. It has been concluded that it is possible to develop a composite with enhanced mechanical properties through fiber hybridization, out of three hybrid combinations. HFRC with a combination of carbon – steel exhibited the best performance because of similar modulus, graded in length and synergetic interaction.

N Banthia et al. (2004), Investigated the fiber synergy in high strength matrices of 85 MPa concrete. The main objective of the investigation was to identify the synergy between different kinds of fibers. In order to achieve this, HFRC with a combination of two and three different kinds of fibers (macro and micro-fibers of steel, carbon, and polypropylene) was compared with the control mix. Based on the tests conducted on high-strength concrete it was concluded that there was no significant improvement in compressive strength observed with the addition of fibers, and it was identified that hybridization of steel macro-fiber with polypropylene, demonstrated some synergy. It has also been concluded that HFRC containing two-diner polypropylene fiber had shown maximum synergy compared to the three diner variant.

L.Vandewalle (2004), studied the post-cracking behaviour of hybrid steel fiber reinforced concrete. In this investigation two short steel fibers of 6 mm and 13 mm length with diameter 0.16 mm and one long hooked-end steel fiber of length 35 mm with 0.55 mm diameter were used. From the experimental results it is observed that, concrete reinforced with short fibers able to control the formation of cracks efficiently and then leads to a higher peak strength. Because they are in very fine size, more number present at the crack arresting and less spacing between them. However, concrete with large fibers restrains the propagation of large cracks, and it provides the ductility. It has been concluded that, combination of short and long steel fibers significantly enhanced the strength and ductility of concrete.

John S. Lawler et al. (2005), studied the Micro-fiber and Macro-fiber Hybrid Fiber-Reinforced Concrete. Combination of polyvinyl alcohol (PVA), micro-steel and macro-steel fibers used in this study. It has been concluded that percentage improvement in flexural strength is more with the addition of PVA fiber, the strength effectiveness of PVA fiber is more compared to steel macro fibers. It has also been concluded that hybridization of micro-fibers with macro-fibers significantly improved the tensile strength as well as toughness of the concrete.

Mustafa Sahmaran et al. (2005), Investigated the influence of different types of steel fiber on the fresh and mechanical properties of the hardened concrete. The hybridization of steel fibers in the concrete resulted increased workability and toughness when compared to the individual fiber addition in the concrete mix. In order to achieve maximum workability with

FRC, the quantity of cement paste in the mix must be increased to provide better fiber dispersion in the composite.

A Sivakumar et al. (2007), investigated the mechanical properties of high strength concrete reinforced with metallic and non-metallic fibers at a total fiber volume fraction of 0.5%. Here low fiber volume fraction was taken primarily from the viewpoint of good workability. In this investigation, three hybrid combinations were employed, i.e., steel – glass, steel – polyester and steel- polypropylene. Mechanical properties namely compressive strength, flexural strength and split tensile strength investigated. It has been concluded that among all hybrid combinations steel – polypropylene gave the better results in flexure compared to other combinations, and HFRC with more amount of non-metallic fiber content is less effective this is due to non-metallic does not enhance the concrete after the matric has been cracked, this is observed from loading and reloading of flexure specimens. HFRC with steel – glass combination shows the poor performance because of high stiffness and owing to its small length fiber are pulled out from the surface.

Benjamin A. Graybeal et al. (2007), conducted the experiments to investigate the stress-strain response of an ultra-high performance fiber-reinforced concrete (UPHFRC). Straight steel fibers of length 13mm at a fiber dosage of 2% used in this study. Uni-axial compression test was performed on cylinders (78mm diameter – 150mm length) and the results were analysed to compute the peak stress, young's modulus, strain at failure, and complete stress-strain response of UHPFRC. It was concluded that this concrete exhibited an exponential improvement in compressive strength and a significant increase in stiffness. Equations are established for pre-peak stress-strain behaviour of UHPFRC and post-peak stress-strain response and these equations are good agreement with the experimental results.

Machine et al. (2008), studied the mechanical properties of polypropylene hybrid fiber reinforced concrete. Two types of polypropylene fibers used i.e. coarse mono-filament and staple fiber at fiber dosage of 3, 6 and 9 kg/m^3. Mechanical properties namely compressive, splitting and flexural strength conducted in this investigation. From the experimental results it is observed that combination of coarse mono-filament and fine staple fiber enhanced the mechanical properties compared to mono-fiber reinforced concrete. Main observation from the study are combination of coarse and fine PP fiber enhanced the flexure toughness and also reduced the drying shrinkage strain cracks.

S.F.U. Ahmed et al. (2008), Studied tensile strain hardening and multiple cracking behaviours of fiber reinforced cementitious composites containing different hybrid combinations of steel (length:12mm and 18mm) and polyethylene (length: 12mm and 18mm) fibers. Polyethylene fibers are found to improve the tensile strain capacity of hybrid fiber composites whereas steel fibers contributed to the improvement of the ultimate tensile strength of hybrid fiber composites. By increasing the length of polyethylene fibers by 1.5 times, significant increase in tensile strain capacity as well as improvement in strain hardening and multiple cracking behaviour of hybrid fiber composites is observed.

Dong Joo Kim et al. (2011), investigated the comparative flexural behaviour of hybrid ultra high-herformance fiber reinforced concrete with different macro fibers. The main objective of this investigation is to study the effect of macro-fiber hybridization on flexure performance of ultra-high performance concrete. In this investigation four different kinds of macro-steel fibers and one kind of micro-fiber used (long smooth (LS), hooked-end (HB), and twisted (T) fiber). From the experimental results, it has been concluded that blending of high-strength steel macro fibers combined with micro-fibers produced a considerable increase in modulus of rupture and toughness compared to composite with the only micro-fibers. From the study it is observed that the order of performance regarding flexural strength, deflection capacity and toughness of hybrid ultra-high performance fiber reinforced concrete with a combination of 1% macro fibers with 1.5% micro-fiber are HB>T>LS fibers.

Shaikh Faiz Uddin Ahmed et al. (2011), reported the experimental results on the strain hardening and multiple cracking behaviour of two different types of PVA fiber reinforced cementitious composites under bending. The composite containing 2% thicker PVA fibers of 12 mm length together with 1% thinner PVA fibers of 6 mm length and the composite containing 2% thicker PVA fibers of 24 mm length together with 1% thinner PVA fibers of 6 mm length showed the best performance in terms of highest ultimate load, largest CMOD and multiple cracking behaviour. Strain hardening behaviour in light-weight hybrid PVA fibers reinforced cementitious composites is also achieved.

Seung Hun Park et al. (2012), investigated the tensile behaviour of ultra-high-performance hybrid fiber reinforced concrete was. Four types of macro-fiber with different lengths and geometry's and one type of micro-fiber are considered in this study. To develop an HFRC, 1% of macro-fiber kept constant and micro-fiber volume varied from 0.0% to 1.5%. The Main conclusions from the study are composite with more number of micro-fibers favourable for strain hardening and multiple cracking; it has also been observed that HFRC contains twisted fibers sown best performance regarding tensile strain hardening behaviour. From this investigation, the ranking performance of the HFRC at 1.5% of micro-fiber was T (Twisted) > HB (Hooked) > LS (Long smooth fibers).

T.A. Soylev et al. (2014), investigated the influence of polypropylene, glass and Steel fiber combinations in concrete at low fiber volume fractions. The mechanical properties of concrete under two different water-cement ratios (w/c=0.45, w/c=0.65) and two curing (air and moist curing) conditions were considered. From the experimental investigation it has been concluded that moist curing was found to be more effective in FRC. It has also been concluded that slight increase in flexural strength, split tensile strength was observed for both the w/c ratios whereas compressive strength slightly increased for w/c=0.65 and decreased for w/c=0.45. Moreover, SFRC has the lowest entrapped air content, and GFRC has the highest. The strength effectiveness of GFRC and control concrete are 72% and 46% for 0.45-w/c and 0.65-w/c respectively.

N. Banthia et al. (2014), studied the Fiber synergy in hybrid fiber reinforced concrete (HyFRC) in flexure and direct shear. In this research two types of steel fibers (hooked-end steel and double deformed steel fiber of 30mm length and 0.5mm diameter) and natural cellulose fiber used. From the experimental results, it has been concluded that in mono FRC, hooked-end steel fiber shown slightly better performance compared to double deformed steel fibers and concrete mixed with mono cellulose fiber did not import ay increase in toughness in either mode of loading. It has also been concluded that Composite with the combination of steel and cellulose fiber shown better performance compared to mono FRC.

Stamatina et al. (2017), investigated the hybrid fiber effect on mechanical properties of normal strength concrete. In which two types of fibers used, i.e., high strength steel fibers (13mm) and hooked-end macro fibers (30mm). Results were compared with hybrid specimens to mono-fiber reinforced concrete with the same fiber volume ratio. In this investigation, a novel configuration direct tension test was developed, which is more suitable for FRC and it is easy to construct and test. The investigation is mainly carried out focused on a study of the synergy effect at a material and structural level which in terms of failure mode, displacement and strength. It has been observed that there is no significant effect on compressive strength with the addition of fibers. And Confinement effect was observed in specimens reinforced with short fibers and these short fibers significantly affect the stress-strain curve. Test results shows that post-peak toughness enhanced with fiber hybridization. The major conclusion from the study was HFRC could arrest multi-cracks and enhances the fracture toughness compared to mono FRC.

Piotr Smarzewski et al. (2018), assessed the performance of hybrid fiber-reinforced ultra-high performance concrete. In this investigation high strength steel (length-50mm, aspect ratio-12mm) and polypropylene (length 12mm, diameter 25 micron) fibers were used. The main objective of the investigation is to study the effect of steel-polypropylene hybrid fibers on micro-structure and mechanical properties of the composite. The main conclusions of the study are, the addition of steel fiber increased the compressive strength at 1% volume fraction is only about 2.6% whereas the addition of PP fiber shown 55% decrease in compressive strength at 1% volume fraction because of the baling effect of fibers. It has also been observed that HFRC contains a high amount of steel fibers shown better flexural properties observed from the micro-structure studies.

2.4 Summary of the literature

Following observations are made from the detailed literature survey:

- Fracture in the concrete is a gradual and multi-scale process.
- Hybridization of fibers is an effective solution for concrete brittleness and early age shrinkage cracks
- Incorporation short and long length of hybrid fibers can enhance the concrete performance at different scale of cracking
- High aspect ratio fibers can apparently increase the fiber availability in the matrix and restricts the crack orientation at a point.
- Compared to straight fiber, hooked end steel fiber contribute to better interlocking.

Many researchers have developed HFRC using two different kind of fibers such as metallic and non-metallic fibers having low and high modulus. They often may not arrest the cracks at all stress levels developed in the concrete during its service.

To counter act the fracture process and to enhance overall performance of HFRC, fibers added should be in graded form in terms of length, diameter and tensile strength in view point to arrest the cracks at various stress levels developed in concrete. HFRC must be developed so as to have good strength characteristics, high ductility and high toughness.

CHAPTER 3

SCOPE AND OBJECTIVES OF THE INVESTIGATION

3.1 General

Concrete brittleness and resistance to crack growth are the major shortcomings of the concrete. Traditionally provided reinforcement bars can improve the ductility of concrete. But the improvement is limited to a particular extent only, and also resistance to crack growth formation throughout the concrete is problematic. Moreover, reinforcement shares a substantial part of the total cost of construction regarding material cost and labour cost. On the contrary, short random discrete fibers bridge the cracks throughout the concrete, but the concrete remains as a brittle material because the fracture in concrete is a gradual and multi-scale process. To obtain an optimal response therefore, different types of fibers varying in aspect ratio, Young's modules and tensile strength must be rationally combined, which forms a hybrid fiber reinforced concrete.

In chapter 2, to avoid the problem associated with the concrete brittleness and ductility of concrete. An extensive literature review of literature is made on shortcomings of concrete; fiber reinforced concrete and hybrid fiber reinforced concrete.

3.2 Scope of the investigation

After going throw the through literature it is understood that the following issues are to be addressed:

- There is a need to develop HFRC which can counteract the fracture process in concrete at all stress levels.

- There is a need to develop HFRC which enhances the properties of concrete at all ages.
- The synergy between metallic-non-metallic hybridization is need to be studied further.
- The synergy effect of triangularly shaped cross-section fibers need to be addressed where most of the researchers used circular cross-section fibers.
- Thus, the study aims to develop and assess the influence of metallic and non-metallic fiber on strength and constitutive stress-strain behaviour of hybrid fiber reinforced concrete. The hybrid fiber effect on low (30 MPa), Medium (50 MPa) and high strength concrete (70 MPa) are to be investigated.

3.3 Research significance

The aim of the investigation is to develop hybrid fiber reinforced concrete and to assess the benefits obtained by the fiber hybridization on strength and constitutive stress-strain behaviour. In this investigation concrete is reinforced with a combination of steel, polyester, and polypropylene fibers, these fibers are graded in length, diameter and tensile strength. Inspiration is obtained from particle packing theory where different sizes of aggregate are combined to develop well-graded aggregates. Similar to this various types of fibers with different sizes are combined to arrest multi-scale cracks developed at various stress-levels in concrete. In addition, slab like structures where plastic-shrinkage cracks and micro-cracks are dominant due to wear and tear caused by moving vehicles. Therefore, an effective crack control system is necessary to prevent them. To address these issues combination of polyester and polypropylene Non-metallic HFRC is developed initially and obtained optimum hybrid combinations are systematically added to steel fibers to develop metallic and non-metallic HFRC. The developed HFRC can counter act the fracture process of concrete and also enhances the tensile properties and energy absorption capacity of the composite.

3.4 Objectives of the research work

Keeping above issues in mind, the objectives of the present investigation are;

- To study the mechanical behaviour of mono polyester, polypropylene and steel fiber reinforced concrete.
- To develop and study the mechanical properties of Non-metallic HFRC using polyester and polypropylene fibers compared to mono-fiber composites.
- To develop and study the mechanical properties of HFRC using metallic and non-metallic fibers.
- To study the constitutive stress-strain behaviour of HFRC under uni-axial stresses.
- To model the HFRC using ATENA software in order to avoid the comprehensive experimentation.

From the scope and objectives of the research of work, the entire experimental programme is divided into 4 phases as follows.

Phase 1 – Mechanical behaviour of mono FRC

To develop a perfect HFRC it is necessary to study the effect of mono-fiber on behaviour of concrete. Because not every combination gives a positive synergy, In fact for some mixtures synergy may be seen under particular loading conditions only (Banthia et al. 2014). The objective of the investigation in phase - I is to study the mechanical behaviour of mono steel, polyester and polypropylene fiber reinforced concrete. For this compressive strength, direct tensile strength, flexural strength are determined and the stress-strain behaviour of mono FRC under uni-axial stresses (tension and compression) is also studied. Results obtained from the phase 1 gave an idea about mono-fiber behaviour in concrete and paved the way for developing the HFRC in the further investigation.

Phase 2 – Mechanical behavior of non-metallic HFRC (Polyester and polypropylene HFRC)

The second phase of the investigation is to develop and study the mechanical behaviour of non-metallic HFRC. The non-metallic HFRC aims to counteract the plastic shrinkage cracks forming at early stages of concrete and also to bridge the micro-cracks forming at low-stress levels of harden concrete, using polyester and polypropylene hybridization. Even though Young's modulus of both polyester and polypropylene fibers are nearer, due to the variation in tensile strength and aspect ratios of the fibers, non-metallic HFRC can enhance the tensile strength of concrete without compromising the plastic shrinkage cracks. The positive synergy between the non-metallic fibers drives further develop metallic and non-metallic HFRC.

Phase 3 – Mechanical behaviour of metallic – non-metallic HFRC

The third phase of the investigation is to develop and study the metallic – non-metallic HFRC which can counteract the fracture process of concrete and achieve the overall performance of concrete. From the phase 2 experimental results, it is observed that non-metallic HFRC is increased the tensile strength of the concrete but the toughness at post crack region is marginal. To increase the toughness at post crack region, steel fibers are added to the composite to form metallic – non-metallic HFRC. Compressive strength, direct tensile strength, flexural strength and stress-strain behaviour under uni-axial stresses are studied. Results from the phase 4 delivered satisfactory results.

Phase – 4

The fourth phase of the investigation consist of modelling of HFRC using ATENA software. Small prism of size 200 x 100 x 100 mm is modelled in ATEN to get the stress-strain curve analytically. The results obtained from the ATENA model are compared with the experimental values. The results shown good agreement with the experimental values within 15% variation. Later with the inputs from 200 x 100 x 100 model, flexure specimen of 500 x 100 x 100 model has been generated and analysed in ATENA. Results obtained from the flexure model are validated with experimental results. Experimental results and values obtained by the ATENA model is within 10% variation.

CHAPTER 4

MATERIAL USED AND EXPERMENTAL METHODS

4.1 General

This chapter presents the details of various materials and experimental methods used in this study. Since the main objective of the investigation is to study the effect of fiber hybridization on different grades of concrete. Details of concrete mix proportions, properties of various fibers used, experimental methods and types of the sample prepared are discussed in this chapter**.**

4.2 Materials used

4.2.1 *Cement*

Ordinary Portland cement (OPC) of 53 grade confirming to IS 12269 (BIS, 2013) used. Properties of Cement: Specific Gravity - 3.11, Standard Consistency - 33%. Initial setting time 43 min and final setting time 123 min respectively.

4.2.2 *Mineral Admixture*

Class F Flyash conforming to IS 3812-Part 1 (BIS, 2003) was used as a mineral admixture which was obtained from Ramagundam thermal power station. Silica fume conforming to IS 15388 (BIS, 2003) was used in the production of high-strength (70 MPa) concrete.

4.2.3 *Fine Aggregate*

Locally available River sand conforming to IS 383 (BIS, 2016) was used, the specific gravity and fineness modulus of fine aggregate are 2.68 and 2.64 respectively.

4.2.4 *Coarse Aggregate*

Well graded crushed granite conforming to IS 383 (BIS, 2016), Specific gravity and fineness moduli are 2.78 and 7.1 respectively.

4.2.5 ***Super-plasticizer***

Conplast SP430 of FOSROC chemicals was used in all mixes as per IS 9103 (R 2004) (BIS, 2004) to obtain the desired workability.

4.2.6 ***Fibers***

Non-metallic fibers of polypropylene (PP), polyester (PO) and metallic fibers of hooked-end steel fibers (HS) were used. Properties of the fibers are shown in table 4.1. Fibers used in the study are shown in figure 4.1.

Polypropylene fiber **Polyester fiber** **Hooked-End steek fiber**

Figure 4.1 Fibers used in the study

Table 4.1 Properties of the fibers used in the study

Property	Hooked-end Steel fiber	Polyester	Polypropylene
Fiber code	HS	PO	PP
Length (mm)	25	12	6
Diameter (mm)	0.4	0.045	0.035
Aspect ratio	62.5	266	170
Specific gravity	78.4	1.34	0.91
Elastic modulus (GPa)	210	9.5	4.5
Tensile strength (MPa)	1100	875	560
Fiber geometry	Hooked-end	Straight	Straight
Fiber cross-section	Circular	Triangular	Triangular

4.3 Mixture proportions

An experimental programme was designed to achieve the low, medium and high strength concrete with a target compressive strength of 30 MPa, 50 MPa and 70 MPa concrete respectively. The final optimized mix proportions are arrived based on several trails. Mix proportions of all grades of concrete are presented in table 4.2

Table 4.2 Mix proportions of 30, 50 and 70MPa concrete per cubic meter

Grade of concrete	Cement (kg/m^3)	Fly ash (kg/m^3)	Silica Fume (kg/m^3)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)	Water (kg/m^3)	Super plasticizer ml/kg
30 MPa	283	100	-	650	1180	180	5
50 MPa	400	100	-	700	1000	196	10
70 MPa	500	110	40	650	945	201	15

4.4 Casting of specimens

Firstly, fine aggregate and coarse aggregate were mixed in a pan mixture of 100kg capacity and dry mixed for 1 minute. Then, cement and mineral admixtures were mixed separately until a uniform coloured binding material was obtained and then it was transferred into the pan mixer and mixed for 1 minute, then potable water was slowly added and mixed for 2minutes. After which fibers were added and all the ingredients are mixed for 3 minutes. Super-plasticizer was added to get required workability according to IS 456:2000 (BIS-2000). Figure 4.2 represents the mix preparation, casting and curing. Details of the standard specimens were cast to determent the mechanical preparation of HFRC and are presented in table 4.3. Table vibrator was used for compacting the concrete in moulds. After twenty-eight days of curing the specimens, strengths of specimens were obtained from the average of three similar specimens.

Fig 2a Dry mix of the concrete

Fig 2b Wet mix of the concrete

Fig 2c Casting of specimens

Fig 2d Curing of concrete specimens

Figure 4.2. HFRC While mixing, casting and curing

Table 4.3 Details of the specimen cast

Strength Property	Specimen	Dimensions
Compressive strength	Cube	150 x 150 x 150 mm
Flexural Strength	Prism	500 x 100 x 100 mm
Uni-axial compression stress-strain curve	Small prism	200 x 100 x 100 mm
Uni-axial tension stress-strain curve	Dog-bone (I Section)	Dimensions are shown in Fig. 4.3

4.5 Experimental methods

4.5.1 *Compressive strength*

To get the compressive strength, standard cubes of size 150x150x150mm were cast. After 28 days of curing, specimens were removed and allowed them to dry. The specimens were placed in compression testing machine in such a manner that load is applied on the faces orthogonal to the direction of casting the cubes. The compressive strength of concrete is obtained as per IS 516: 1959 (BIS, 1959), Tinius-Olsen of 3000 kN capacity was used to measure the compressive strength at a loading rate of 14 N/mm^2/min as shown in figure 4.3 and the tested specimen are shown fig 4.4.

Figure 4.3 Testing of concrete cube under compression

Figure 4.4 Specimens tested under direct compression

4.5.2 *Flexural strength of concrete*

Flexural strength of concrete was measured by testing the specimen under four-point flexure test according to IS 516: 1959 (BIS, 1969) is shown in figure 4.5 and the tested specimens are shown in figure 4.6. Flexural specimens are tested in universal testing machine of 1000 kN capacity, specimens are placed in the machine in such a manner that the load shell be applied to the uppermost surface as cast in the mould along two lines spaced at 13.3 cm apart. The maximum load applied on the specimen was recorded and flexural strength of the specimen was calculated using following equation.

$$F_f = \frac{PL}{bd^2} \text{ …….. Eq (4.1)}$$

Where F_f *is* the flexural strength of the specimen

P = maximum load applied on the specimen

L=Effective length of the specimen

b and d are the breadth and depth of the specimen

Figure 4.5 Flexure strength test

Figure 4.6 Specimens tested under flexural loading

4.5.3 *Uni-axial tensile strength test.*

4.5.3.1 Configuration of direct tension specimen

To find the tensile strength of concrete, splitting tensile test and flexure test are used in the traditional methods. These methods are easy to construct and test. These methods are well established in guidelines that these are the indirect method to measure the tensile performance of concrete in the absence of better and more reliable methods. These traditional methods works well for regular concrete but for fiber reinforced concrete specimens there is a need for direct and reliable test because of uncertainties associated with the performance of FRC in tension (naaman et al. 2006). To address these issues direct tensile strength test was performed. The uniaxial tensile test was performed on dog-bone shaped specimens as shown in figure 4.7 and 4.8. The sample has a shoulder at each end and a gauge section in between. Dog bone sample is designed to ensure the highest probability that the sample will fail in the middle of the gauge section. Nuts and double ring arrangement of test setup ensures to avoid eccentricity Steel plates and steel grips to hold the specimen which enables the self-alignment of specimen under load. Uniaxial tensile test was performed with a servo hydraulic testing machine of capacity 50kN under displacement control (0.01 mm/s) as shown in figure 4.9 and the specimen after the testing is shown in figure 4.10. Data acquisition system is used to record the load and corresponding displacement continuously. Tensile strength of specimens was calculated from the average of three test specimen results.

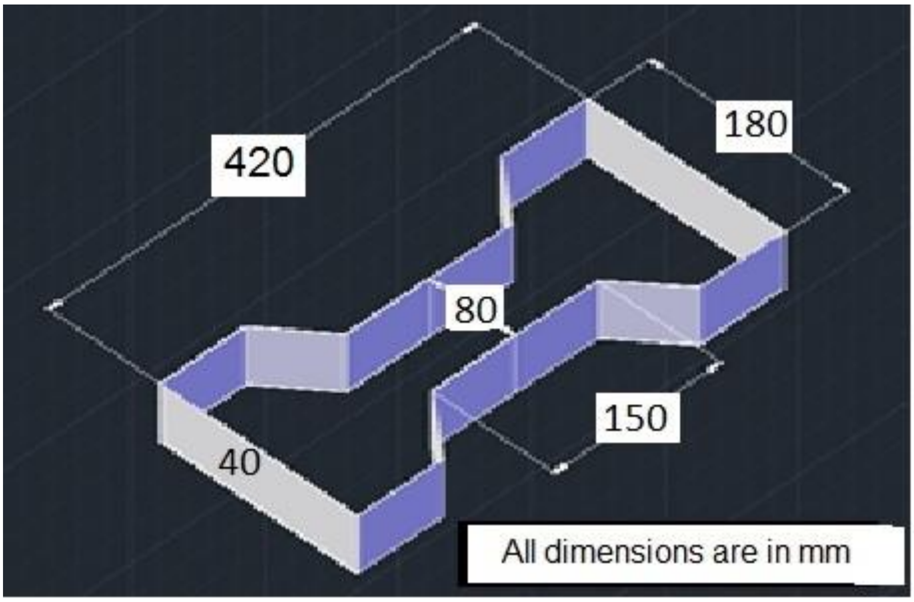


Figure 4.7 Geometry of dog-bone specimen

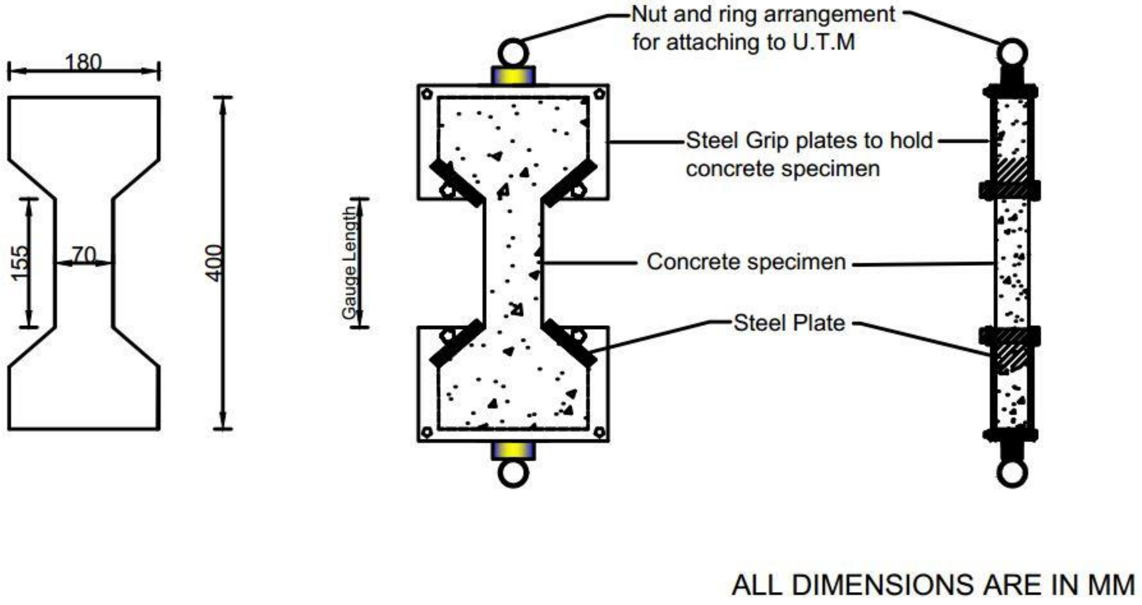


Figure 4.8 Direct tensile test specimen and grip details

Figure 4.9 Direct tensile strength test

Figure 4.10 Specimens tested under direct tension loading

4.5.4 *Uniaxial compression test*

To get the stress-strain values the concrete specimens of size 200 x 100 x 100mm were used. Prisms were fitted with two LVDTs (linearly varying displacement transducers) and the loading is applied on Tinus-Olsen Testing Machine of 2000 kN capacity as shown in figure 4.11. Uniaxial deformations were measured using LVDTs which are placed at the opposite corners to obtain the displacement and the corresponding load applied were measured using load cell. Both LVDTs and load cell were connected to the data acquisition system (DAC). The axis of the specimen was carefully aligned at the centre of the loading frame. The load is applied gradually on the specimens and deformations are recorded till failure of the specimen as shown in figure 4.13. Average of three specimen's results considered to obtain stress-strain values.

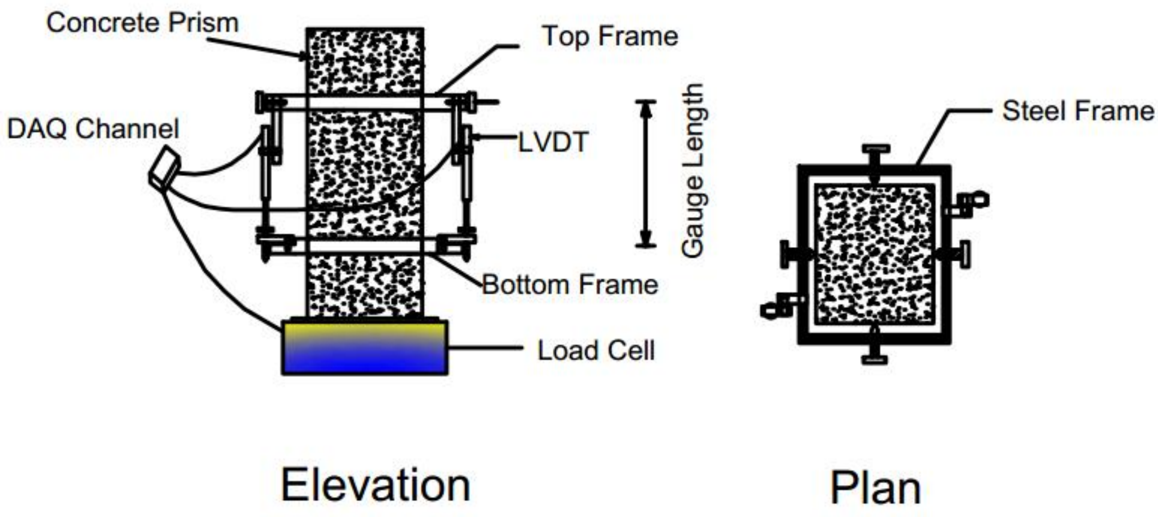


Figure 4.11 Schematic diagram of uni-axial compression test

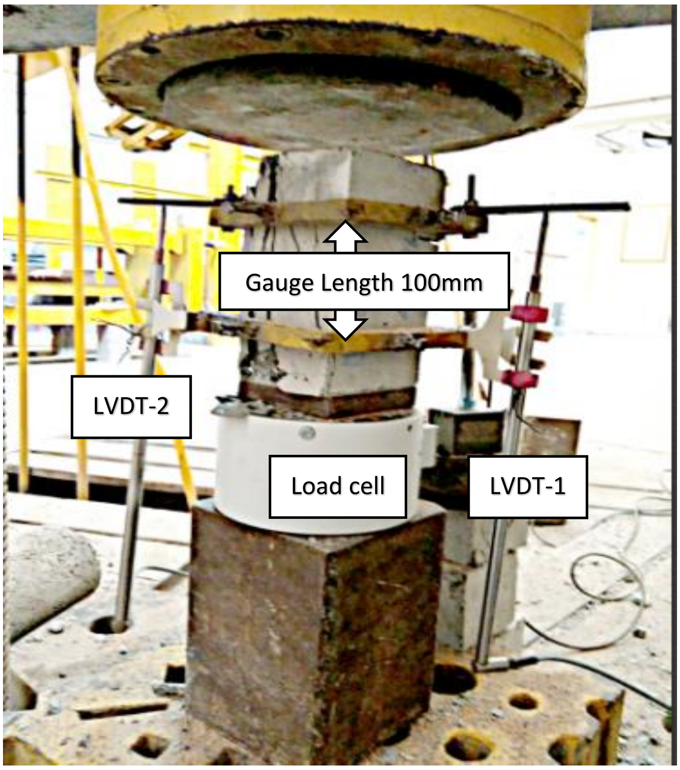


Figure 4.12 Testing of prism under uniaxial compression

Figure 4.13 Tested specimens of concrete under uni-axial compression

4.6 Concluding remarks

This chapter covered the materials used and mix proportions adopted for the HFRC preparation. And also includes types of fibers used its properties, sample preparation, and methods used to test the concrete were presented.

CHAPTER 5

PHASE – I: MECHANICAL PROPERTIES OF MONO-FIBER REINFORCED CONCRETE

5.1 General

This chapter presents the experimental results of mechanical properties of mono-FRC and the results are compared with the control concrete mix (non-fibrous concrete). The investigation aims to identify the effect of mono-fiber on different grades of concrete. The fiber dosages of non-metallic fibers (Polyester and Polypropylene) varied from 0.0, 0.05, 0.1, 0.15% and 0.2% and the fiber dosage of metallic fiber (Hooked-end Steel) varied from 0.0, 0.5, 0.75, 1.0, and 1.25%. The section also discusses relative advantages of metallic and non-metallic fibers. To investigate the basic mechanical properties, three tests have been conducted, i.e. compressive strength, flexure strength and direct tensile strength test. Stress-strain behaviour of concrete under uniaxial compression and uniaxial tension conducted and the experimental results were compared with the control mix. The details of the experimentation methods discussed earlier in chapter 4.

The nomenclature of the mix Id’s and percentage of the fibers investigated for mono-FRC are presented in Table 5.1

Table 5.1 Nomenclature and fiber dosages of mono-FRC

Mix ID	Fiber dosage (%)		
	Hooked-end steel (HS)	**Polyester (PO)**	**Polypropylene (PP)**
HS 0.5	0.5		
HS 0.75	0.75		
HS 1	1		
HS 1.25	1.25		
PO 0.05		0.05	
PO 0.1		0.1	
PO 0.15		0.15	
PO 0.2		0.2	
PP 0.05			0.05
PP 0.1			0.1
PP 0.15			0.15
PP 0.2			0.2
***Nomenclature** HS 0.5 - HS represents the type of fiber and the 0.5 represents the fiber dosage in terms of volume fraction of concrete			

5.2 Results and discussions

5.2.1 *Compressive Strength*

The Compressive strength of mono-FRC and its strength-effectiveness was compared with the control mix. The results are presented in Table 5.2. It is understood that there is no significant improvement in compressive strength was observed with the addition of non-metallic mono-fibers in concrete. Similar kind of outcomes were observed by *Francesco et al. (2008) and G.M. Sadiqul et al. (2016).* However, a marginal improvement in compressive strength observed with the addition of steel fibers compared to non-metallic fibers. There is more percentage strength improvement in HS-FRC at a fiber volume fraction of 1% for low-strength concrete (30 MPa) is 7.9%, for medium-strength concrete (50 MPa) improvement is 5.6% and for high-strength concrete (70 MPa) it is 2.1%. It is also observed that there is a decrease in strength observed with increase in grade of concrete, it is understood that, in high-strength concretes the compressive crack passes throw the aggregate rather than matrix indicates that reinforcing effect is not fully utilized.

Table 5.2 Compressive strength of mono-FRC

Mix ID	30 MPa		50 MPa		70 MPa	
	f_{ck} (MPa)	Percentage increase (%)	f_{ck} (MPa)	Percentage increase (%)	f_{ck} (MPa)	Percentage increase (%)
CM	36.2	-	58.0	-	75.9	-
PP 0.05	36.4	0.6%	58.2	0.5%	76.3	0.5%
PP 0.1	36.7	1.4%	58.9	1.5%	77.1	1.5%
PP 0.15	**37.1**	**2.4%**	**59.2**	**2.1%**	**77.2**	**1.7%**
PP 0.2	36.6	1.2%	58.6	1.1%	76.7	1.0%
PO 0.05	36.5	0.7%	58.2	0.5%	76.4	0.6%
PO 0.1	36.7	1.3%	58.7	1.3%	76.7	1.1%
PO 0.15	**37.1**	**2.4%**	**59.1**	**2.0%**	**77.4**	**2.0%**
PO 0.2	36.8	1.7%	58.8	1.5%	76.5	0.8%
HS 0.5	37.6	3.9%	60.0	3.5%	78.3	3.2%
HS 0.75	38.0	5.0%	60.8	4.8%	78.6	3.6%
HS 1	**39.1**	**7.9%**	**61.2**	**5.6%**	**77.5**	**2.1%**
HS 1.25	37.0	2.1%	58.7	1.2%	76.7	1.1%

*** f_{ck} – Compressive strength**

5.2.3 *Direct tensile strength*

Unlike the concrete in compression, strength-effectiveness of fiber is more in tensile strength and flexure strength of the concrete. Results for the direct tensile strength and percentage strength improvement compared to control mix are presented in Table 5.3.

Table 5.3 Direct tensile strength of mono-FRC

Mix ID	30 MPa		50 MPa		70 MPa	
	f_{dt} (MPa)	Percentage increase (%)	f_{dt} (MPa)	Percentage increase (%)	f_{dt} (MPa)	Percentage increase (%)
CM	3.18	-	4.63	-	5.06	-
PP 0.05	3.30	3.6%	4.87	5.3%	5.29	4.6%
PP 0.1	3.33	4.6%	4.93	6.6%	5.44	7.6%
PP 0.15	**3.45**	**8.6%**	**5.11**	**10.3%**	**5.70**	**12.6%**
PP 0.2	3.40	7.0%	5.01	8.2%	5.58	10.2%
PO 0.05	3.39	6.7%	4.89	5.7%	5.44	7.5%
PO 0.1	3.46	8.7%	5.12	10.7%	5.69	12.5%
PO 0.15	**3.64**	**14.5%**	**5.24**	**13.2%**	**5.89**	**16.3%**
PO 0.2	3.48	9.3%	5.15	11.3%	5.69	12.5%
HS 0.5	3.49	9.6%	5.21	12.6%	5.79	14.5%
HS 0.75	3.63	14.2%	5.35	15.5%	5.95	17.7%
HS 1	**3.76**	**18.3%**	**5.49**	**18.6%**	**6.15**	**21.5%**
HS 1.25	3.49	9.6%	5.15	11.2%	5.82	15.0%

* **f_{dt} – Direct tensile strength**

Percentage strength improvement of PP-FRC and PO-FRC is maximum at 0.15% fiber dosage, whereas percentage strength improvement of HS-FRC is maximum at 1% fiber dosage. There is a decrease in strength observed with the more fiber dosage, this may be due to cement-matrix is replaced by more number of fibers and also due to poor workability. From the Table 5.3 it is observed that strength-effectiveness of metallic fibers is more compared to non-metallic fibers may be due to metallic fibers are longer in length and having high Young's modulus compared to non-metallic fibers. Strength improvement in PP-FRC at an optimum dosage of 0.15% is 8.6% for 30 MPa, 10.3% for 50 MPa and 12.6% for 70 MPa concrete. Percentage strength improvement in PO-FRC is 12.5% for 30 MPa, 13.2%for 50 MPa and

16.3% for 70 MPa. It is observed that strength effectiveness PO-FRC is more compared to PP-FRC because of PO fibers are stiffer than PP fibers. It is also observed that strength effectiveness of metallic fibers is more compared to non-metallic fibers because of hooked-end steel fibers are stiffer and longer in length, but the fiber dosage is more compared to non-metallic fibers. Strength improvement in HS-FRC at an optimum dosage of 1% is 18.3% for 30 MPa, 18.6% for 50 MPa and for 21.5% for 70 MPa concrete.

5.2.4 *Flexure Strength*

Flexural strength of mono-FRC and control mix are presented in Table 5.4. It is observed that flexural strength of mono-FRC is more compared to direct tensile strength it may be due to formation of crack under flexural load starts at well below the neutral axis at low stress levels, further increase in load leads to propagation of cracks above the neutral axis. Whereas direct tensile strength crack is well defined. i.e., single crack is formed perpendicular to the loading direction. Strength effectiveness of PP-FRC is 12.7% for 30 MPa, 13.7% is for 50 MPa and 16.6% is for 70 MPa concrete at an optimum dosage of 0.15% volume fraction. Percent increase in flexural strength of PO-FRC is 15.4% for 30 MPa, 17.4% is for 50 MPa and 18.7% is for 70 MPa concrete at 0.15% volume fraction. Here in flexural strength similar trend observed like direct tensile strength i.e. strength improvement for PO-FRC is more compared to PP-FRC reasons have been discussed earlier in direct tensile strength (section 5.2.3). Strength effectiveness HS-FRC at an optimum dosage of 1% is 20.3% for 30 MPa, 21.6% for 50 MPa and 23.5% for 70 MPa grade of concrete. Strength increase in metallic fiber is more due to higher stiffness and anchorage mechanism because of hooks at end of steel fiber.

Table 5.4 Flexural strength and strength effectiveness of mono-FRC

Mix ID	30 MPa		50 MPa		70 MPa	
	f_{ft} (MPa)	**Percentage increase (%)**	**f_{ft} (MPa)**	**Percentage increase (%)**	**f_{ft} (MPa)**	**Percentage increase (%)**
CM	4.10	-	5.42	-	6.02	-
PP 0.05	4.29	4.6%	5.78	6.6%	6.48	7.6%
PP 0.1	4.49	9.4%	6.09	12.4%	6.82	13.3%
PP 0.15	**4.62**	**12.7%**	**6.17**	**13.7%**	**7.02**	**16.6%**
PP 0.2	4.32	5.4%	5.93	9.4%	6.64	10.4%
PO 0.05	4.39	7.0%	6.02	11.0%	6.77	12.4%
PO 0.1	4.57	11.4%	6.15	13.4%	6.95	15.4%
PO 0.15	**4.73**	**15.4%**	**6.36**	**17.4%**	**7.14**	**18.7%**
PO 0.2	4.44	8.4%	5.96	10.0%	6.62	10.0%
HS 0.5	4.60	12.3%	6.25	15.2%	7.08	17.5%
HS 0.75	4.74	15.6%	6.37	17.5%	7.26	20.6%
HS 1	**4.93**	**20.3%**	**6.59**	**21.6%**	**7.44**	**23.5%**
HS 1.25	4.57	11.5%	6.14	13.2%	6.94	15.2%

*** f_{ft} – Flexural Strength**

5.2.5 *Effectiveness of fiber on different grades of concrete*

Strength effectiveness of PP-FRC, PO-FRC and HS-FRC on different grades of concrete are graphically presented in Figure 5.1 to 5.3 respectively. In all three grades of concrete for non-metallic FRC there no significant variation in compressive strength observed. It is also noticed from experimental results, as the grade of the concrete increases there is decrease in compressive strength observed this may be due to failure mode in high strength concrete through the aggregate rather than matrix, therefore reinforcement effect of fibers is not fully utilized. But strength effectiveness of fiber in direct tensile strength and flexural strength is increased with the increase in cementatious material in concrete, this is because as the cementatious material increases fiber distribution is more even and also chances of balling effect is minimum (Quin et al. 2004). Similar kind of observation was found by Thomas and Ananth Ramaswamy (2007).

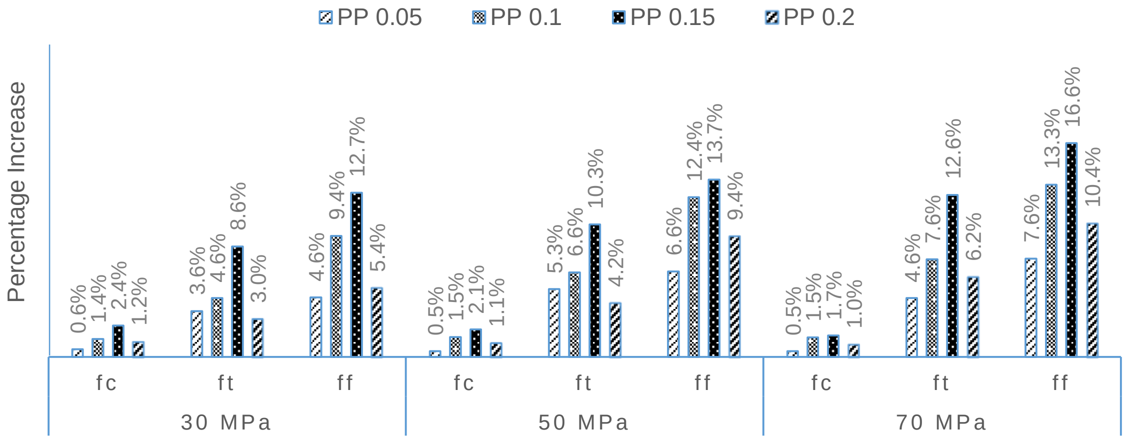


Figure 5.1 Strength-effectiveness of PP-FRC

Note: Graph drawn between percentage improvement on y-axis and grade of the concrete on x-axis which is reference line.

(*FC – Compressive strength, FT– Direct tensile strength, FF – Flexural strength)

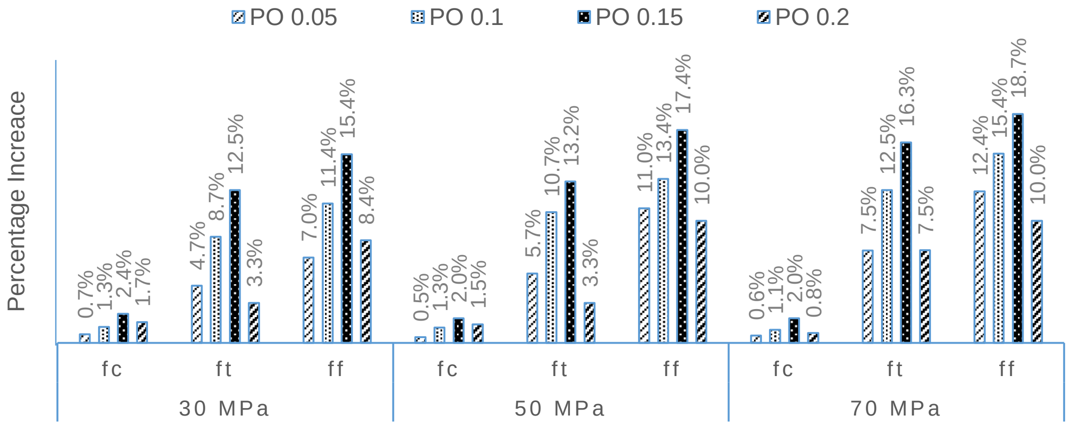


Figure 5.2 Strength-effectiveness of PO-FRC

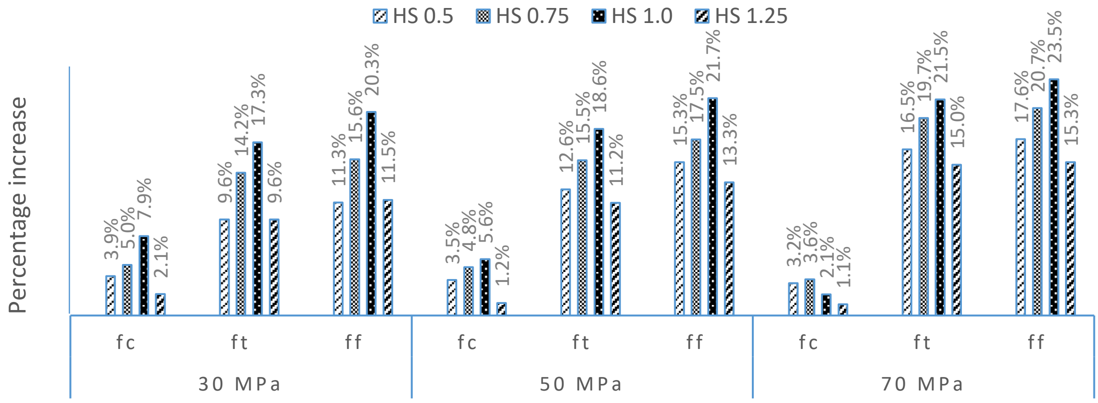


Figure 5.3 Strength-effectiveness of HS-FRC

5.2.6 *Stress-strain behaviour of mono-FRC under uniaxial compression*

Typical properties of the stress-strain curve of FRC is shown in Figure 5.4. The values of stresses and strains of the concrete specimens were calculated from the uni-axial compression test and stress-strain curves have been plotted. Stress-strain curves of concrete reinforced with PP, PO and HS fibres for three grades of concrete are presented in Figures. 5.5 to 5.7 and summary of the results are presented in Table 5.5 to 5.6 respectively.

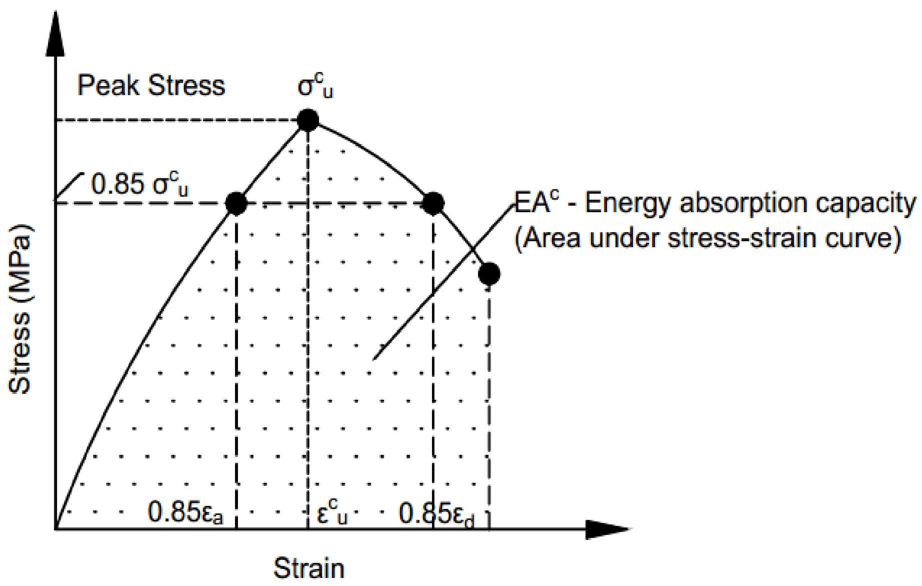


Figure 5.4 typical stress-strain plot for FRC

5.2.6.1 Strength parameters from stress-strain curve of the concrete

The stress-strain plots for mono-FRC at different fiber volume fractions as shown in Figures 5.5 to 5.7. Various strength parameters obtained as follows

Peak strength (σ^c_u): The maximum stress that can take the concrete without causing plastic deformations

Strain at peak-stress (ε^c_u): Strain at peak stress is an indication of deformation at maximum stress that can be developed in a material without causing plastic deformation.

Young's modulus of concrete (E_s): Slope of the linear portion of the ascending branch of stress - strain curve.

Ductility Factor (D_f): It is the ratio of strain at 0.85 % peak stress of descending portion of stress-strain curve ($0.85\varepsilon_a$) to the strain at 0.85 % peak stress of ascending branch of stress-strain curve ($0.85\varepsilon_b$).

Energy absorption capacity (EA^c): It is the area under the stress-strain curve.

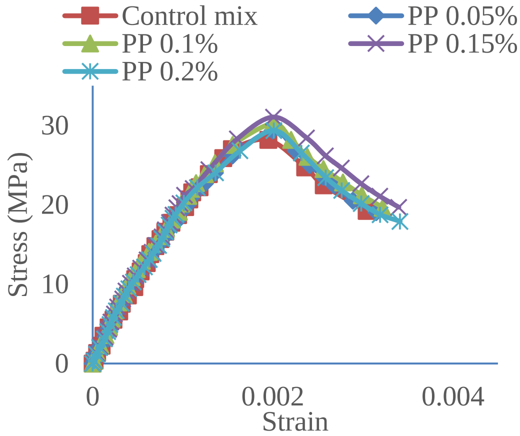


Fig 5.5a Stress-strain curve for PP-FRC

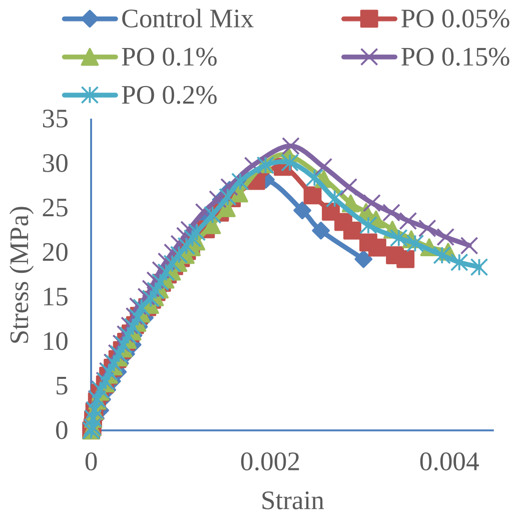


Fig 5.5b Stress-strain curve for PO-FRC

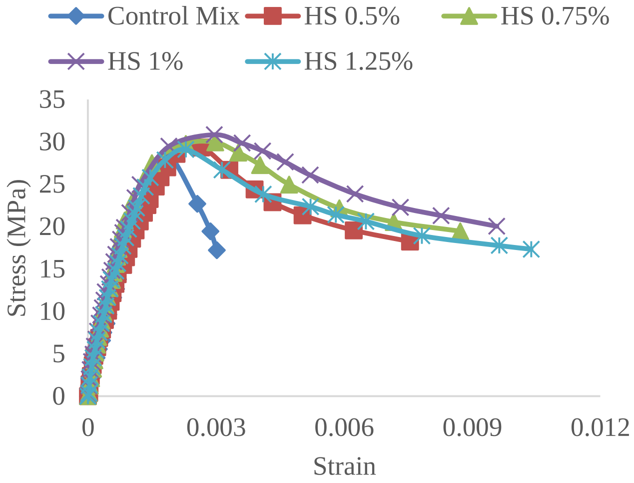


Fig 5.5c Stress-strain curve for HS-FRC

Figure 5.5 Stress-strain curve of mono-FRC for 30 MPa concrete under uni-axial compression

Table 5.5 Summary of results for 30 MPa concrete under uni-axial compression

Mix ID (1)	**σ^c_u (MPa) (2)**	**% Increase (3)**	**ε^c_u x 10^{-2} (4)**	**E_s x10^3 (MPa) (5)**	**D_f (6)**	**EA^c (7)**	**T_f (8)**
CM	28.19	-	19.5	25.26	2.24	0.0734	1
PP 0.05	29.36	4.2	20.04	25.32	2.26	0.0789	1.08
PP 0.1	30.24	7.3	20.01	25.55	2.29	0.0817	1.11
PP 0.15	**31.07**	**10.2**	**20.12**	**25.86**	**2.35**	**0.0887**	**1.21**
PP 0.2	29.39	4.3	20.17	25.92	2.33	0.0834	1.14
PO 0.05	29.61	5.0	21.42	25.03	2.31	0.0851	1.16
PO 0.1	30.91	9.7	22.06	25.00	2.42	0.0980	1.34
PO 0.15	**31.96**	**13.4**	**22.32**	**25.91**	**2.63**	**0.1034**	**1.41**
PO 0.2	30.10	6.8	22.29	25.07	2.55	0.0988	1.35
HS 0.5	29.34	4.1	26.57	25.09	3.10	0.1424	1.94
HS 0.75	29.94	6.2	29.31	25.90	3.42	0.1594	2.17
HS 1	**30.87**	**9.5**	**29.54**	**25.99**	**3.50**	**0.1808**	**2.47**
HS 1.25	29.11	3.3	29.91	24.19	3.52	0.1714	2.34

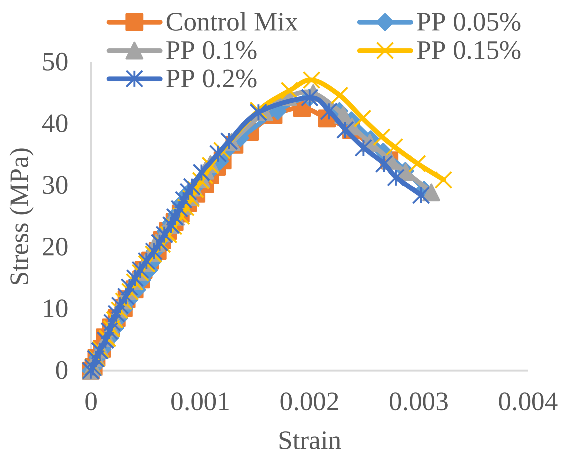


Fig 5.6a Stress-strain curve for PP-FRC

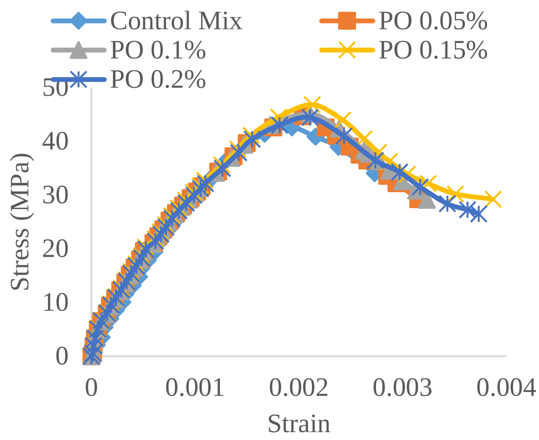


Fig 5.6b Stress-strain curve for PO-FRC

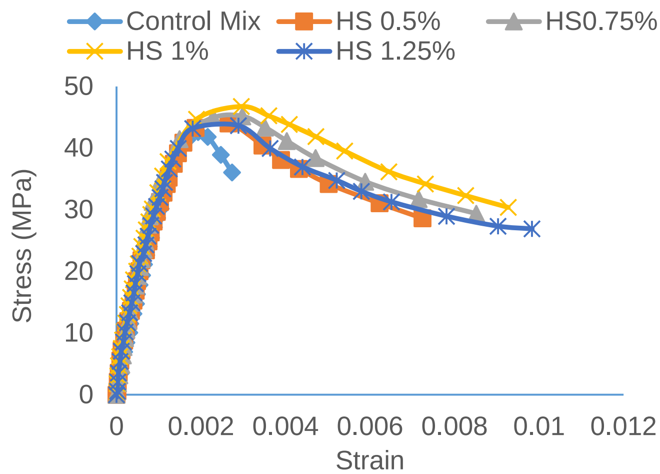


Fig 5.6c Stress-strain curve for HS-FRC

Figure 5.6 stress-strain curve for mono-FRC for 50 MPa concrete under uni-axial compression

Table 5.6 Summary of results for 50 MPa concrete under uni-axial compression

Mix ID (1)	**σ^c_u (MPa) (2)**	**% Increase (3)**	**ε^c_u x 10^{-2} (4)**	**E_s x10^3 (MPa) (5)**	**D_f (6)**	**EA^c (7)**	**T_f (8)**
CM	42.59	-	19.3	33.83	2.21	0.0979	1
PP 0.05	44.22	3.8	19.5	33.41	2.24	0.1171	1.20
PP 0.1	44.99	5.6	20.4	34.08	2.26	0.1198	1.22
PP 0.15	**47.08**	**10.6**	**20.2**	**33.92**	**2.30**	**0.1298**	**1.33**
PP 0.2	44.22	3.8	20.0	33.47	2.28	0.1142	1.17

PO 0.05	44.67	4.9	20.4	34.44	2.29	0.1193	1.22
PO 0.1	45.12	5.9	21.0	32.86	2.35	0.1239	1.26
PO 0.15	**46.80**	**9.7**	**21.3**	**33.69**	**2.52**	**0.1421**	**1.45**
PO 0.2	44.39	4.2	21.1	33.85	2.37	0.1333	1.36
HS 0.5	44.03	3.4	26.5	36.62	2.35	0.2064	2.11
HS 0.75	45.18	6.1	29.8	37.89	2.90	0.2403	2.45
HS 1	**46.76**	**9.8**	**29.5**	**38.97**	**3.32**	**0.2709**	**2.77**
HS 1.25	43.64	2.5	29.9	39.98	3.30	0.2513	2.57

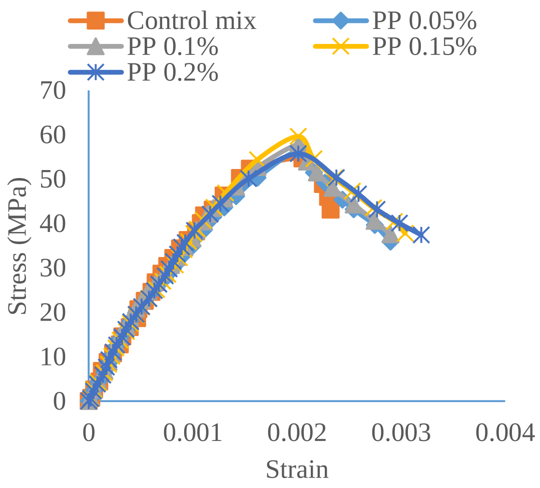


Fig 5.7a Stress-strain curve for PP-FRC

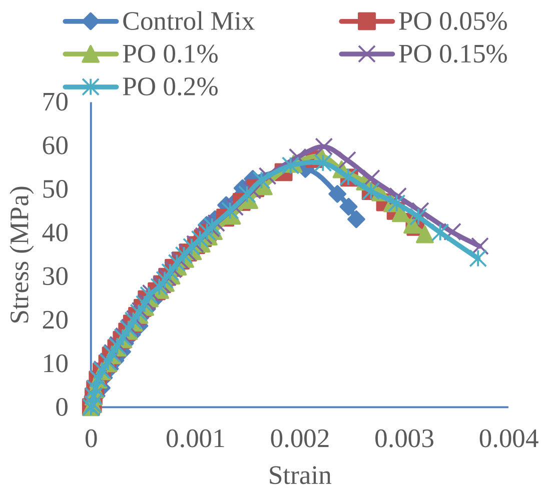


Fig 5.7b Stress-strain curve for PO-FRC

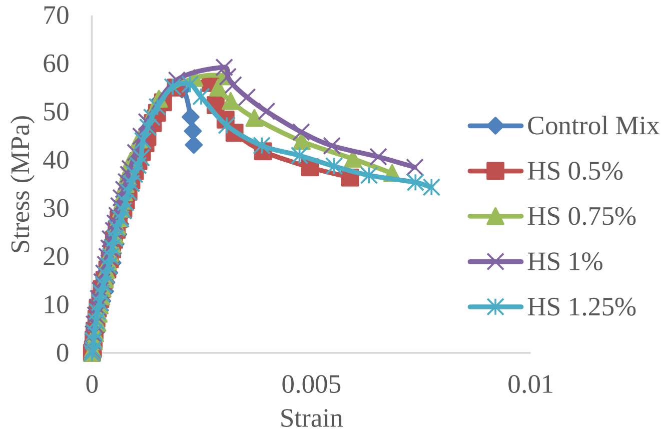


Fig 5.7c Stress-strain curve for HS-FRC

Figure 5.7 stress-strain curve for mono-FRC for 70 MPa concrete under uni-axial compression

Table 5.7 Summary of results for 70 MPa concrete under uni-axial compression

Mix ID (1)	σ^c_u (MPa) (2)	% Increase (3)	ε^c_u x 10^{-2} (4)	E_s x10^3 (MPa) (5)	D_f (6)	EA^c (7)	T_f (8)
CM	54.65	-	20.5	45.21	2.01	0.1153	1
PP 0.05	56.37	3.1	20.1	45.99	2.13	0.1473	1.28
PP 0.1	57.84	5.8	20.2	46.08	2.21	0.1486	1.29
PP 0.15	**59.63**	**9.1**	**20.1**	**46.12**	**2.24**	**0.1606**	**1.39**
PP 0.2	55.73	2.0	20.1	46.01	2.22	0.1500	1.30
PO 0.05	56.94	4.2	21.4	46.22	2.24	0.1504	1.30
PO 0.1	57.63	5.5	22.0	46.64	2.26	0.1598	1.39
PO 0.15	**59.81**	**9.4**	**22.3**	**46.80**	**2.31**	**0.1857**	**1.61**
PO 0.2	56.01	2.5	21.3	46.81	2.41	0.1706	1.48
HS 0.5	54.86	2.4	30.8	46.57	2.61	0.2181	1.89
HS 0.75	57.94	5.0	30.0	47.16	3.12	0.2550	2.21
HS 1	**59.82**	**8.4**	**30.8**	**47.40**	**3.20**	**0.2786**	**2.42**
HS 1.25	56.91	2.0	30.8	46.54	3.19	0.2591	2.25
σ^c_u – Peak Stress, ε^c_u – Strain at peak stress, E_s – Young's modulus, D_f – Ductility factor ($0.85\varepsilon_a/0.85\varepsilon_d$), EA^c – Energy absorption capacity of concrete in compression, T_f – Toughness Factor (EA^c FRC/EA^c C), Superscript "c" represents the values in compression							

5.2.6.2 Stress-strain behaviour of FRC

The behaviour of stress-strain curves of FRC is similar to conventional concrete, linear in the initial portion up to 90% of the corresponding ultimate strength followed by non-linear up to the failure of the specimen. From the Figures 5.5 to 5.7 it is observed that fibes in concrete significantly affecting the pre-peak and post-peak behaviour of concrete. The increment of peak strength is noticed with the addition of fibres both for non-metallic fibers and metallic fibers up to optimum dosages. The percentage Increment in peak-strength with the addition of fibers is understood that fibres bridge the micro-cracks and delays the crack propagation. Percentage increase of peak-strength compared to control mix, at an optimum dosage of 0.15%

for PP-FRC is 11.2% for 30 MPa, 10.6% for 50 MPa and 9.1% for 70 MPa concrete. It is also observed that as the grade of the concrete increase there is decrement in peak-strength observed from column 3 of Table 5.5 to 5.7, this may be due to crack progress through aggregate rather than matrix so reinforcement effect is not fully utilised. Similarly percentage strength improvement for PO FRC at optimum dosage of 0.15% is 13.4% for 30 MPa, 9.7% for 50 MPa and 9.2% for 70 MPa concrete. Strength-effectiveness of PO-FRC is more compared to PP-FRC because, stiffness of the PO fiber is little higher compared to PP fibers and also owing to its longer length delays the formation of micro-cracks and also arrest the propagation of macro-cracks. Percentage increase in pre-peak strength with addition of metallic-fiber at an optimum dosage of 1% is 9.2% for 30 MPa, 9.8% for 50 MPa and 8.4% for 70 MPa. Strength-effectiveness of metallic fiber in uniaxial compression observed less compared to non-metallic fibers, this may be regarded as that steel fibers are having very high stiffness also owing to its long-length and lower aspect-ratio, availability of the fiber throughout the concrete is less. Therefore steel fiber are more effective in the concrete mix once the matrix has been cracked. Whereas, non-metallic fibers have lower modulus and smaller in length owing to its high aspect-ratio numerous fibers are available throughout the concrete which control the formation of micro-cracks (A. Siva Kumar et al 2007).

From the Table 5.5 to 5.6 (column-4), it is understood that strain at peak-stress increased with the addition of fiber. It is understood that fibers are participating in delaying the crack formation and bridging the cracks. Strain at peak-stress increased with the increase in fiber content, but the increment is seen marginal for non-metallic fibers. There is a consistent increment in peak-strain noticed i.e., 36.2% to 53.3% with the addition of 0.5% - 1.25% fiber dosage. Irrespective of fibre dosages and length of the fibres, strain at the peak-stress is in between 0.002 to 0.003 for all FRC mixes.

Fiber effect on concrete clearly indicated by the stress-stain curves of FRC. From the Figure 5.5 to 5.7 it is observed that, there is a definite improvement in load carrying capacity at post-peak with the addition of fibers. Toughness is calculated by area under stress-strain curve which is a measure of ductility. Table 5.5 to 5.7 (column-7) presented the toughness values of FRC mixes. Toughness of PP-FRC at an optimum dosage of 0.15% is 0.0887 MPa for 30 MPa, 0.1298 MPa for 50 MPa and 0.1662 for 70 MPa grade of concrete, average increment in toughness of all three grades compared to control mix is around 32%. Toughness of PO-FRC at an optimum dosage of 0.15% is 0.1034 MPa for 30 MPa, 0.1421 MPa for 50 MPa and 0.1706 for 70 MPa grade of concrete, the average increment in toughness of all grades compared to control mix is 40%. But in non-metallic FRC there is no significant improvement observed after the matrix has been cracked (post-peak toughness) because these fibers cannot withstand the loads at higher stress levels hence they will undergo fracture or pull-out from the surface. Whereas in metallic-fibers significant improvement observed at post-crack region compared to non-metallic fibers. Toughness of HS-FRC at an optimum dosage of 1% is 0.1808 for 30 MPa, 0.2709 for 50 MPa and 0.2786 for 70 MPa grade of concrete, the increment in toughness for all three grades of concrete is 168% which is much higher than non-metallic fibers because of area under stress-strain curve at post-peak is higher, which means steel fibers can effectively arrest the propagation of macro-cracks thereby load-bearing capacity after the peak-stress has been increased.

5.2.6.3 Fiber effect on different grades on concrete

Figure 5.8 presents the stress-strain curves of optimum dosages of mono-FRC for 30, 50 and 70 MPa grades of concrete. Ductility factor and Young's modulus of all three grades of concrete with respect to optimum fiber dosages are presented in Figure 5.9 and 5.10 respectively.

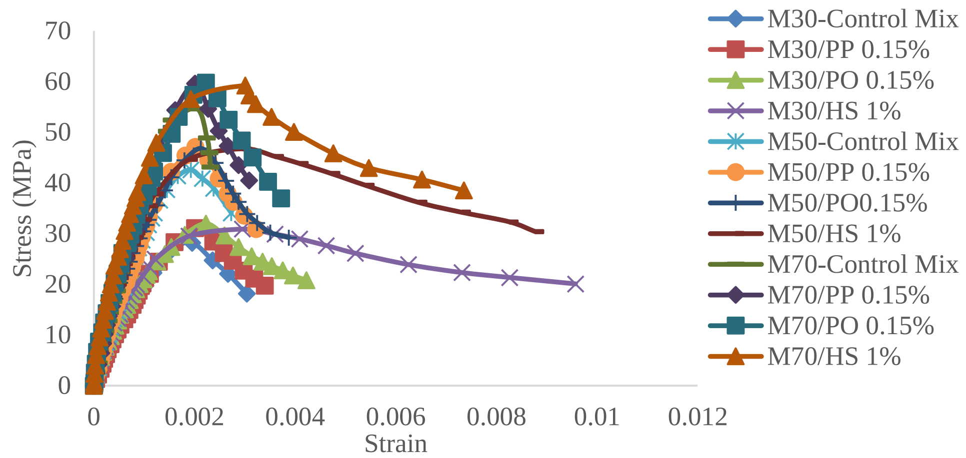


Figure 5.8 Stress-strain curves of mono-FRC for 30, 50 and 70 MPa concretes

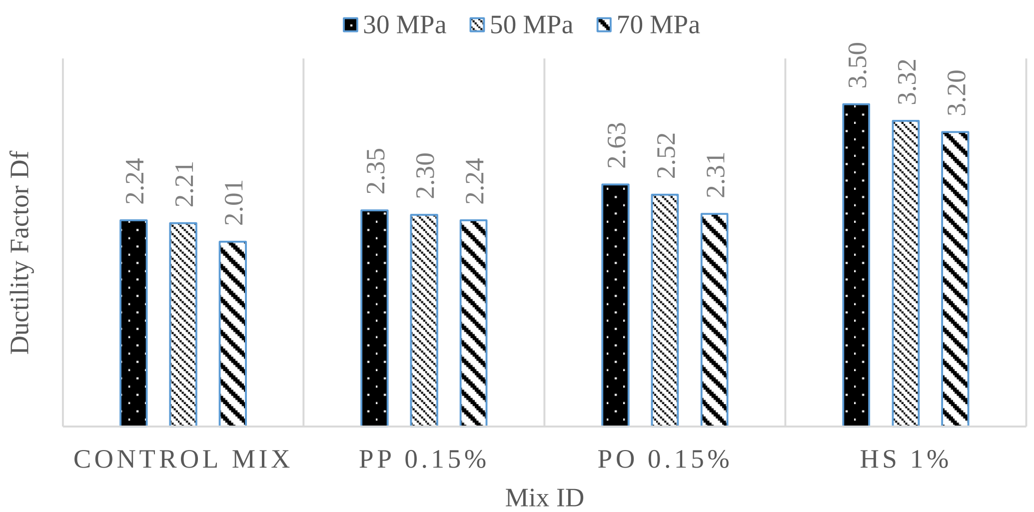


Figure 5.9 Ductility Factor v_s fiber volume fraction

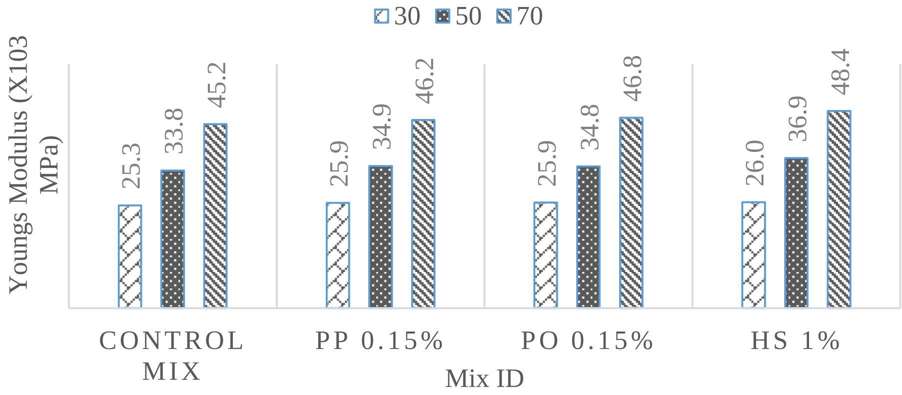


Figure 5.10 Young's modulus's Vs Fiber volume Fraction

Ductility factor is a mesure of concrete ductility. From the Figure 5.9 it is observed that addition of fibers to the concrete increasing the ductility even at higher grades of concrete. It is noticed from the Figure 5.9 ductility factor of the concrete reduced with the increase in the grade of the concrete may be due to concrete becomes brittle at higher grade of concrete. Concrete becomes more ductile with the addition of metallic fiber compared to non-metallic fibers. There is an increase in Young's modulus of composite observed with the addition of fiber noticed from Table 5.5 to 5.7. Young's modulus of metallic fiber shown a greater response compared to non-metallic fibers as shown in Figure 5.10.

5.2.7 *Stress-strain response of concrete under uniaxial tension*

The uniaxial tension test has been performed on dog-bone shaped specimen. Details of the experimentation and configuration of test specimen explained in chapter 4.5.3. Typical stress-strain plot for concrete under uni-axial tension and its strength properties are presented in Figure 5.11. Stress-strain cures of concrete under uni-axial tension of all FRC mixes for three grades of concrete (30 MPa, 50 MPa and 70 MPa) are presented in Figure 5.12 to 5.13 and corresponding summary of the results are presented in Table 5.8 to 5.10 respectively.

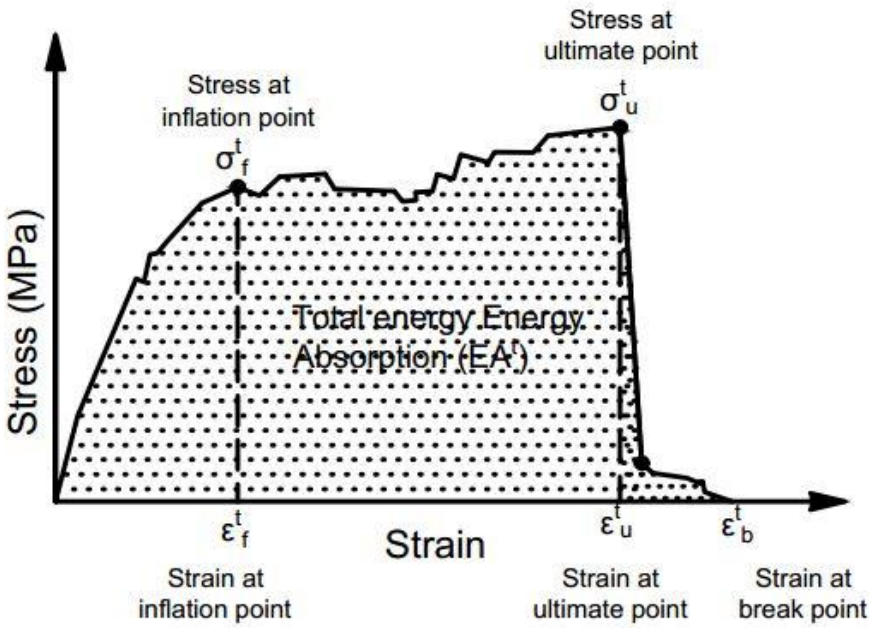


Figure 5.11 Typical stress-strain plot for FRC under uni-axial tension

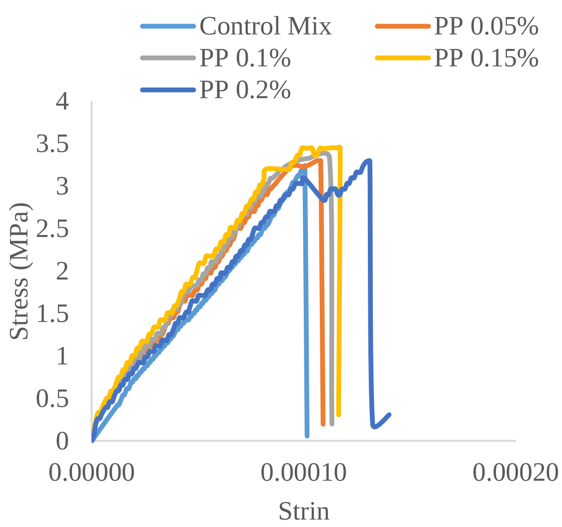


Fig 5.12a Stress-strain curve for PP FRC

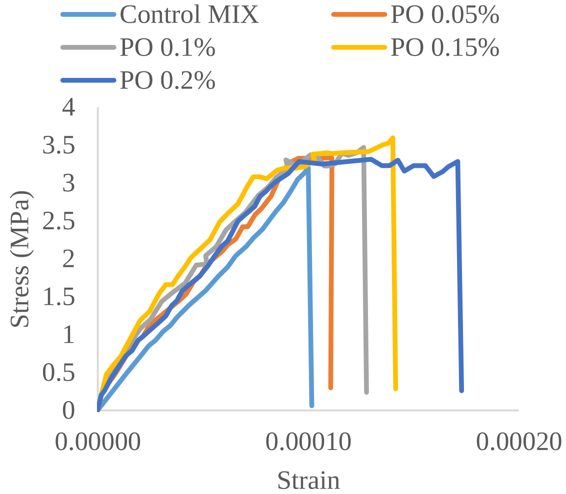


Fig 5.12b Stress-strain curve for PO FRC

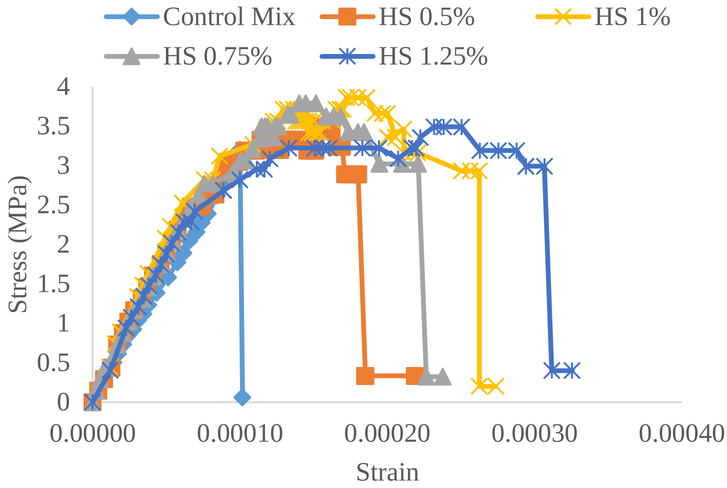


Fig 5.12c Stress-strain curves for HS FRC

Figure 5.12 Stress-strain curve for mono-FRC for 30 MPa concrete under uni-axial tension

Table 5.8 Summary of results for 30 MPa concrete under uni-axial tension

Mix ID (1)	**σ^t_f (MPa) (2)**	**ε^t_f x 10^{-5} (3)**	**σ^t_u (MPa) (4)**	**ε^t_b x 10^{-5} (5)**	**EA^t x 10^{-5} (MPa) (6)**
Control Mix	3.20	10.0	3.20	10.2	48.15
PP 0.05	3.23	10.08	3.30	10.9	50.26
PP 0.1	3.23	10.11	3.33	11.9	54.44
PP 0.15	**3.38**	**10.25**	**3.45**	**12.3**	**59.46**
PP 0.2	3.03	10.32	3.28	13.8	66.09
PO 0.05	3.26	9.0	3.33	11.1	50.26
PO 0.1	3.30	9.93	3.46	12.8	63.07
PO 0.15	**3.31**	**9.84**	**3.58**	**14.2**	**65.01**
PO 0.2	3.28	9.55	3.29	17.3	80.26
HS 0.5	3.19	12.72	3.49	21.9	86.35
HS 0.75	3.21	10.83	3.79	23.8	102.75
HS 1	**3.27**	**10.88**	**3.86**	**27.4**	**128.40**
HS 1.25	3.09	12.04	3.49	32.6	127.57

σ^t_f – Stress at inflation point, ε^t_f – Strain at inflation point, σ^t_u – Stress at ultimate point, ε^t_b – Strain at break point, EA^t – Energy absorption capacity, where superscript "t" values in tension.

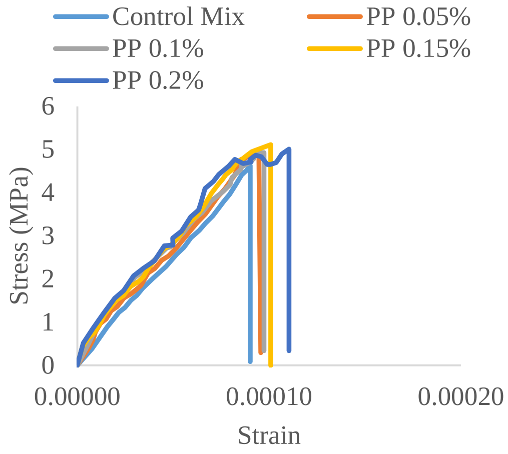


Figure 5.13a Stress-strain curve for PP FRC

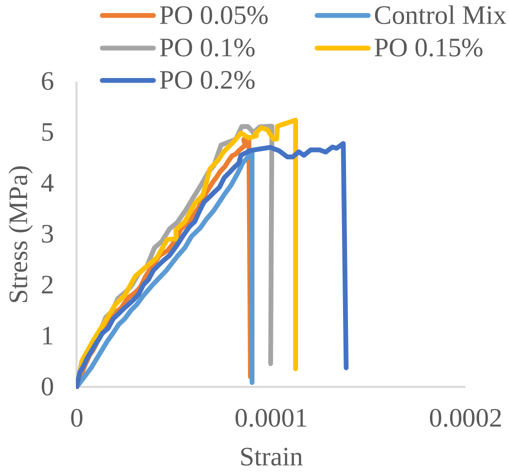


Figure 5.13b Stress-strain curve for PO FRC

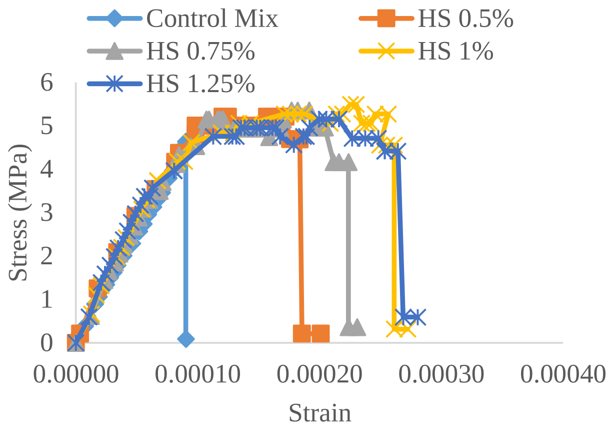


Figure 5.13c Stress-strain curves for HS FRC

Fig 5.13 Stress-strain curve for mono-FRC for 50 MPa concrete under uni-axial tension

Table 5.9 Summary of results for 50 MPa concrete under uni-axial tension

Mix ID (1)	**σ^t_f (MPa) (2)**	**ε^t_f x 10^{-5} (3)**	**σ^t_u (MPa) (4)**	**ε^t_b x 10^{-5} (5)**	**EA^t x 10^{-5} (MPa) (6)**
Control Mix	4.63	9.02	4.63	9.02	63.0
PP 0.05	4.70	9.03	4.87	9.60	67.0
PP 0.1	4.78	9.15	4.93	9.7	67.9
PP 0.15	**4.83**	**9.23**	**5.11**	**10.1**	**74.0**
PP 0.2	4.65	10.8	5.01	11.0	78.1
PO 0.05	4.74	9.08	4.89	10.1	63.0
PO 0.1	4.86	8.99	5.12	10.0	71.0
PO 0.15	**4.93**	**9.26**	**5.24**	**11.3**	**85.2**
PO 0.2	4.64	8.95	5.15	13.9	92.8

HS 0.5	4.79	9.81	5.21	20.1	125.8
HS 0.75	5.12	10.71	5.35	23.1	155.4
HS 1	**5.27**	**11.25**	**5.49**	**25.9**	**181.6**
HS 1.25	4.95	12.17	5.15	28.1	169.4
σ^t_f – Stress at inflation point, ε^t_f – Strain at inflation point, σ^t_u – Stress at ultimate point, ε^t_b – Strain at break point, EA^t – Energy absorption capacity, where superscript "t" values in tension.					

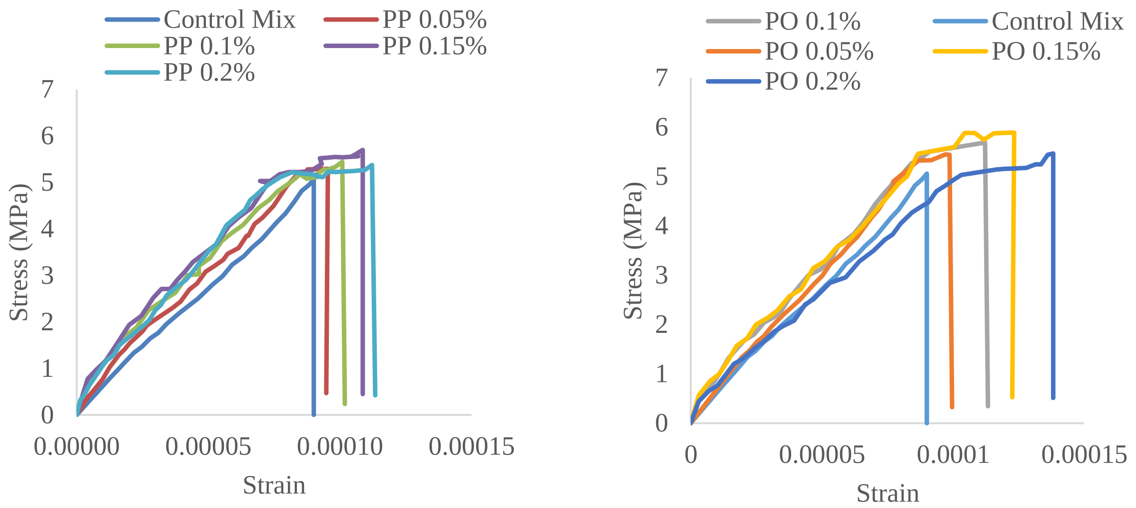


Fig 5.14a Stress-strain curve for PP FRC

Fig 5.14b Stress-strain curve for PO FRC

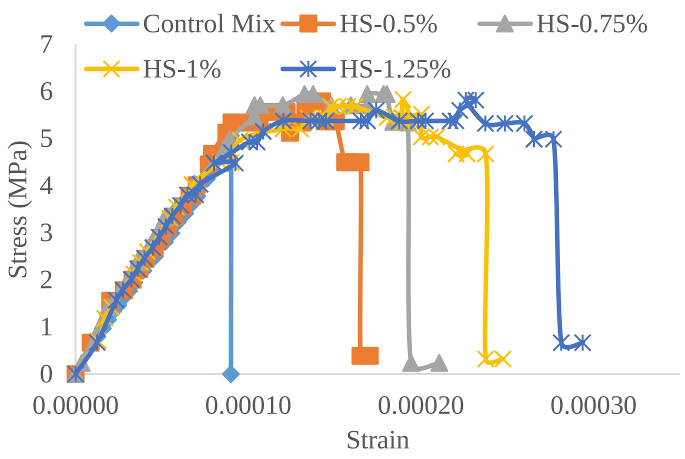


Fig 5.14c Stress-strain curves for HS FRC

Figure 5.14 Stress-strain curve for mono-FRC for 70 MPa grade of concrete under uni-axial tension

Table 5.10 Summary of results for 70 MPa concrete under uni-axial tension

Mix ID (1)	σ^t_f (MPa) (2)	ε^t_f x 10^{-5} (3)	σ^t_u (MPa) (4)	ε^t_b x 10^{-5} (5)	EA^t x 10^{-5} (MPa) (6)
Control Mix	5.05	9.0	5.06	9.0	68.6
PP 0.05	5.18	9.20	5.29	9.5	70.4
PP 0.1	5.28	9.42	5.44	10.2	79.3
PP 0.15	**5.39**	**9.45**	**5.70**	**10.9**	**82.9**
PP 0.2	5.13	8.75	5.37	11.3	83.6
PO 0.05	5.32	9.02	5.44	10.0	79.1
PO 0.1	5.38	9.12	5.69	11.3	87.0
PO 0.15	**5.46**	**9.26**	**5.89**	**12.3**	**99.1**
PO 0.2	5.39	10.3	5.44	13.8	106.0
HS 0.5	5.12	9.15	5.9	17.0	131.1
HS 0.75	5.46	10.35	6.05	21.1	149.7
HS 1	**5.45**	**10.42**	**6.15**	**24.8**	**178.8**
HS 1.25	5.14	10.87	5.82	29.4	194.8

σ^t_f – Stress at inflation point, ε^t_f – Strain at inflation point, σ^t_u – Stress at ultimate point, ε^t_b – Strain at break point, EA^t – Energy absorption capacity, where superscript "t" values in tension.

From the Figures 5.12 to 5.14 it is observed that for the control mix (without fibers) the stress of the concrete increased with the increase in strain linearly right up to the ultimate-stress and failed suddenly. The ultimate strain for the plain concrete for the all three grades of concrete is in the range of 0.00009 - 0.0001. It is understood that the ultimate strain of the concrete under tension reduced with the increase in the grade of concrete. Values of the ultimate strain of mono-FRC and control mix are presented in Table 5.8 to 5.10 (column 6). Specimens with PP fibers shown similar kind of behaviour, stresses increased with the increase in strain linearly with a marginal improvement in ultimate stress and failed suddenly. The maximum percentage increase in ultimate-stress observed at an optimum dosage of 0.15% i.e. 8.6% for 30 MPa concrete, 10.3% for 50MPa concrete and 12.6% for 70MPa concrete. From the Tables

5.8 – 5.10 it is noticed that with the addition of PP fibers, there is no significant improvement in failure strain observed and behaves almost like a plane concrete. Energy absorption (EA^t) is a mesure of concrete ductility. Energy absorption capacity of the concrete is obtained from area under stress-strain curve. The percentage increase in energy absorption capacity (Toughness) for PP-FRC is maximum at an optimum dosage of 0.15% fiber dosage, values are reported in Table 5.8 to 5.10 (Column 6).

The behaviour of the stress strain curve for the PO-FRC is almost similar for PP-FRC and plain concrete right up to the point of inflation (Figure 5.11) i.e. Stress of the concrete increased with the increase in strain linearly right up to the inflation point and curve becoming non-linear and exhibited strain hardening behaviour up to the failure of the specimen. The inflation stress for PO-FRC are presented in Table 5.8 to 5.10 (Column – 3). The ultimate stress for PO-FRC is 14.5% for 30 MPa concrete, 13.2% for 50 MPa concrete and 16.3% for 70 MPa concrete. The average percentage improvement in energy absorption capacity for PO FRC at an optimum fiber dosage of 0.15% is 42%.

Stress-strain curves for HS-FRC under uniaxial tension are shown in Figure 5.12c to 5.14c. The behaviour of the stress-strain curve is similar to the plane concrete up to the inflation point, after that curve exhibiting strain hardening behaviour right up to the failure of the specimen. The percentage improvement in ultimate stress of HS-FRC for 30 MPa concrete is 18.2%, for 50 MPa concrete is 18.6% and for 70 MPa concrete is 21.6%. The stress at inflation point for HS-FRC is on par with the plane concrete ultimate stress with a marginal improvement, from this it is understood that fibers in concrete delaying the crack formation and increases the tensile strength. Strain at inflation point is also nearer to the plane concrete varied from 10.42×10^{-5} to 10.88×10^{-5} for the all three grades of concrete. There is exponential increase in failure strain observed with the addition of metallic fibers compared to non-metallic

PP and PO fibers. However the first cracking strength of HS-FRC remained same as tensile strength of plain concrete, but the ductility of the HS FRC larger than that of plain concrete. Strain hardening occurred from 0.015mm to 0.045mm there after that a sudden failure occurred. The average increase in toughness compared to control mix for HS-FRC is 186% at an optimum dosage of 1%

5.3 Concluding remarks from PHASE I

In this chapter mechanical behaviour of mono fiber reinforced concrete using polyester, polypropylene and steel have been studied and the results were compared with control mix. The potential difference between the mechanical behaviour of metallic fiber and non-metallic fiber compared to control mix also discussed. Following conclusions are drawn in this phase of experimental investigation.

- Optimum dosage of PP and PO fibers achieved at 0.15% volume fraction. Optimum dosage of hooked end steel fiber achieved at 1% in mono-FRC. Thereafter there is decrease in strength characteristics observed due to more number of fibers replaced the cement matrix.
- Strength-effectiveness of metallic fiber is more pronounced compared to the non-metallic fibers at higher dosages.
- Improvement of compressive strength is not significant with the addition of non-metallic fibers, due to presents of numerous fibers leads to improper compaction and unnecessary voids. Whereas strength improvement in compression for metallic fiber is also marginal. But enhancement in direct tensile strength and flexural strength is observed more, this may be due to fibers in concrete controls the formation of crack growth.
- Fiber effect in pre-peak region of stress-strain curve is more significant in addition of non-metallic fibers, whereas metallic fibers improved the load carrying capacity at post-crack

region this is due to the stiffness of steel fibers control crack growth even after the crack formation.

- Behaviour of stress-strain curve of PO-FRC and HS-FRC under direct tension is similar up to inflection point and exhibiting strain hardening behaviour their after right up to failure of specimens.

CHAPTER 6

PHASE II – MECHANICAL BEHAVIOUR OF NON-METALLIC HYBRID FIBER REINFORCED CONCRETE (HFRC)

6.1 General

In previous chapter mechanical behaviour of mono-FRC has been discussed. The potential difference between metallic fibers and non-metallic fibers and their effect on mechanical properties were investigated. In this chapter the combined effect of polypropylene (PP) and polyester (PO) fibers on strength properties were investigated. Even though stiffness of the fibers nearly same, the gradation of fibers which means varied in length significantly improve the overall performance of concrete concluded by many authors (Hanuma et al. 2017 and Ahmed et al. 2011). Moreover fibers which are graded with respect to tensile strength and having triangular cross-section, their effect on strength properties need to be studied. Keeping this in mind, three hybrid combinations considered in that is 75% of PP combined with 25% of PO (75% PP + 25%PO), 50% of PP combined with 50% of P0 (50% PP + 50% PO) and 25% of PP combined with 75% of PO (25% PP + 75% PO) at a total fiber volume fractions varied from 0.1%, 0.15%, 0.2% and 0.25%. The main objective of this investigation is to find the optimum hybrid fiber combination which have positive impact on strength characteristics. This non-metallic HFRC can be used in structures where the use of steel fibers restricted because of corrosion problems and conductivity issues like runways of airport, high speed railway systems etc.

6.2 Experimental programme

Compressive strength, direct tensile strength, flexural strength and stress-strain behaviour of concrete under uni-axial stress are investigated in this chapter. Fiber combinations and nomenclature of mix labels are presented in Table 6.1

Table 6.1 Nomenclature and fiber dosages of non-metallic FRC

Mix ID	**Total fiber dosage (%)**	**Polyester (%)**	**Polypropylene (%)**
NM 0.1 (1)	0.1	0.075 (75%)	0.025 (25%)
NM 0.1 (2)		0.05 (50%)	0.05 (50%)
NM 0.1 (3)		0.025 (25%)	0.075 (75%)
NM 0.15 (1)	0.15	0.1125 (75%)	0.0375 (25%)
NM 0.15 (2)		0.075 (50%)	0.075 (50%)
NM 0.15 (3)		0.0375 (25%)	0.01125 (75%)
NM 0.2 (1)	0.2	0.15 (75%)	0.05 (25%)
NM 0.2 (2)		0.1 (50%)	0.1 (50%)
NM 0.2 (3)		0.05 (25%)	0.15 (75%)
NM 0.25 (1)	0.25	0.1875 (75%)	0.0625 (25%)
NM 0.25 (2)		0.125 (50%)	0.125 (50%)
NM 0.25 (3)		0.0625 (25%)	0.1875 (75%)

***Nomenclature**

NM 0.1 (1)

"NM" Represents the non-metallic (polyester and polypropylene) HFRC,

"0.1" Represents the fiber dosage in terms of volume fraction of concrete,

"(1)" Represents the type of hybrid combination (75% PO + 25 % PP) at a total fiber volume fraction of 0.1%,

"(2)" Represents the type of hybrid combination (50% PO + 50 % PP) at a total fiber volume fraction of 0.1%,

"(3)" Represents the type of hybrid combination (25% PO + 75 % PP) at a total fiber volume fraction of 0.1%.

6.3 Results and discussion

6.3.1 *Compressive strength*

Compressive strength values of non-metallic HFRC consists of PP and PO fibers was compared with mono-FRC having same fiber volume fraction are presented in Table 6.2. From the experimental results, it is understood that improvement in compressive strength is very marginal with the fiber hybridization. This may be due to failure mode is fracture, hence reinforcing effect is not fully utilised.

Table 6.2 Compressive strength of non-metallic HFRC

Mix ID	30 MPa		50 MPa		70 MPa	
	f_{ck} (MPa)	**% increase**	**f_{ck} (MPa)**	**% increase**	**f_{ck} (MPa)**	**% increase**
CM	36.2	-	58.0	-	75.9	-
PP 0.1	36.7	1.4%	58.9	1.5%	77.1	1.5%
PO 0.1	36.7	1.3%	58.7	1.3%	76.7	1.1%
NM 0.1 (1)	36.6	1.1%	58.8	1.4%	76.8	1.2%
NM 0.1 (2)	36.8	1.7%	58.9	1.6%	77.2	1.6%
NM 0.1 (3)	**36.9**	**2.0%**	**59.0**	**1.8%**	**77.1**	**1.6%**
PP 0.15	37.1	2.4%	59.2	2.1%	77.2	1.7%
PO 0.15	37.1	2.4%	59.1	2.0%	77.4	2.0%
NM 0.15 (1)	36.9	2.0%	58.6	1.0%	76.7	1.1%
NM 0.15 (2)	37.0	2.1%	58.9	1.7%	76.8	1.2%
NM 0.15 (3)	**37.1**	**2.4%**	**59.3**	**2.3%**	**77.4**	**1.9%**
PP 0.2	36.6	1.2%	58.6	1.1%	76.7	1.0%
PO 0.2	36.8	1.7%	58.8	1.5%	76.5	0.8%
NM 0.2 (1)	37.2	2.7%	58.8	1.4%	76.7	1.0%
NM 0.2 (2)	37.2	2.8%	59.1	2.0%	77.3	1.8%
NM 0.2 (3)	**37.5**	**3.7%**	**59.5**	**2.6%**	**77.6**	**2.2%**
NM 0.25 (1)	36.6	1.0%	58.7	1.3%	76.6	1.0%
NM 0.25 (2)	36.6	1.1%	58.6	1.1%	76.8	1.1%
NM 0.25 (3)	**36.7**	**1.3%**	**58.9**	**1.5%**	**76.9**	**1.3%**

6.3.2 *Direct tensile strength*

Direct tensile strength values of non-metallic HFRC compared with mono-FRC and are presented in Table 6.3. It is observed that percentage strength improvement of non-metallic HFRC is more compared to mono-FRC. The average percentage strength improvement in all three grades of concrete is 22% which is achieved at a total fiber volume fraction of 0.2%. Irrespective of total fiber volume fractions, direct tensile strength is maximum at a hybrid combination of 75% PO combined with 25% of PP (75% PO + 25% PP). Tensile strength is maximum for HFRC may be because of combination of PO and PP fibers together lodged at crack orientation point because of this delay in the crack propagation.

Table 6.3 Direct tensile strength of non-metallic HFRC

Mix ID	30 MPa		50 MPa		70 MPa	
	f_{dt} (MPa)	% Increase	f_{dt} (MPa)	% Increase	f_{dt} (MPa)	% Increase
CM	3.2	-	4.6	-	5.1	-
PP 0.1	3.3	4.6%	4.9	7.0%	5.4	7.6%
PO 0.1	3.5	9.0%	5.1	11.0%	5.7	12.5%
NM 0.1 (1)	3.4	3.6%	5.2	11.3%	5.7	13.3%
NM 0.1 (2)	3.5	4.6%	5.2	12.1%	5.8	15.1%
NM 0.1 (3)	**3.6**	**8.6%**	**5.3**	**14.6%**	**6.0**	**17.6%**
PP 0.15	5.1	10.0%	5.1	10.3%	5.7	12.6%
PO 0.15	5.2	13.0%	5.2	11.3%	5.9	16.3%
NM 0.15 (1)	3.6	16.2%	5.4	16.2%	5.8	15.2%
NM 0.15 (2)	3.6	17.2%	5.4	17.2%	5.9	17.2%
NM 0.15 (3)	**3.6**	**17.7%**	**5.4**	**17.7%**	**6.0**	**19.0%**
PP 0.2	5.0	8.2%	5.0	8.2%	5.6	10.2%
PO 0.2	5.2	11.3%	5.2	11.3%	5.7	12.5%
NM 0.2 (1)	3.7	16.3%	5.4	16.3%	6.0	21.3%
NM 0.2 (2)	3.7	19.2%	5.5	19.2%	6.1	23.2%
NM 0.2 (3)	**3.8**	**20.2%**	**5.6**	**20.2%**	**6.2**	**24.2%**
NM 0.25 (1)	3.4	8.9%	5.0	8.9%	6.3	8.9%
NM 0.25 (2)	3.5	10.0%	5.1	10.0%	5.5	11.0%
NM 0.25 (3)	**3.5**	**11.1%**	**5.1**	**11.1%**	**5.6**	**11.1%**

6.3.3 *Flexure strength*

Flexural strength values of non-metallic HFRC compared with mono-FRC are presented in Table 6.4. Fiber effect on flexural strength is more compared to compressive strength, this may be due to fibers in concrete delay the crack formation and propagation there by flexural strength increased. It is noticed from Table 6.4 increase in flexural strength is more with the fiber hybridization compared to mono-FRC because of shorter length PP fibers control the growth of plastic-shrinkage cracks at early stage of concrete. At high stress-levels, PP fibers cannot withstand the load, at this stage these fibers pulls out from the surface or they may undergo fracture. At this stage PO fibers arrest the propagation of micro-cracks, thereby flexure strength of the concrete increases. The optimum hybrid combination of 75% PO combined with 25% of PP (75% PO + 25% PP) is achieved at all total fiber volume fractions i.e. NM 0.1 (3), NM 0.15 (3), NM 0.2 (3), NM 0.25 (3). The maximum percentage strength improvement in flexural strength compared to control mix is 22% for 30 MPa concrete, 24% for 50 MPa concrete and 28% for 70 MPa concrete, this is achieved at a total fiber volume fraction of 0.2%. It is also noticed that there is a percentage strength improvement of flexural strength increased marginally with the increase of grade of concrete may be due to fiber distribution is even with the increase in cementations material, similar kind of results observed in *job Thomas et al (2007).*

Table 6.4 Flexural strength of non-metallic HFRC

Mix ID	30 MPa		50 MPa		70 MPa	
	f_{ft} (MPa)	% Increase	f_{ft} (MPa)	% Increase	f_{ft} (MPa)	% Increase
CM	4.1	-	5.4	-	6.0	-
PP 0.1	4.3	5.0%	6.1	12.0%	6.8	13.0%
PO 0.1	4.57	11.0%	6.1	13.0%	6.9	15.0%
NM 0.1 (1)	4.6	12.0%	6.2	14.0%	6.9	15.0%
NM 0.1 (2)	4.6	12.7%	6.2	15.3%	7.1	17.3%

NM 0.1 (3)	**4.9**	**19.0%**	**6.5**	**19.0%**	**7.2**	**20.0%**
PP 0.15	4.6	13.0%	6.2	14.0%	7.0	17.0%
PO 0.15	4.7	15.0%	6.3	17.0%	7.1	19.0%
NM 0.15 (1)	4.7	15.6%	6.3	15.6%	7.1	17.6%
NM 0.15 (2)	4.8	17.3%	6.4	18.3%	7.2	20.3%
NM 0.15 (3)	**4.9**	**20.0%**	**6.6**	**21.0%**	**7.3**	**22.0%**
PP 0.2	4.3	5.0%	5.9	9.0%	6.6	10.0%
PO 0.2	4.4	8.0%	5.6	17.0%	6.2	10.0%
NM 0.2 (1)	4.9	19.3%	6.5	20.3%	7.5	24.4%
NM 0.2 (2)	4.9	20.2%	6.6	21.2%	7.6	26.2%
NM 0.2 (3)	**5.0**	**22.2%**	**6.7**	**24.2%**	**7.7**	**28.2%**
NM 0.25 (1)	4.5	10.4%	6.0	10.4%	7.0	16.4%
NM 0.25 (2)	4.6	11.3%	6.1	12.3%	6.9	15.3%
NM 0.25 (3)	**4.6**	**12.2%**	**6.2**	**15.2%**	**7.1**	**18.2%**

6.3.4 *Stress-strain behaviour of non-metallic HFRC under compression*

The stress-strain curves of non-metallic HFRC under uniaxial compression is presented in Figure 6.1 to 6.3 and the corresponding summary of the results are presented in Table 6.5 to 6.7.

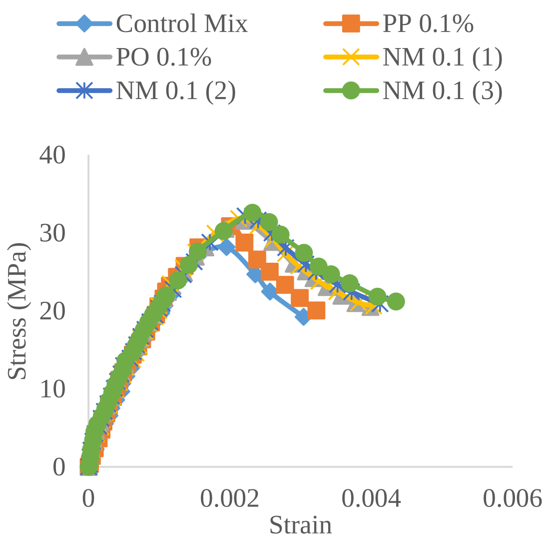


Fig 6.1a Stress-strain curves for non-metallic HFRC at 0.1% fiber dosage

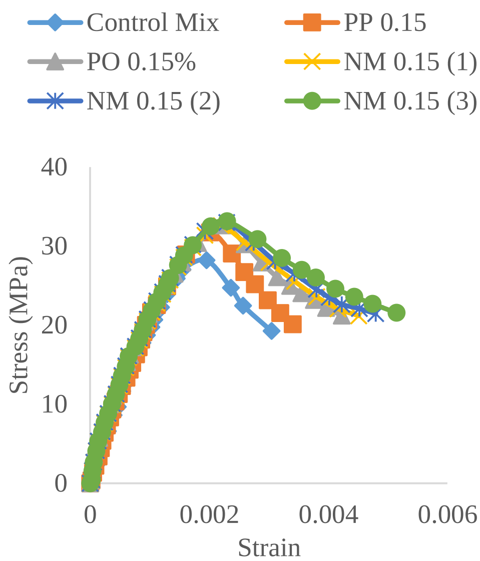


Fig 6.1b Stress-strain curves for non-metallic HFRC at 0.15% fiber dosage

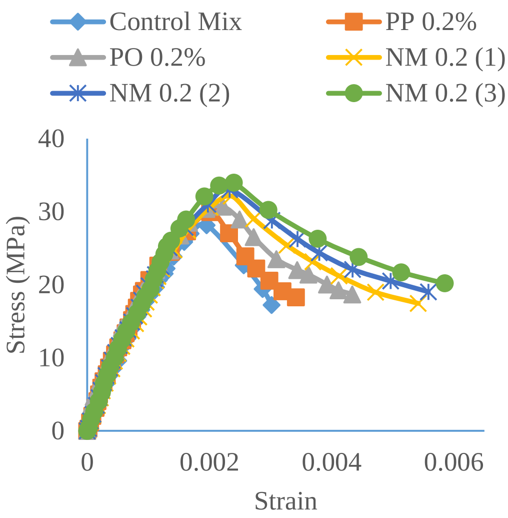


Fig 6.1c Stress-strain curves for non-metallic HFRC at 0.2% fiber dosage

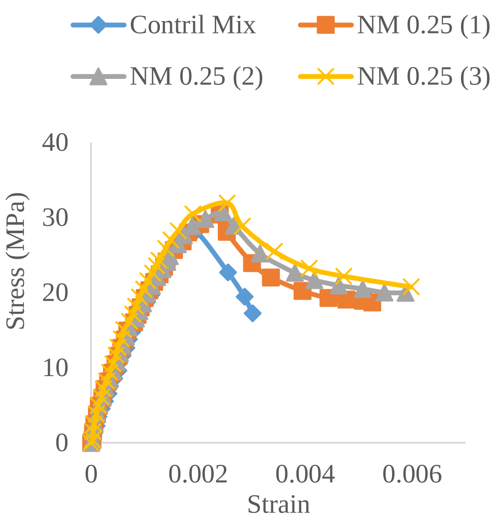


Fig 6.1d Stress-strain curves for non-metallic HFRC at 0.25% fiber dosage

Figure 6.1 Stress-strain curves of non-metallic HFRC for 30 MPa concrete

Table 6.5 Summary of the results for 30 MPa grade of concrete

Mix ID (1)	**σ^c_u (MPa)** (2)	**% Increase** (3)	**ε^c_u x 10^{-4}** (4)	**E_s x10^3 (MPa)** (5)	**D_f** (6)	**EA^c** (7)	**T_f** (8)
Control Mix	28.19	-	19.5	25.26	2.24	0.0734	1
NM 0.1 (1)	31.86	13.0	21.3	24.8	2.52	0.1004	1.37
NM 0.1 (2)	32.16	14.1	22.1	25.96	2.60	0.1040	1.42
NM 0.1 (3)	**32.60**	**15.6**	**23.2**	**26.01**	**2.65**	**0.1091**	**1.49**
NM 0.15 (1)	32.56	15.5	22.0	25.74	2.74	0.1004	1.37
NM 0.15 (2)	32.97	17.0	22.9	26.02	2.82	0.1040	1.42
NM 0.15 (3)	**33.15**	**17.6**	**23.0**	**27.20**	**2.90**	**0.1233**	**1.68**
NM 0.2 (1)	32.16	14.1	23.6	27.33	3.02	0.1285	1.75
NM 0.2 (2)	33.06	17.3	23.3	27.52	3.15	0.1335	1.82
NM 0.2 (3)	**34.00**	**20.6**	**24.0**	**27.56**	**3.26**	**0.1417**	**1.93**
NM 0.25 (1)	30.42	7.9	24.0	28.32	2.99	0.1112	1.52
NM 0.25 (2)	30.71	8.2	24.7	28.23	3.02	0.1209	1.65

NM 0.25 (3)	**31.97**	**13.4**	**25.7**	**28.81**	**3.12**	**0.1273**	**1.74**

σ^c_u – Peak Stress, ε^c_u – Strain at peak stress, E_s – young's modulus, D_f – Ductility factor ($0.85\varepsilon_a/0.85\varepsilon_d$), EA^c – Energy absorption capacity of concrete in compression, T_f – Toughness Factor (EA^c FRC/EA^c C), Superscript "c" represents the values in compression.

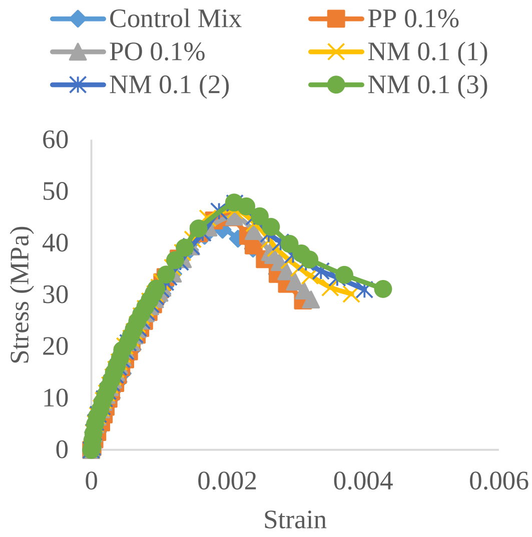


Fig 6.2a Stress-strain curves for non-metallic HFRC at 0.1% fiber dosage

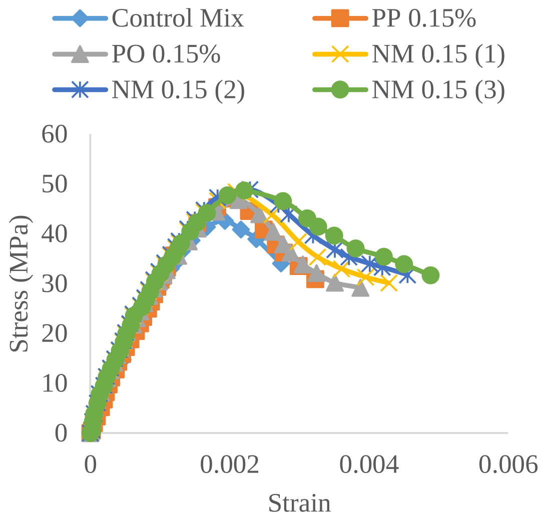


Fig 6.2b Stress-strain curves for non-metallic HFRC at 0.15% fiber dosage

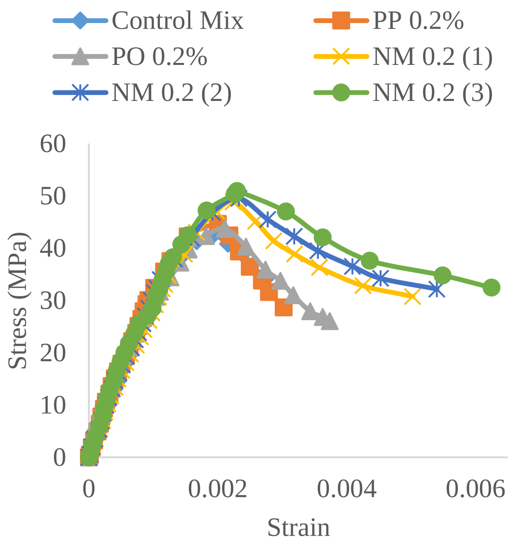


Fig 6.2c Stress-strain curves for non-metallic HFRC at 0.2% fiber dosage

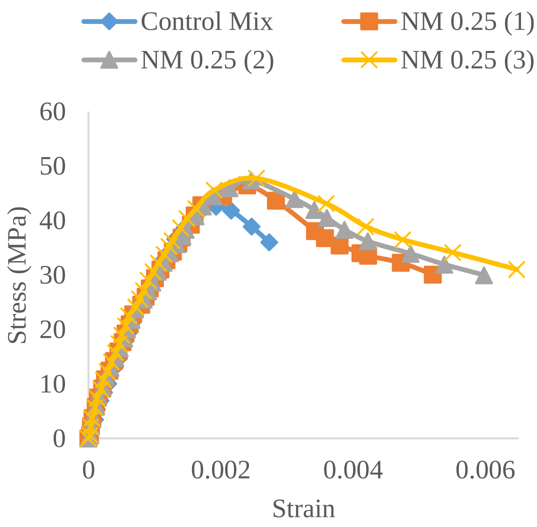


Fig 6.2d Stress-strain curves for non-metallic HFRC at 0.25% fiber dosage

Figure 6.2 Stress-strain curves of non-metallic HFRC for 50 MPa concrete

Table 6.6 Summary of the results for 50 MPa grade of concrete

Mix ID (1)	σ^c_u (MPa) (2)	% Increase (3)	ε^c_u x 10^{-4} (4)	E_s x10^3 (MPa) (5)	D_f (6)	EA^c (7)	T_f (8)
CM	52.59	-	19.3	33.83	2.21	0.0979	1
NM 0.1 (1)	46.33	8.8	21.2	35.11	2.25	0.1376	1.40
NM 0.1 (2)	47.72	12.0	21.1	35.09	2.35	0.1492	1.52
NM 0.1 (3)	**47.87**	**12.4**	**21.1**	**36.41**	**2.42**	**0.1543**	**1.58**
NM 0.15 (1)	48.48	13.8	20.0	36.28	2.58	0.1561	1.59
NM 0.15 (2)	48.89	14.8	22.9	37.90	2.67	0.1648	1.68
NM 0.15 (3)	**48.70**	**14.3**	**22.1**	**37.24**	**2.75**	**0.1754**	**1.79**
NM 0.2 (1)	48.91	14.8	22.4	38.63	2.81	0.1813	1.85
NM 0.2 (2)	49.53	16.3	23.3	38.23	2.95	0.1949	1.99
NM 0.2 (3)	**49.95**	**17.3**	**23.0**	**38.85**	**3.02**	**0.2178**	**2.22**
NM 0.25 (1)	46.47	9.10	24.0	39.25	2.94	0.2024	2.07
NM 0.25 (2)	47.36	11.2	24.7	39.04	3.04	0.2142	2.19
NM 0.25 (3)	**47.77**	**12.2**	**25.4**	**38.60**	**3.11**	**0.2264**	**2.31**

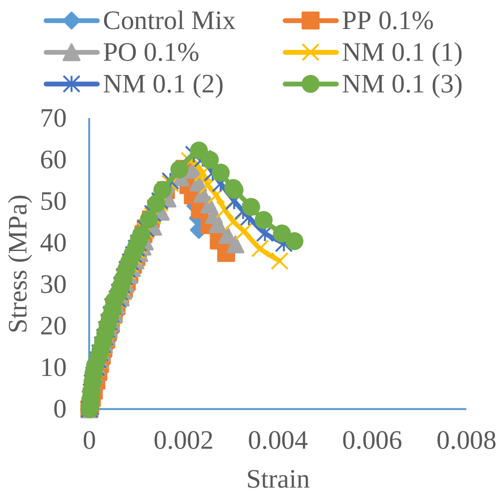


Fig 6.3a Stress-strain curves for non-metallic HFRC at 0.1%

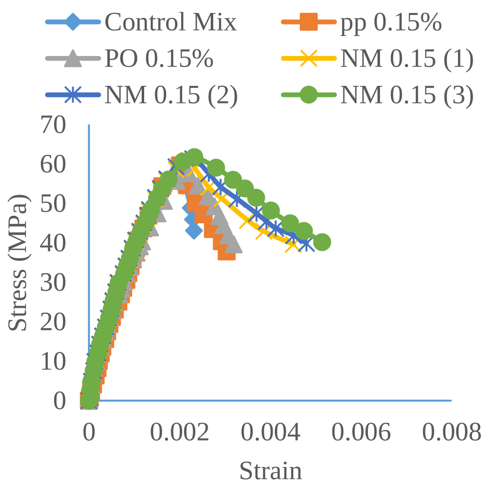


Fig 6.3b Stress-strain curves for non-metallic HFRC at 0.15%

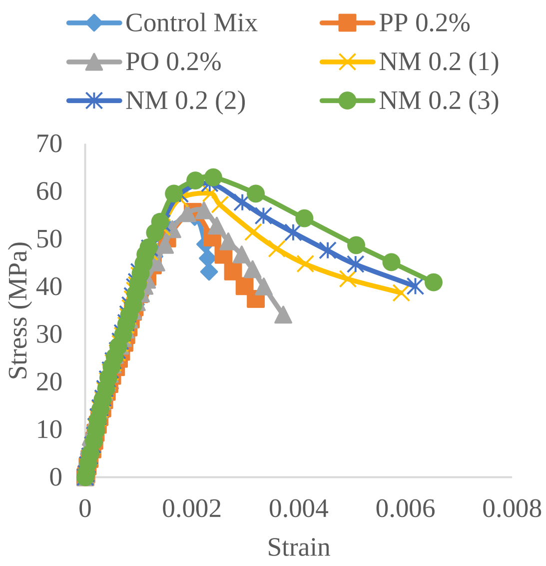


Fig 6.3c Stress-strain curves for non-metallic HFRC at 0.2%

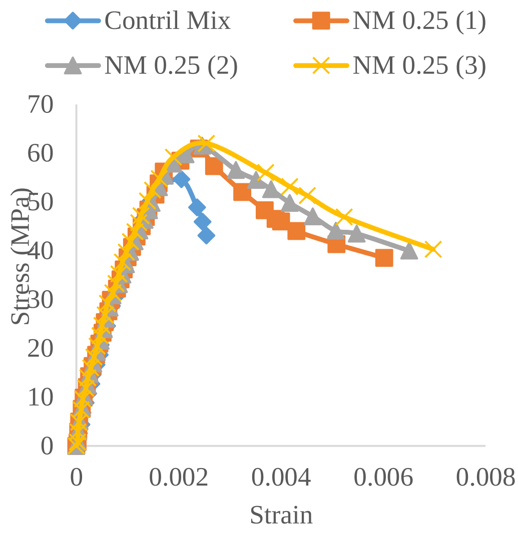


Fig 6.3d Stress-strain curves for non-metallic HFRC at 0.25%

Figure 6.3 Stress-strain curves of non-metallic HFRC for 70 MPa concrete

Table 6.7 Summary of the results for 70 MPa grade of concrete

Mix ID (1)	**σ^c_u (MPa)** (2)	**% Increase** (3)	**ε^c_u x 10^{-4}** (4)	**E_s x10^3 (MPa)** (5)	**D_f** (6)	**EA^c** (7)	**T_f** (8)
CM	54.65	-	20.5	45.21	2.01	0.1153	1
NM 0.1 (1)	57.98	6.1	21.3	48.81	2.28	0.1874	1.62
NM 0.1 (2)	59.50	8.9	22.1	51.11	2.31	0.1945	1.69
NM 0.1 (3)	**60.38**	**10.5**	**23.2**	**51.21**	**2.34**	**0.2036**	**1.76**
NM 0.15 (1)	60.93	11.5	22.0	51.18	2.39	0.1874	1.62
NM 0.15 (2)	61.39	12.3	22.9	51.57	2.42	0.1945	1.69
NM 0.15 (3)	**61.80**	**13.1**	**23.2**	**52.64**	**2.59**	**0.2352**	**2.04**
NM 0.2 (1)	59.57	9.0	23.6	52.36	2.53	0.2352	2.04
NM 0.2 (2)	61.71	12.9	23.3	53.27	2.69	0.2592	2.25
NM 0.2 (3)	**62.97**	**15.2**	**24.0**	**53.81**	**2.73**	**0.2826**	**2.45**
NM 0.25 (1)	60.98	11.6	24.0	54.15	2.64	0.2496	2.16
NM 0.25 (2)	61.54	12.6	24.7	54.93	2.68	0.2714	2.35
NM 0.25 (3)	**62.02**	**13.5**	**25.4**	**54.24**	**2.72**	**0.2903**	**2.52**

In a well-designed HFRC, the positive interaction between mono fibers and the resulting HFRC should exceeds the sum of the individual fibers performances this phenomenon is termed as synergy, explained by N Banthia et al. (2007). From the Figures 6.5 to 6.7 it is clearly observed that HFRC taking the advantage from each of the individual fibers in the concrete. Stress-strain behaviour of HFRC at a total fiber volume fractions of 0.1%, 0.15%, 0.2% and 0.25% are plotted with three different hybrid combinations (PO 75% + PP 25%, PO 50% + PP 50% and PO 25% + PP 75%) and all these are compared with mono-FRC for the same fiber volume fraction and also with control mix. It is noticed that the hybridization of fibers significantly influencing both pre-peak and post-peak behaviour of stress-strain curve. Strain at peak stress significantly improved with fiber hybridization in all the mixes. There is an increment in overall performance of the concrete observed with the fiber hybridization for all the total fiber dosages i.e. 0.1, 0.15, 0.2 and 0.25%. Irrespective of total fiber dosages, HFRC shown better performance at a hybrid combination of 75% P0 combined with 25% PP (75% PO + 25% PP).

Peak-stress of non-metallic HFRC increased with the increase in fiber content up to 0.2% volume fraction, thereafter there is a little decrees in peak-stress observed at 0.25% volume fraction. This may be due to more number of fibers in the concrete replaces the cement matrix which is responsible for strength and also mix becomes harsh and difficult to compact which intern increases the voids in concrete mix. The maximum percentage increase in peak-stress of 20.6% for 30 MPa concrete, 17.3% for 50 MPa concrete and 15.2% for 70 MPa concrete was observed at a hybrid combination of 75% P0 + 25% PP (NM 0.2 (3)) at a total fiber volume fraction of 0.2%. It is also observed that, there is a decrease in peak stress with the increase in cementitious material in concrete. This may be because of at higher grade concrete is brittle and fiber effect is not fully utilized by the concrete as the crack progresses through the aggregate.

Strain at peak-stress is an indication of deformation at maximum stress that is developed in a material without causing plastic deformation. From the Table 6.5 to 6.7 (column 4) it is observed that strain at peak-stress increase with fiber hybridization compared to mono-FRC. Irrespective of grade of concrete strain at peak stress varied from 21.3 x 10^{-4} to 25.7 x 10^{-4} for non-metallic hybridization. There is no significant variation in peak-strain observed with the increase in grade of concrete. The maximum peak-strain observed at a total fiber volume fraction of 0.25% is 20% more compared to control mix. Young's modulus of non-metallic HFRC are presented in Table 6.5 to 6.7 (column 5). From the experimental values it is observed that, Young's modulus of the concrete increased with the fiber hybridization and concrete becomes stiffer with the increase in grade. Area under stress-strain curve is a measure of concrete energy absorption capacity shown in column 8, Table 6.5 to 6.7 for non-metallic HFRC. Toughness of the composite significantly effected through non-metallic hybridization. The maximum toughness achieved at a hybrid combination of 75% PO + 25% PP for all fiber volume fractions i.e. NM 0.1 (3), NM 0.15 (3), NM 0.2 (3), NM 0.25 (3). The maximum percentage increase in toughness of 220% achieved at a total fiber volume fraction of 0.2%. From this it can be understood that hybridization of fibers in concrete delaying the formation of cracks at various stress levels there by concrete becomes stiffer and hence the peak-strain increases and also Young's modulus of the composite increases.

The increase in pre-peak and post-peak behaviour of concrete is mainly attributed to the combination of 6mm PP and 12 mm PO fibers which are effectively arrested the both micro and macro cracks. Here short length and low-tensile strength PP fibers having higher aspect-ratio, fibers evenly disperse through-out the concrete, hence these fibers can bridge the micro-cracks effectively at lower stress levels in concrete. When stresses reaches to higher because of low-stiffness and shorter in length PP fibers cannot with stand the loads at this stage, fibers are pulled out from the surface or they undergo fracture and then the stresses are transferred from the PP fibers to PO fiber substantially. Theses PO fibers can effetely arrest the propagation of macro-cracks thereby overall stress-strain behaviour of the concrete increases both at pre-peak and post-peak region.

6.3.4.1 *Hybrid fiber effect on different grades of concrete.*

Figure 6.4 shows the stress-strain curves of non-metallic HFRC compared with mono-FRC and control mix for 30, 50 and 70 MPa grade of concrete. From the Figure it is noticed that there is significant difference in behaviour of stress-strain curve observed with the increase in grade of concrete in terms of young's modulus, ductility factor and energy absorption capacity of the composite. Figure 6.5 to 6.7 indicates the ductility factor, young's modulus and energy absorption capacity of non-metallic HFRC compared to mono-FRC and control mix respectively. From the Figures 6.5, it is observed that concrete becomes brittle to ductile with the addition of fibers but ductility factor of the concrete decreased with the increase in grade of concrete may be due to a higher grades of concrete is more brittle compared to lower grades of concrete.

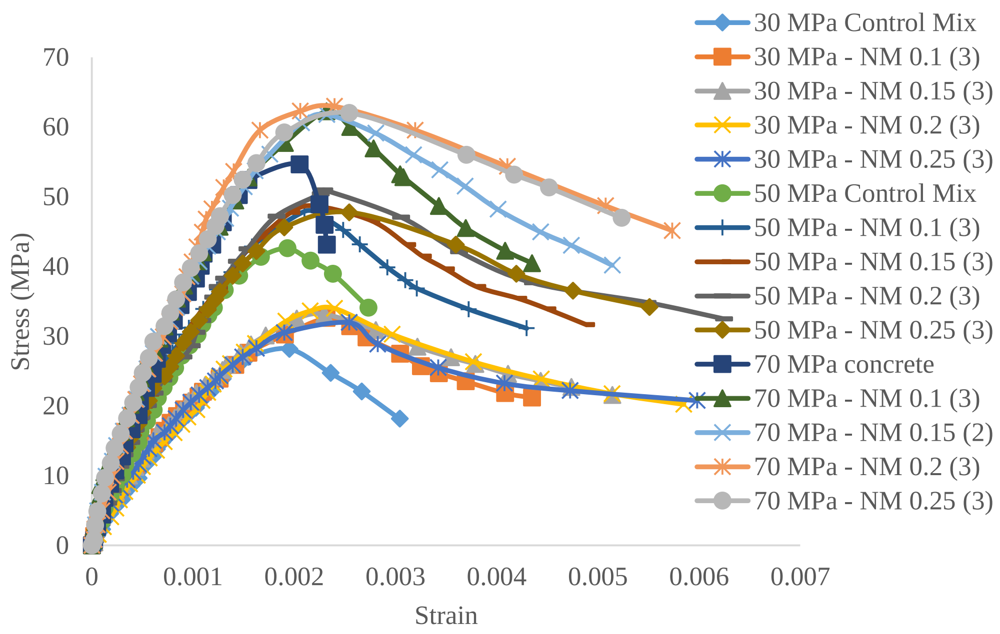


Figure 6.4 Stress-strain behaviour of non-metallic HFRC at optimum hybrid combination

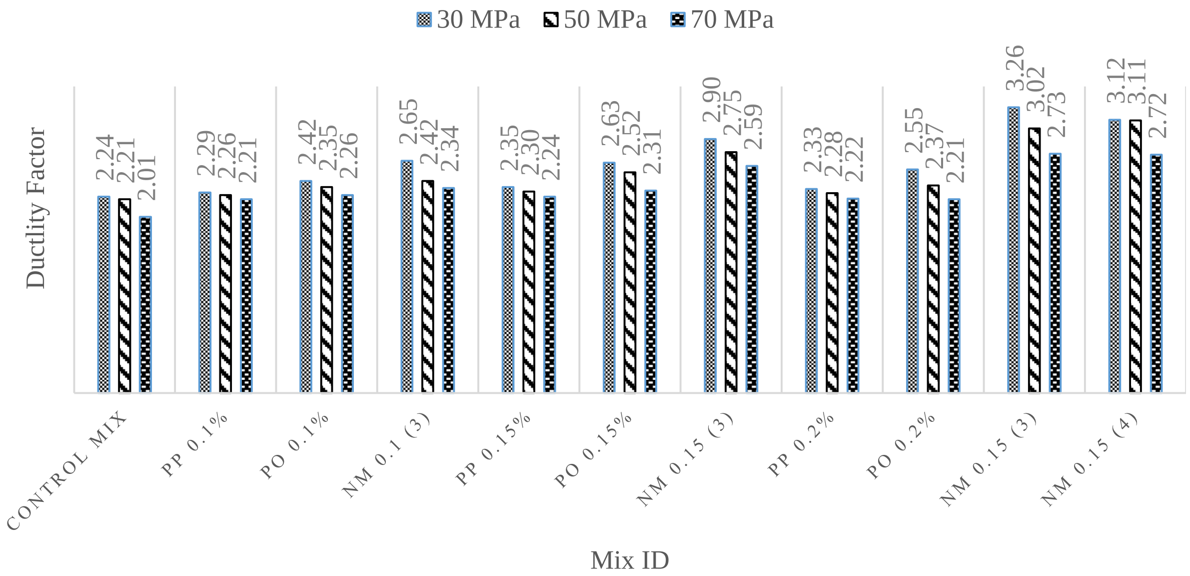


Figure 6.5 Ductility factor of mono and non-metallic HFRC

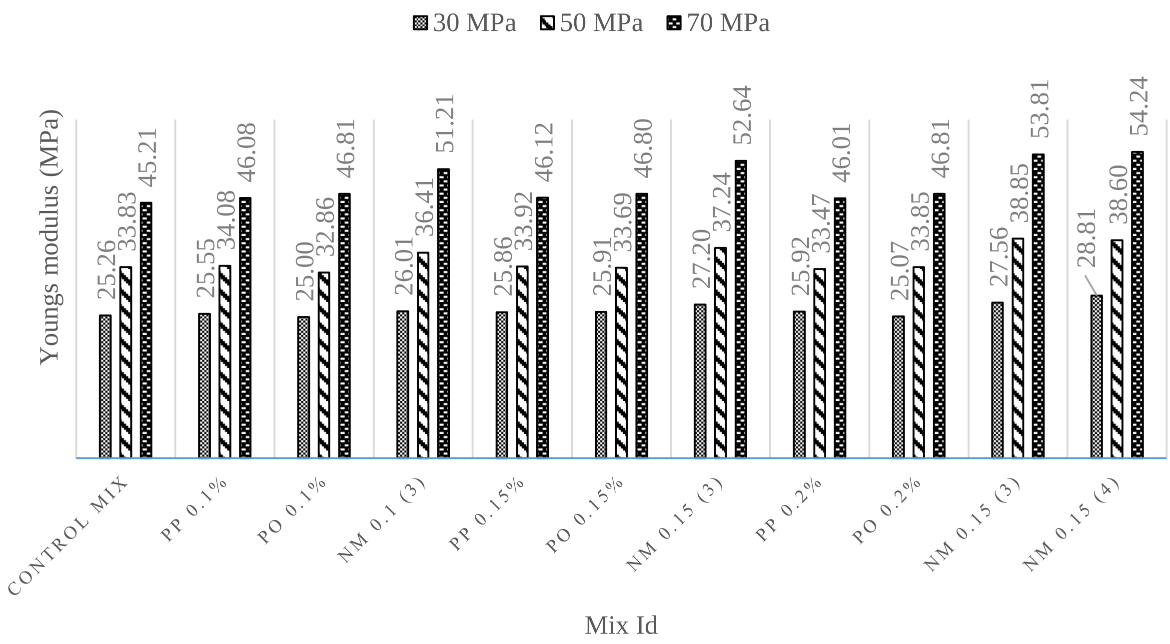


Figure 6.6 young's modulus of mono and non-metallic HFRC

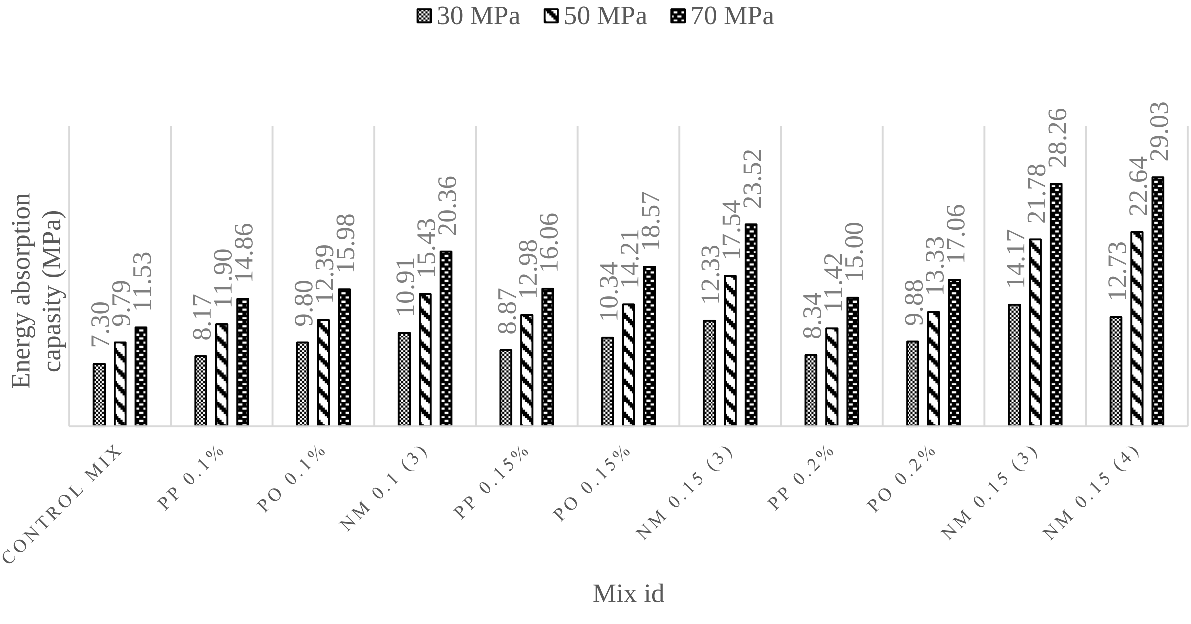


Figure 6.7 Energy absorption capacity of mono and non-metallic HFRC

6.3.5 *Stress- strain curves behaviour of concrete under uniaxial tension*

The stress-strain curves of non-metallic HFRC compared with mono-FRC and control mix are presented in Figure 6.8 to 6.10 corresponding summary of the results are presented in Table 6.8 to 6.10.

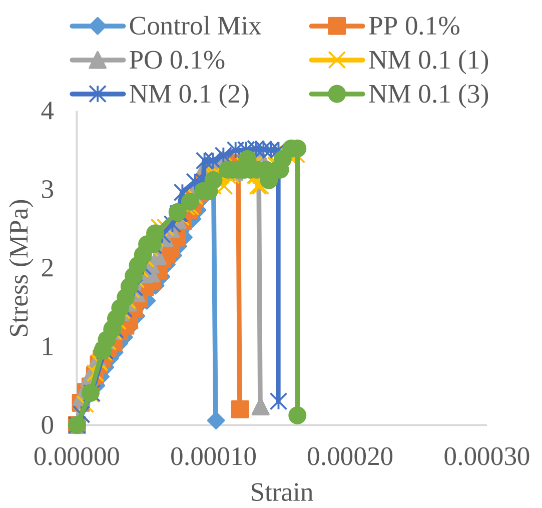


Fig 6.8a stress-strain for non-metallic HFRC at 0.1% fiber dosage

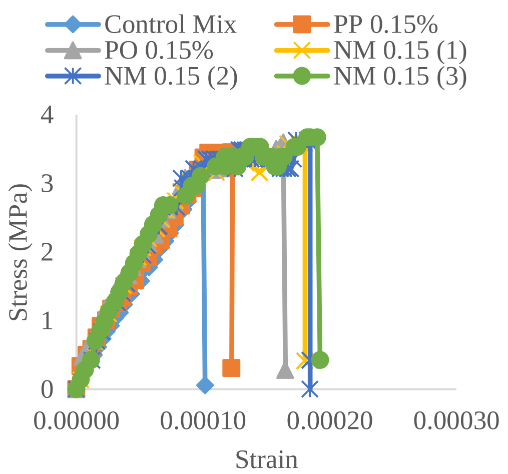


Fig 6.8b stress-strain for non-metallic HFRC at 0.15% fiber dosage

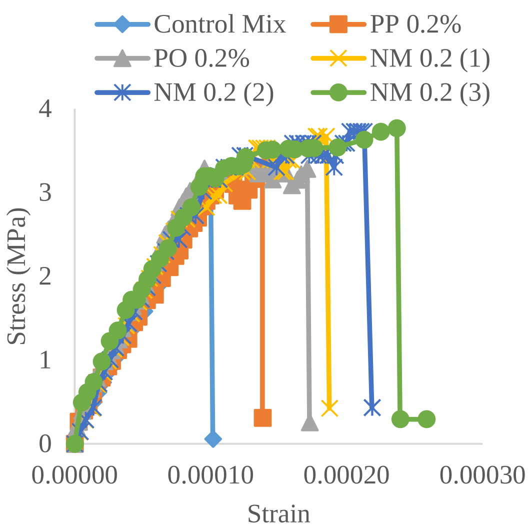


Fig 6.8c stress-strain for non-metallic HFRC at 0.2% fiber dosage

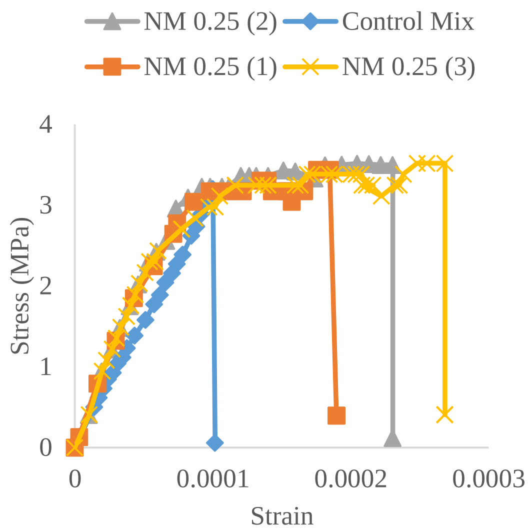


Fig 6.8d stress-strain for non-metallic HFRC at 0.25% fiber dosage

Figure 6.8 Stress-strain curves for non-metallic HFRC under uniaxial tension for 30 MPa grade of concrete.

Table 6.8 Summary of the results for 30 MPa grade of concrete

Mix ID (1)	σ^t_f **(MPa)** (2)	ε^t_f **x 10^{-5}** (3)	σ^t_u **(MPa)** (4)	ε^t_b **x 10^{-5}** (5)	**EA^t x 10^{-5} (MPa)** (6)
Control Mix	3.20	10.0	3.20	10.2	48.15
NM 0.1 (1)	3.31	10.01	3.44	16.1	53.98
NM 0.1 (2)	3.33	10.22	3.50	14.7	63.49
NM 0.1 (3)	**3.98**	**10.32**	**3.52**	**16.1**	**80.35**
NM 0.15 (1)	3.35	10.35	3.57	18.1	86.68
NM 0.15 (2)	3.39	10.39	3.63	18.5	99.11
NM 0.15 (3)	**3.41**	**10.40**	**3.66**	**19.3**	**98.88**
NM 0.2 (1)	3.41	11.01	3.66	18.7	94.90
NM 0.2 (2)	3.45	11.12	3.73	21.9	109.88
NM 0.2 (3)	**3.41**	**11.22**	**3.76**	**25.9**	**110.12**
NM 0.25 (1)	3.31	10.99	3.43	19.0	85.64
NM 0.25 (2)	3.30	11.21	3.50	23.0	99.73
NM 0.25 (3)	**3.34**	**11.98**	**3.51**	**24.8**	**120.52**

σ^t_f – Stress at inflection point, ε^t_f – Strain at inflection point, σ^t_u – Stress at ultimate point, ε^t_b – Strain at break point, EA^t – Energy absorption capacity, where superscript "t" values in tension.

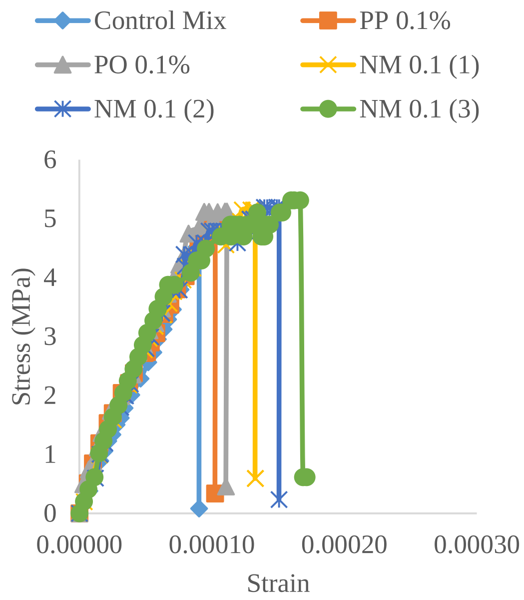


Fig 6.9a stress-strain curve for non-metallic HFRC at 0.1% fiber dosage

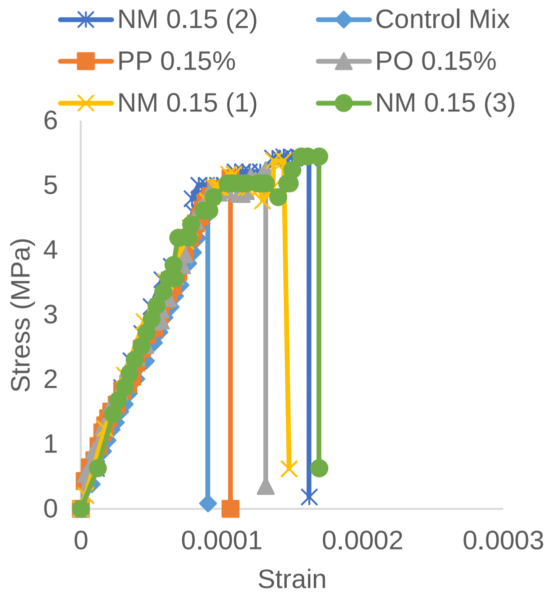


Fig 6.9b stress-strain curve for non-metallic HFRC at 0.15% fiber dosage

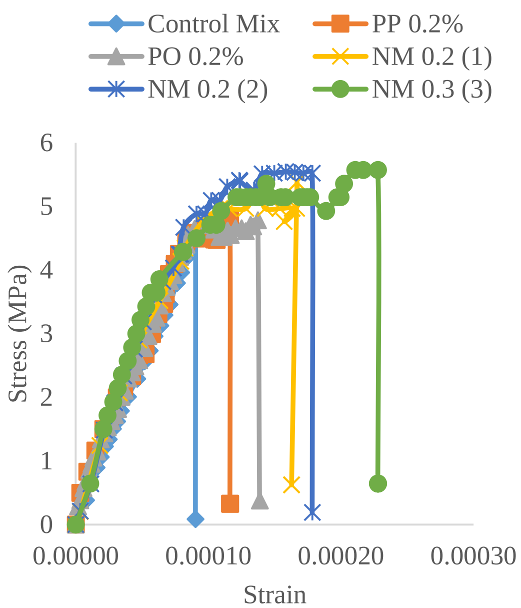


Fig 6.9c stress-strain curve for non-metallic HFRC at 0.2% fiber dosage

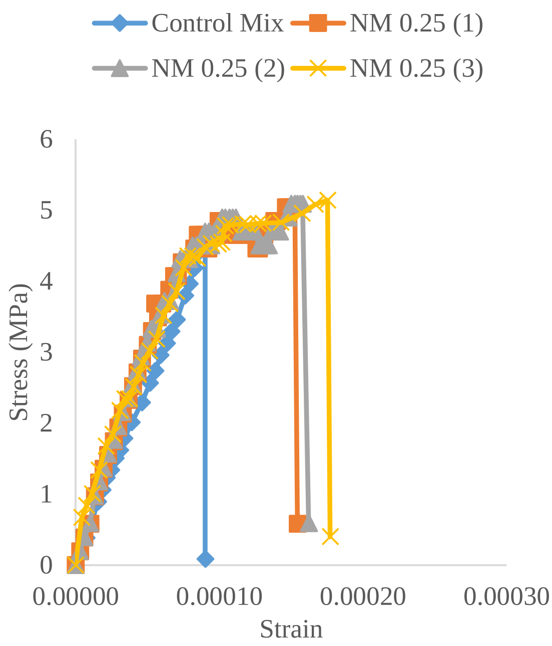
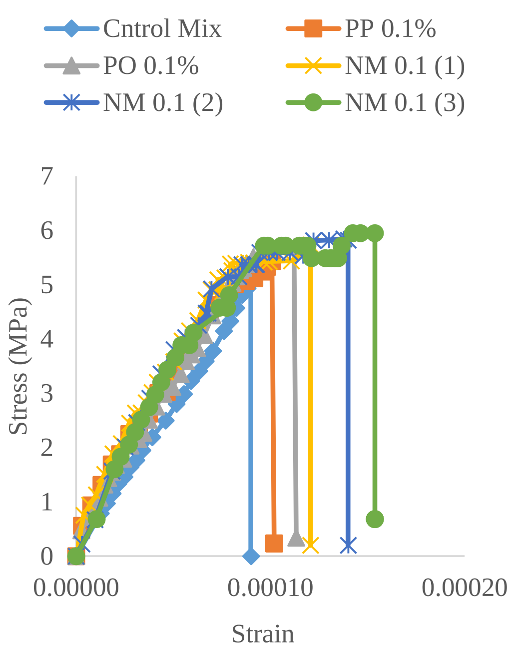


Fig 6.9d stress-strain curve for non-metallic HFRC at 0.25% fiber dosage

Figure 6.9 Stress-strain curves for non-metallic HFRC under uniaxial tension for 50 MPa grade of concrete.

Table 6.9 Summary of the results for 50 MPa Grade of concrete

Mix ID	σ^t_f (MPa)	ε^t_f x 10^{-5}	σ^t_u (MPa)	ε^t_b x 10^{-5}	EA^t x 10^{-5} (MPa)
Control Mix	4.63	9.02	4.63	9.02	63.0
NM 0.1 (1)	4.88	9.97	5.14	13.3	94.47
NM 0.1 (2)	4.90	10.19	5.19	15.1	112.89
NM 0.1 (3)	**4.92**	**10.2**	**5.3**	**17.1**	**128.42**
NM 0.15 (1)	4.92	9.42	5.3	14.8	110.2
NM 0.15 (2)	4.50	9.36	5.41	16.2	112.83
NM 0.15 (3)	**5.12**	**9.54**	**5.44**	**16.9**	**121.24**
NM 0.2 (1)	5.14	10.97	5.38	16.3	124.56
NM 0.2 (2)	5.12	10.98	5.51	17.8	128.79
NM 0.2 (3)	**5.21**	**11.21**	**5.57**	**22.8**	**165.48**
NM 0.25 (1)	5.12	11.42	5.03	15.4	108.44
NM 0.25 (2)	5.11	11.92	5.08	16.2	113.78
NM 0.25 (3)	**5.21**	**12.22**	**5.13**	**17.8**	**112.75**



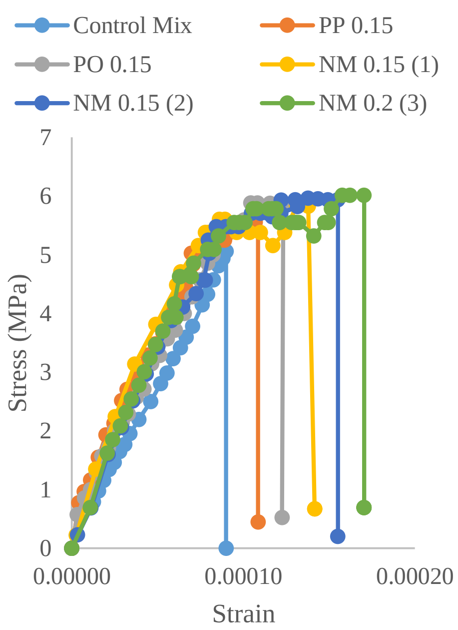
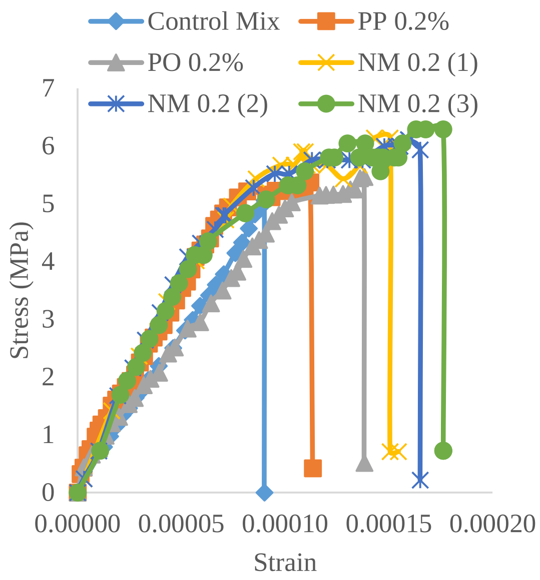


Fig 6.10a stress-strain curve for non-metallic HFRC at 0.1% fiber dosage

Fig 6.10b stress-strain curve for non-metallic HFRC at 0.15% fiber dosage



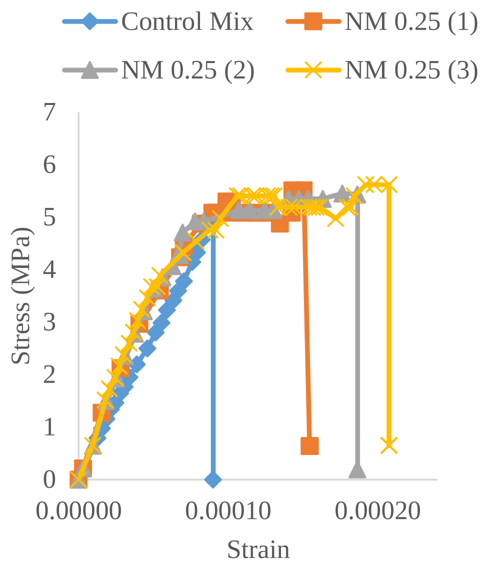


Fig 6.10c stress-strain curve for non-metallic HFRC at 0.2% fiber dosage

Fig 6.10d stress-strain curve for non-metallic HFRC at 0.25% fiber dosage

Figure 6.10 Stress-strain curves for non-metallic HFRC under uniaxial tension for 70 MPa grade of concrete.

Table 6.10 Summary of the results for 70 MPa Grade of concrete

Mix ID	**σ^t_f (MPa)**	**ε^t_f x 10^{-5}**	**σ^t_u (MPa)**	**ε^t_b x 10^{-5}**	**EA^t x 10^{-5} (MPa)**
Control Mix	5.05	9.0	5.06	9.0	68.63
NM 0.1 (1)	5.39	9.12	5.72	12.1	91.4
NM 0.1 (2)	5.42	9.14	5.81	14.0	109.3
NM 0.1 (3)	**5.47**	**9.19**	**5.95**	**15.4**	**119.7**
NM 0.15 (1)	5.40	9.29	5.82	14.2	127.5
NM 0.15 (2)	5.44	9.32	5.93	15.5	127.7
NM 0.15 (3)	**5.51**	**9.56**	**5.78**	**17.0**	**151.6**
NM 0.2 (1)	5.44	10.16	6.14	15.5	127.5
NM 0.2 (2)	5.49	10.24	6.23	16.5	127.7
NM 0.2 (3)	**5.55**	**10.47**	**6.28**	**17.6**	**151.6**

NM 0.25 (1)	5.32	10.29	5.51	15.5	114.5
NM 0.25 (2)	5.39	10.32	5.56	18.7	123.7
NM 0.25 (3)	**5.42**	**10.44**	**5.62**	**20.8**	**150.5**

From the Figure 6.8 to 6.10 of stress-strain curves of non-metallic HFRC, it is observed that stresses in concrete increased with increase in strain up to the point of inflection and exhibited strain hardening behaviour right up to the ultimate-stress and failed suddenly. Also that there is increase stresses and failure strain observed compared to the mono-FRC at same fiber volume fraction. This may be because of hybridization of fibers effectively arrest the multi-level cracks developed at varied stress levels. In this non-metallic hybridization even though both fibers are having nearly same Young's modulus but varied in length i.e. PP of 6mm length and PO of 12mm length in hybridized form exhibited synergy and improved the overall performance of concrete. The failure pattern of the direct tensile specimens is well defined single crack perpendicular to the direction of load. Because of fiber hybridization number of fibers available in the failure plane, herein failure plane shorter PP fibers effectively arrest the plastic shrinkage-cracks and enhances the fresh properties of concrete. Whereas at higher stress-levels PO fibers arrest the crack propagation and participated to improve the toughness after the inflection point, these fibers also effective in exhibiting the strain hardening behaviour of concrete, there by overall performance of the concrete is improved.

Stress at inflection point is on par with the mono-FRC and plane concrete. Irrespective of the grades of concrete the strain at inflection point is 9.12×10^{-5} to 11.98×10^{-5}, it is almost similar to the plane concrete. But there is an exponential increase in failure strain observed with fiber hybridization compared to mono-FRC and control mix. Figure 6.11 presented the failure strain of non-metallic HFRC for all the three grades of concrete. The average increase in failure strain compared to control mix is 145.3% in all three grades of concrete at an optimum fiber combination of 75% PP + 25% PO (NM 0.2 (3)) in a total fiber dosage of 0.2%. It is also observed that there is a decrease in failure strain observed with the increase in grade of concrete.

In all four (0.1,0.15,0.2 and 0.25%) total fiber volume fractions and three hybrid combinations 75% PO+ 25% PP (NM 0.1 (3), NM 0.15 (3), NM 0.2 (3) and NM 0.25 (3)) the best results obtained in all aspects compared to mono-FRC and control mix. Area under stress-strain curve is a measure of energy absorption capacity of concrete. Figure 6.12 presented the toughness factor for non-metallic HFRC compared to control mix. The average increase in energy absorption capacity of concrete in all three grades is 137% achieved at hybrid combination NM 0.2 (3) (75% PO +25% PP at 0.2% fiber dosage).

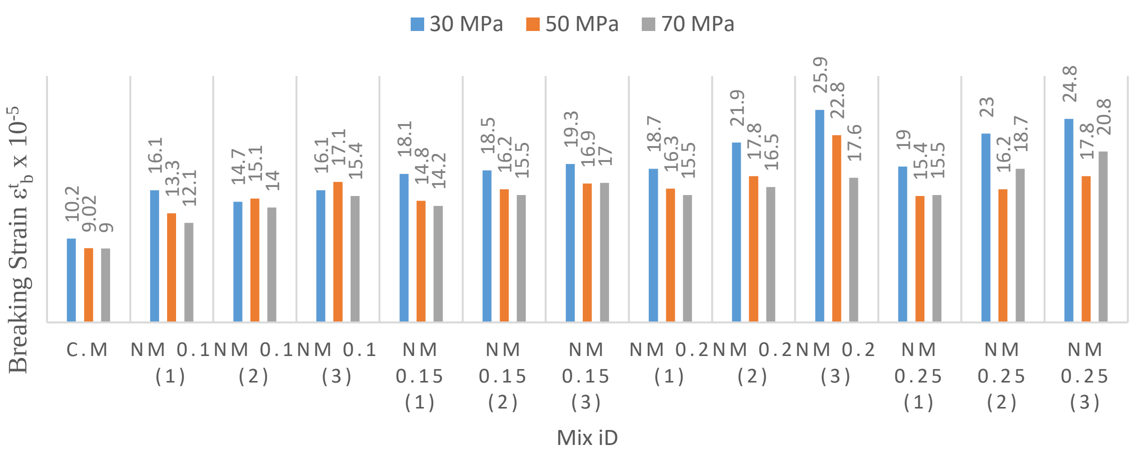


Fig 6.11 Breaking Strain for non-metallic HFRC of 30, 50 and 70 MPa concretes

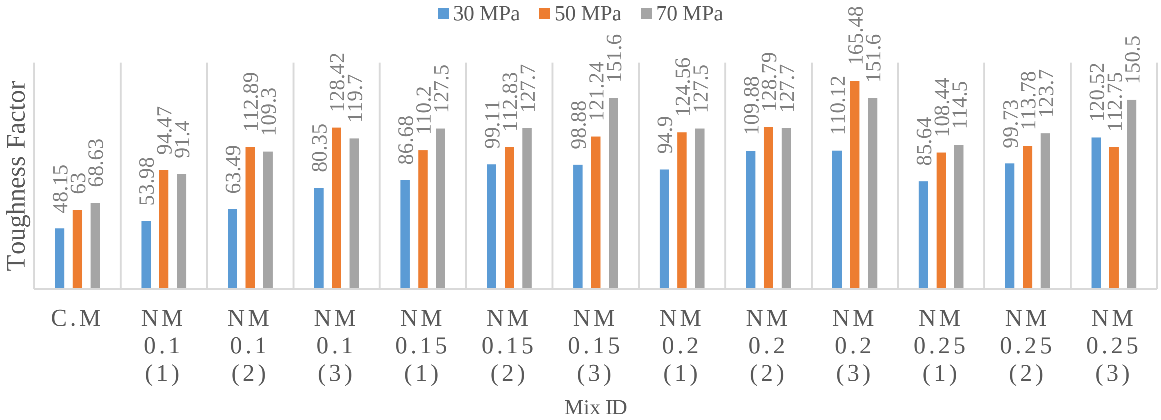


Fig 6.12 Toughness factor for non-metallic HFRC of 30, 50 and 70 MPa concretes

6.4 Concluding remarks from Phase II

In this chapter mechanical behaviour of non-metallic HFRC using PP and PO fibers has been studied, the results obtained are compared with mono-FRC and control mix for the same fiber volume fraction. Total four fiber volume fractions are considered in this investigation with three hybrid combinations. Compressive strength, direct tensile strength, flexural strength and stress-strain behaviour under uni-axial stresses were assessed. Following conclusions are drawn from phase II experimental programme.

- It is possible to develop non-metallic HFRC using PP and PO fibers combinedly for better mechanical properties compared to mono-FRC and control mix.
- Hybrid combination with 75% PO and 25% PP considered to be the best proportion in the composite for all the strength parameters, among all four fiber volume fractions i.e. 0.1, 0.15, 0.2, 0.25%.

- The percentage increase in direct tensile strength and flexure strength is 20.2% and 22% for 30 MPa concrete, 20.2% and 24.2% for 50 MPa concrete and for 70 MPa concrete it is 24.2% and 28.2% respectively for non-metallic HFRC at a total fiber dosage of 0.2%.
- Peak-stress of non-metallic HFRC under uni-axial compression increased with fiber hybridization. The maximum percentage increase in peak-stress is 20.6% for 30 MPa, 17.3% for 50 MPa concrete and 15.2% for 70 MPa concrete observed at a fiber hybrid combination of 75 % PO + 25% PP in a total fiber volume fraction of 0.2%.
- Energy absorption capacity (toughness) of non-metallic HFRC under uni-axial stresses increased with fiber hybridization. The maximum percentage increase in toughness achieved at a hybrid combination of 75% PO+25% PP in a total fiber volume fraction of 0.2%.

CHAPTER 7

PHASE III – MECHANICAL BEHAVIOUR OF METALLIC AND NON-METALLIC HFRC

7.1 General

Previous chapter- 6, the mechanical behaviour of non-metallic HFRC has been investigated and the optimum hybrid combination obtained, i.e., 75% PO combined with 25% of PP (75% PO + 25% PP). In this chapter, an experimental programme has been carried out to investigate the mechanical behaviour of metallic and non-metallic HFRC and the objective is to combine partial amount of metallic fiber with the partial amount of non-metallic fibers in a proportions (0.05, 0.1, 0.15 and 0.2%). The total amount of fiber content considered for metallic and non-metallic HFRC is varied in 0.5%, 0.75%, and 1% volume fraction. Figure 7.1 presents the scheme of hybridization technique used and the nomenclature of hybrid combinations are shown in table 7.1**.** Compressive strength, direct tensile strength, flexural strength and stress-strain behaviour of metallic and non-metallic HFRC are obtained in the experimental investigation.

The developed HFRC composite using metallic and non-metallic fibers expected to counter act the fracture process in concrete and have the superior performance in terms of mechanical behaviour of concrete compared to mono FRC.

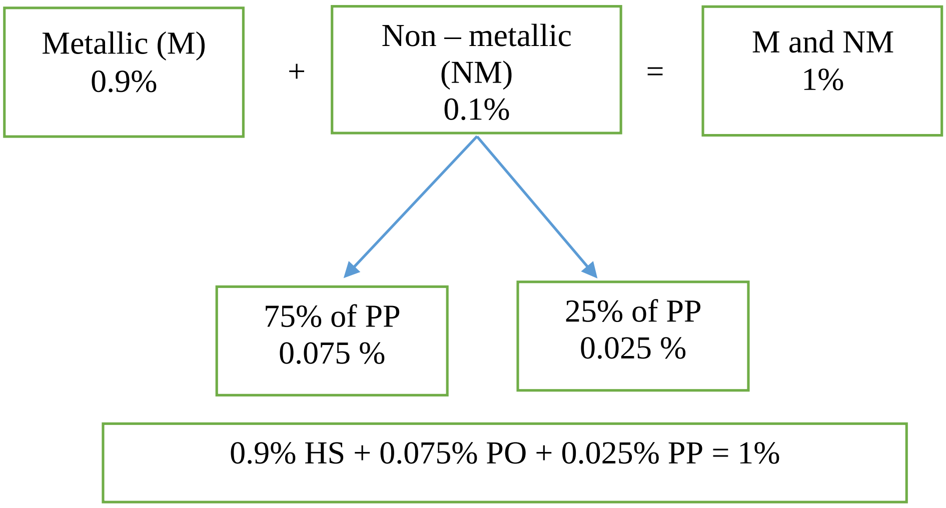


Figure 7.1 Metallic and non-metallic hybridization process

Table 7.1 Nomenclature and hybrid combination of metallic – non-metallic hybrid combinations

Mix ID	Metallic	Non-metallic (75% PO + 25% PP)	Total amount of fiber (%)
M-NM 0.5 (1)	0.45	0.05	0.5
M-NM 0.5 (2)	0.4	0.1	0.5
M-NM 0.5 (3)	0.35	0.15	0.5
M-NM 0.5 (4)	0.3	0.2	0.5
M-NM 0.75 (1)	0.7	0.05	0.75
M-NM 0.75 (2)	0.65	0.1	0.75
M-NM 0.75 (3)	0.6	0.15	0.75
M-NM 0.75 (4)	0.55	0.2	0.75
M-NM 1 (1)	0.95	0.05	1
M-NM 1(2)	0.9	0.1	1
M-NM 1 (3)	0.85	0.15	1
M-NM 1 (4)	0.8	0.2	1

Nomenclature

M-NM 0.5 (1)

M – represents the metallic fiber (hooked-end steel)

NM – represents the non-metallic fiber (combination of polyester and polypropylene fiber in the ration of 75% PO + 25% PP

0.5 – represents the total amount of fiber including metallic and non-metallic fibers.

(1) – In bracket number represents the amount of non-metallic fiber replaced with metallic fiber 1 - 0.05%%, 2 – 0.1%, 3 – 0.15%, 4 – 0.2%.

7.2 Results and discussions

7.2.1 *Compressive strength*

The results of compressive strength of metallic and non-metallic HFRC are compared with mono-FRC and control mix which are presented in table 7.2. Total fiber volume fractions of 0.5, 0.75 and 1% investigated with a four hybrid combinations as presented in table 7.1. It is observed that percentage increase in compressive strength is more with fiber hybridization when compared with mono-FRC of same fiber volume fraction. The maximum strength improvement of 11.1% for 30 MPa concrete at hybrid combination of 0.9% Metallic combined with 0.1% non-metallic (M-NM 1 (2)). The maximum strength improvement for 50 MPa concrete is 9.1% at a hybrid combination of 0.85% metallic combined with 0.15% non-metallic (M-NM 1 (3)) and the strength improvement for 70 MPa is not significant. It is understood from table 7.2 as the strength of the concrete increases percentage increase in compressive strength with the addition of fiber decreases, this is because in high-strength concretes reinforcing effect of fiber is not fully utilised because of concrete brittleness and crack progresses through aggregate rather than matrix.

Table 7.2 Compressive strength of metallic – non-metallic HFRC

Mix ID	30 MPa		50 MPa		70 MPa	
	f_{ck} (MPa)	% increase	f_{ck} (MPa)	% increase	f_{ck} (MPa)	% increase
CM	36.2	-	58.0	-	75.9	-
HS 0.5	37.6	3.9%	60.0	3.5%	78.3	3.2%
M-NM 0.5 (1)	37.7	4.1%	60.4	4.1%	79.0	4.1%
M-NM 0.5 (2)	38.8	7.1%	61.6	6.2%	79.7	5.0%
M-NM 0.5 (3)	38.4	6.1%	62.4	7.6%	79.3	4.4%
M-NM 0.5 (4)	37.0	2.2%	59.9	3.3%	76.8	1.2%
HS 0.75	38.0	5.0%	60.8	4.8%	78.6	3.6%
M-NM 0.75 (1)	38.5	6.2%	60.9	5.1%	78.9	4.0%

M-NM 0.75 (2)	39.3	8.6%	62.0	6.9%	78.9	4.0%
M-NM 0.75 (3)	39.1	8.1%	62.5	7.8%	79.6	4.8%
M-NM 0.75 (4)	37.0	2.2%	59.2	2.2%	77.5	2.1%
HS 1	39.1	7.9%	61.2	5.6%	77.5	2.1%
M-NM 1 (1)	39.6	9.4%	61.3	5.8%	78.1	2.9%
M-NM 1 (2)	40.2	11.1%	62.5	7.9%	78.2	3.0%
M-NM 1 (3)	39.8	9.9%	63.2	9.1%	78.3	3.1%
M-NM 1 (4)	37.0	2.1%	59.5	2.6%	76.4	0.6%

7.2.2 *Flexural strength*

The flexural strength values of metallic and non-metallic HFRC are presented in table 7.3. It is observed that percentage increase in flexural strength is more as compared with the compressive strength because of fibers in concrete delay the crack formation there by flexural strength increases. Total three fiber volume fractions with four hybrid combinations have been studied and the results are compared with mono-FRC. The maximum flexural strength is achieved at 1% fiber volume fraction for 30, 50 and 70 MPa concrete. The percentage increase in flexural strength for 30 MPa concrete is 42.2% at a hybrid combination of 0.9% metallic combined with 0.1% non-metallic (M-NM 1 (2). For 50 MPa and 70 MPa concretes the percentage improvement in flexural strength is 46.2% and 48.2% respectively, at a hybrid combination of 0.85% metallic combined with 0.15% non-metallic fibers (M-NM 1 (3)). It is noticed from the above values that high-strength concretes requires were number of non-metallic fibers. It is also observed that percentage increase in flexural strength is more with the increase in cementatious material in concrete, it is mainly due to fiber distribution is more even because of increase in cementatious material. The percentage increase in flexural strength is more with non-metallic and metallic hybridization because of non-metallic fibers percent in concrete are having low modulus and high aspect-ratio at a combination of 75% PO + 25% PP exhibiting the positive synergy and control the both micro and macro-cracks effectively. At low stress-levels, metallic fibers present in concrete control the propagation of macro-cracks and improve the strength properties at post-cracks region which is responsible for improvement in flexural strength of concrete.

Figure 7.2 shows the relationship between Non-metallic Fiber volume fraction and percentage improvement of flexural strength. It is noticed that at 50 MPa and 70 MPa grade of concrete the requirement of non-metallic fiber is more due to more number of micro-cracks present in higher grades because of low w/c ratio.

Table 7.3 Flexure strength values of metallic – non-metallic HFRC

Mix ID	30 MPa		50 MPa		70 MPa	
	f_{ft} (MPa)	% increase	f_{ft} (MPa)	% increase	f_{ft} (MPa)	% increase
CM	4.1	-	5.4	-	6.0	-
HS 0.5	4.6	12.3%	5.8	15.3%	7.1	17.6%
M-NM 0.5 (1)	5.2	26.1%	6.1	28.2%	7.8	30.2%
M-NM 0.5 (2)	5.4	31.0%	6.2	32.0%	8.2	36.2%
M-NM 0.5 (3)	5.3	30.2%	5.9	36.3%	8.3	38.2%
M-NM 0.5 (4)	4.8	18.2%	6.0	21.0%	7.2	20.1%
HS 0.75	4.7	15.6%	6.4	17.5%	7.3	20.7%
M-NM 0.75 (1)	5.4	32.0%	7.3	34.2%	8.2	36.3%
M-NM 0.75 (2)	5.7	38.2%	7.6	40.2%	8.6	42.5%
M-NM 0.75 (3)	5.6	37.5%	7.7	42.1%	8.8	46.3%
M-NM 0.75 (4)	4.9	20.1%	6.6	22.1%	7.6	26.5%
HS 1	4.9	20.3%	6.6	21.6%	7.4	23.5%
M-NM 1 (1)	5.6	36.5%	7.5	38.0%	8.4	39.2%
M-NM 1(2)	5.8	42.2%	7.8	43.0%	8.7	45.3%
M-NM 1 (3)	5.8	40.2%	7.9	46.2%	8.9	48.2%
M-NM 1 (4)	4.9	20.1%	6.6	22.1%	7.5	24.1%

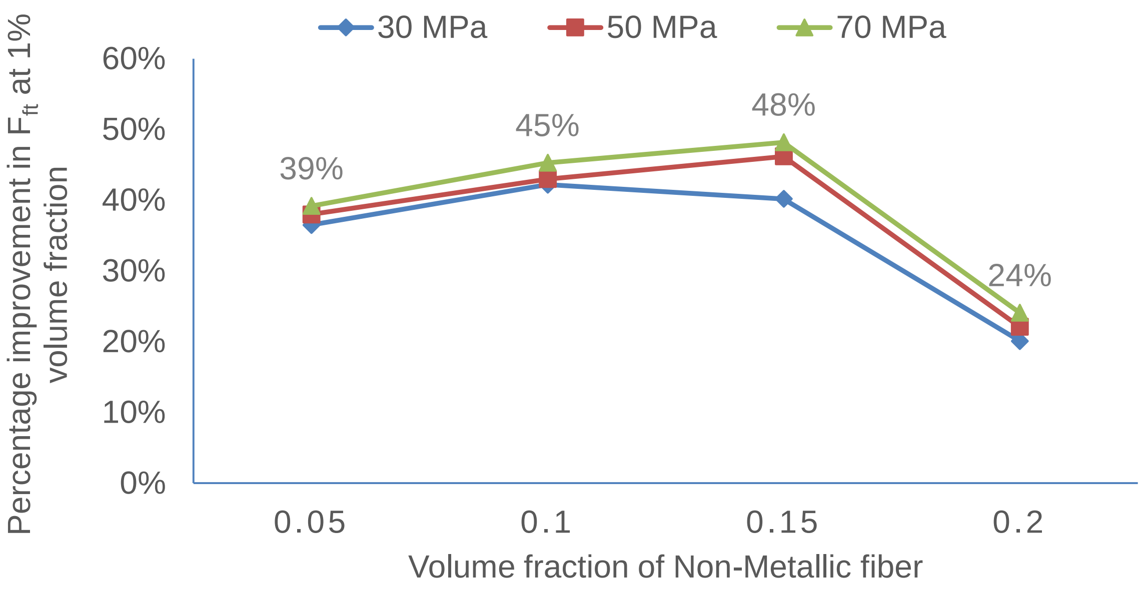


Fig 7.2 Relationship between Non-metallic Fiber volume fraction and percentage improvement of F_{ft} at 1% volume fraction.

7.2.4 *Direct tensile strength.*

The direct tensile strength values of metallic and non-metallic HFRC are shown in table 7.4. There is substantial improvement in direct tensile strength is observed with the fiber hybridization compared with mono-FRC. The maximum strength improvement achieved at a total fiber volume fraction of 1%. The maximum percentage increase in direct tensile strength for 30 MPa concrete is 36.3% at a hybrid combination of 0.8% metallic combined with 0.1% non-metallic fibers (M-NM 1 (2)) and the maximum percentage strength improvement for 50 MPa and 70 MPa concrete is 39.5% and 42.5% respectively. The strength improvement in direct tensile strength with the addition of metallic and non-metallic fibers is manifested as hybridization effect on fracture plane of the concrete, at fracture plane short and low Young's modulus non-metallic PP and PO fibers bridge the micro-cracks at lower stress levels, at higher stress levels theses non-metallic fibers cannot withstand and the stresses are being transferred from non-metallic fibers to metallic fibers, thereafter these metallic fibers came into the action to control the formation of macro-cracks. The more improvement in direct tensile strength is noticed with the increase in grade of concrete, in high-strength concrete because of more cementitious material fiber distribution is more even therefore reinforcement effect of the fiber is more at failure plane. Effect of non-metallic fiber on flexural strength at 1% volume fraction is shown in figure 7.3.

Table 7.4 Direct tensile strength values of metallic – non-metallic HFRC

Mix ID	30 MPa		50 MPa		70 MPa	
	f_{dt} (MPa)	**% increase**	**f_{dt} (MPa)**	**% increase**	**f_{dt} (MPa)**	**% increase**
CM	3.18	-	4.63	0.0%	5.06	0.0%
HS 0.5	3.51	9.6%	5.22	12.6%	5.81	14.5%
M-NM 0.5 (1)	3.86	21.5%	5.73	23.7%	6.35	25.4%
M-NM 0.5 (2)	4.00	25.6%	5.90	27.5%	6.55	29.5%
M-NM 0.5 (3)	3.96	24.6%	6.00	29.6%	6.65	31.4%
M-NM 0.5 (4)	3.76	18.3%	5.67	22.5%	6.30	24.5%
HS 0.75	3.62	14.2%	5.32	15.5%	6.01	17.7%
M-NM 0.75 (1)	4.12	29.4%	6.08	31.3%	6.71	32.5%
M-NM 0.75 (2)	4.20	32.1%	6.17	33.3%	6.79	34.3%
M-NM 0.75 (3)	3.95	29.6%	6.31	36.3%	6.95	37.3%
M-NM 0.75 (4)	3.73	17.3%	5.67	22.5%	6.30	24.6%
HS 1	3.81	18.3%	5.52	18.6%	6.12	21.5%
M-NM 1 (1)	4.27	34.3%	6.23	34.7%	6.89	36.3%
M-NM 1(2)	4.34	36.3%	6.36	37.5%	7.01	38.5%
M-NM 1 (3)	4.09	34.6%	6.46	39.5%	7.21	42.5%
M-NM 1 (4)	3.77	18.5%	5.95	28.5%	6.56	29.6%

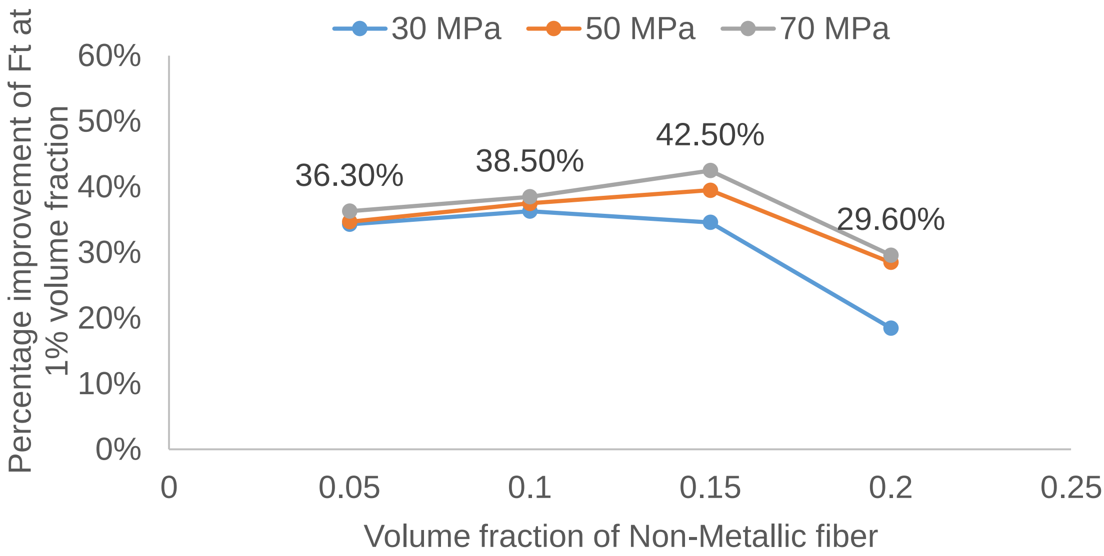


Figure 7.3 Non-metallic Fiber volume fraction and percentage improvement of F_t at 1% volume fraction.

7.2.5 *Stress-strain behaviour of metallic – non-metallic HFRC under uni-axial compression.*

Stress-strain curves of metallic and non-metallic HFRC under uni-axial compression are presented in figure 7.4 to 7.6 and the summary of the results are presented in table 7.5 to 7.7.

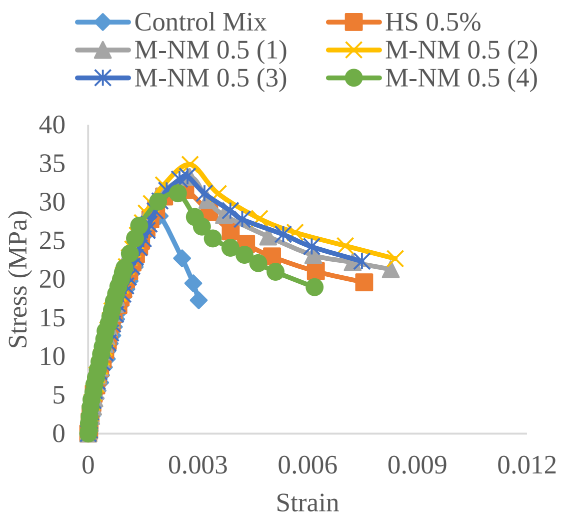


Fig 7.4a Stress-strain curves for metallic - non-metallic HFRC at 0.5% fiber dosage

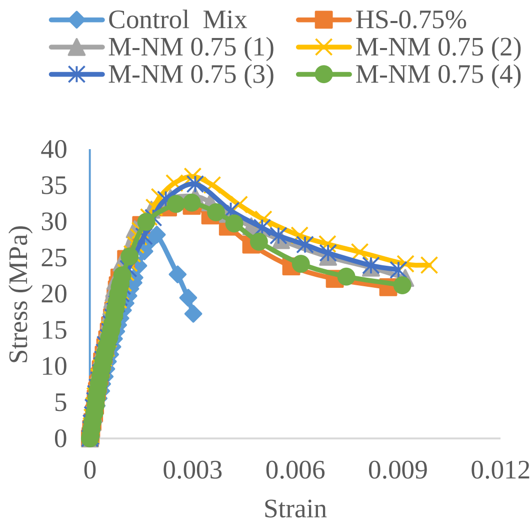


Fig 7.4b Stress-strain curves for metallic - non-metallic HFRC at 0.75% fiber dosage

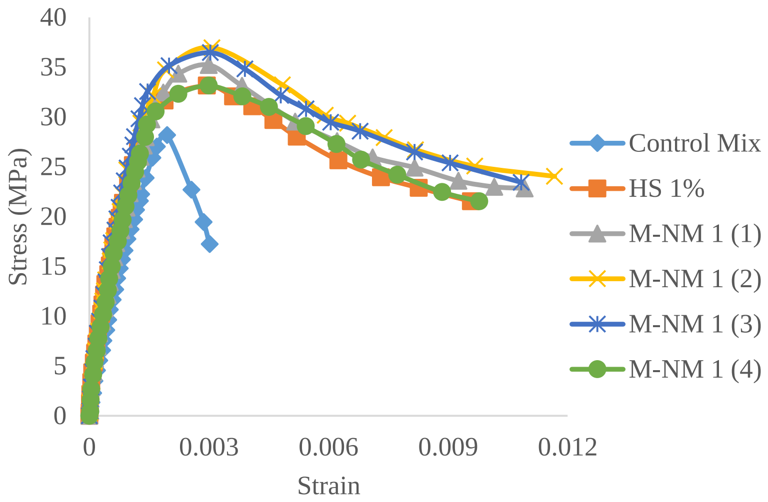


Fig 7.4c Stress-strain curves for metallic - non-metallic HFRC at 1% fiber dosage

Figure 7.4 Stress-strain curves for metallic - non-metallic HFRC for 30 MPa grade of concrete

Table 7.5 Summary of the results for 30 MPa grade of concrete

Mix ID	σ^c_u (MPa)	% Increase	ε^c_u x 10^{-4}	E_s x10^3 (MPa)	D_f	EA^c	T_f
Control Mix	28.19	-	19.5	25.26	2.24	0.0734	1
HS 0.5	29.34	4.1	26.5	25.09	3.10	0.1424	1.94
M-NM 0.5 (1)	33.23	17.9	27.8	25.32	3.31	0.1703	2.32
M-NM 0.5 (2)	34.85	23.6	27.9	25.53	3.59	0.1850	2.52
M-NM 0.5 (3)	33.32	18.2	27.1	25.84	3.45	0.1651	2.25
M-NM 0.5 (4)	31.11	10.5	24.5	26.86	3.40	0.0806	1.10
HS 0.75	29.94	6.2	29.5	25.90	3.42	0.1594	2.17
M-NM 0.75 (1)	33.48	18.8	30.8	26.03	3.55	0.1898	2.59
M-NM 0.75 (2)	36.24	28.6	30.0	26.58	3.85	0.2200	3.00
M-NM 0.75 (3)	35.17	24.8	30.8	26.58	3.92	0.2002	2.73
M-NM 0.75 (4)	32.62	15.7	29.8	26.43	3.89	0.1831	2.50
HS 1	30.87	9.5	29.5	25.99	3.50	0.1808	2.47

M-NM 1 (1)	35.23	25.0	30.0	26.53	4.08	0.2267	3.09
M-NM 1(2)	36.97	31.1	30.8	26.93	4.22	0.2513	3.43
M-NM 1 (3)	36.47	29.4	30.3	26.94	4.58	0.2360	3.22
M-NM 1 (4)	33.16	17.6	30.0	27.78	4.43	0.2034	2.77

σ^c_u – Peak Stress, ε^c_u – Strain at peak stress, E_s – young's modulus, D_f – Ductility factor ($0.85\varepsilon_a/0.85\varepsilon_d$), EA^c – Energy absorption capacity of concrete in compression, T_f – Toughness Factor (EA^c FRC/EA^c C), Superscript "c" represents the values in compression.

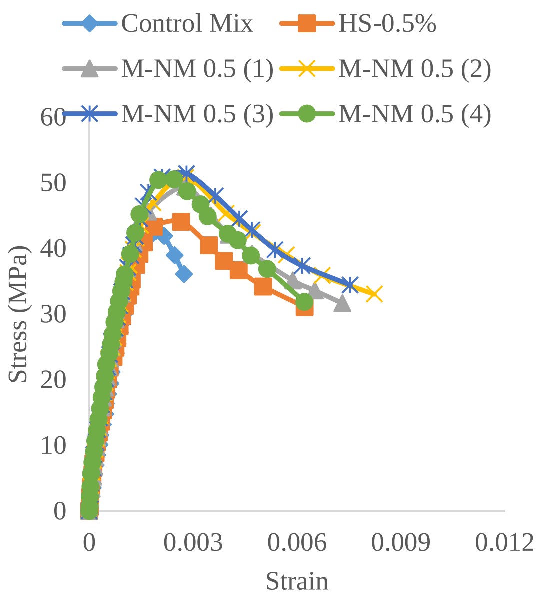


Fig 7.5a Stress-strain curves for metallic - non-metallic HFRC at 0.5% fiber dosage

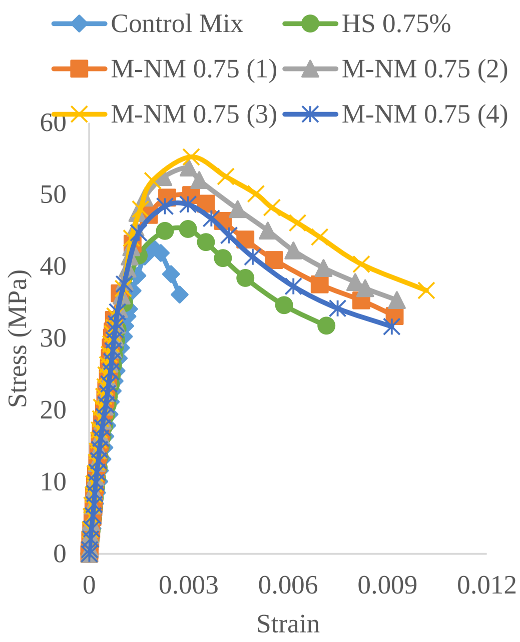


Fig 7.5b Stress-strain curves for metallic - non-metallic HFRC at 0.75% fiber dosage

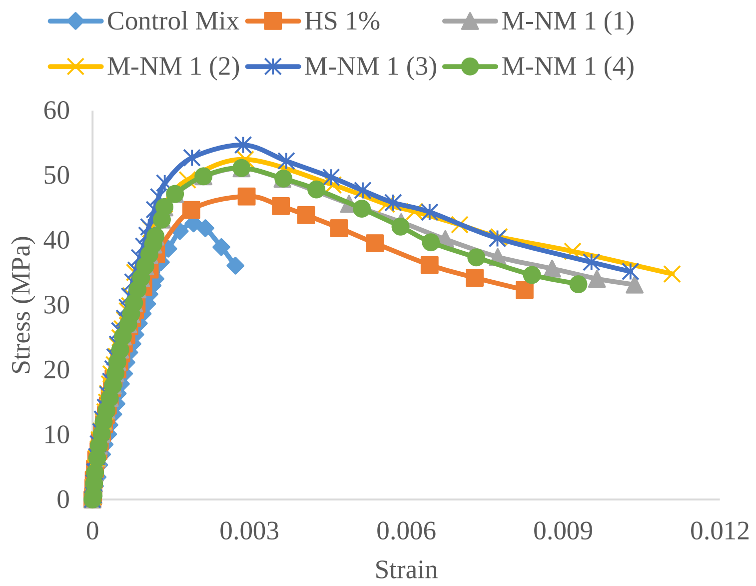


Fig 7.5c Stress-strain curves for metallic - non-metallic HFRC at 1% fiber dosage

Figure 7.5 Stress-strain curves for metallic - non-metallic HFRC for 50 MPa grade of concrete

Table 7.6 Summary of the results for 50 MPa grade of concrete

Mix ID	σ^c_u (MPa)	% Increase	ε^c_u x 10^{-4}	E_s x10^3 (MPa)	D_f	EA^c	T_f
Control Mix	42.59	-	19.3	33.83	2.21	0.0979	1
HS 0.5	44.03	3.4	26.5	36.62	2.35	0.2064	2.11
M-NM 0.5 (1)	49.38	15.9	27.8	40.87	2.98	0.2355	2.40
M-NM 0.5 (2)	50.80	19.3	28.9	42.91	3.12	0.2663	2.72
M-NM 0.5 (3)	51.40	20.7	29.1	42.77	3.11	0.2507	2.56
M-NM 0.5 (4)	50.52	18.6	28.5	41.31	2.88	0.1445	1.48
HS 0.75	45.18	6.1	29.8	37.89	2.90	0.2403	2.45
M-NM 0.75 (1)	49.92	17.2	30.0	44.32	3.26	0.2830	2.89
M-NM 0.75 (2)	53.74	26.2	30.5	45.72	3.54	0.3099	3.16
M-NM 0.75 (3)	55.24	29.7	30.9	49.21	3.92	0.3485	3.56

M-NM 0.75 (4)	48.64	14.2	29.8	48.57	3.22	0.2729	2.79
HS 1	46.76	9.8	29.5	38.97	3.32	0.2709	2.45
M-NM 1 (1)	51.11	20.0	30.6	45.36	3.94	0.3215	3.28
M-NM 1(2)	52.47	23.2	30.9	49.83	3.99	0.3484	3.56
M-NM 1 (3)	54.68	28.4	31.2	50.98	4.12	0.3417	3.49
M-NM 1 (4)	51.15	20.1	30.0	50.98	3.57	0.2982	3.04

σ^c_u – Peak Stress, ε^c_u – Strain at peak stress, E_s – young's modulus, D_f – Ductility factor ($0.85\varepsilon_a/0.85\varepsilon_d$), EA^c – Energy absorption capacity of concrete in compression, T_f – Toughness Factor (EA^c FRC/EA^c C), Superscript "c" represents the values in compression.

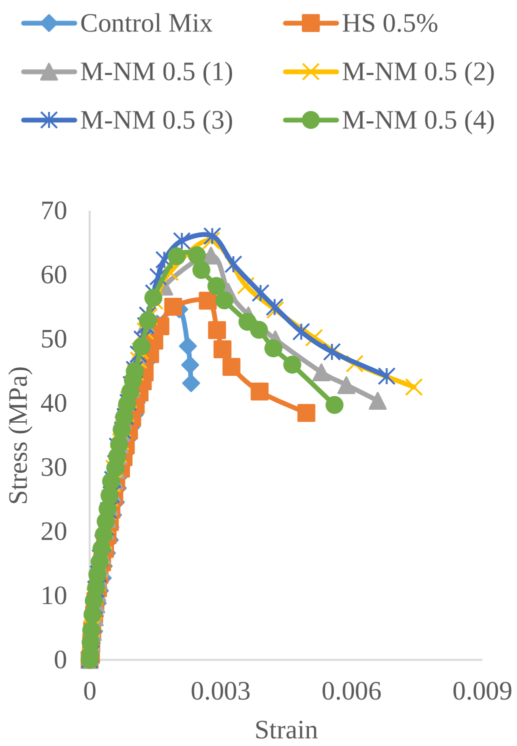


Fig 7.6a Stress-strain curves for metallic - non-metallic HFRC at 0.75% fiber dosage

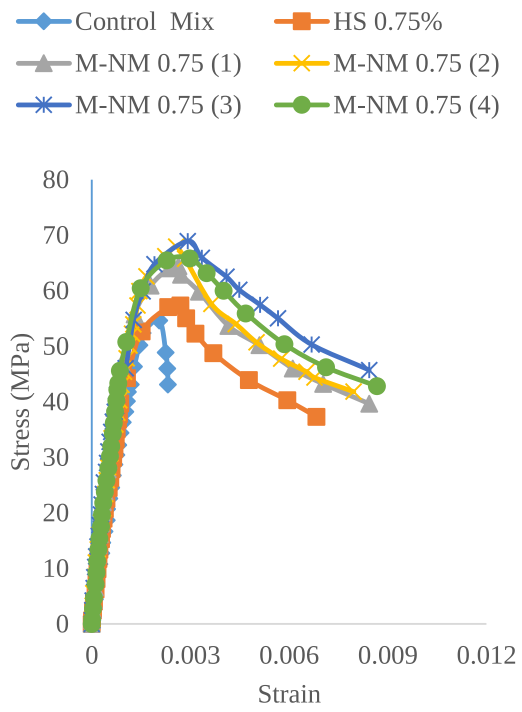


Fig 7.6b Stress-strain curves for metallic - non-metallic HFRC at 0.75% fiber dosage

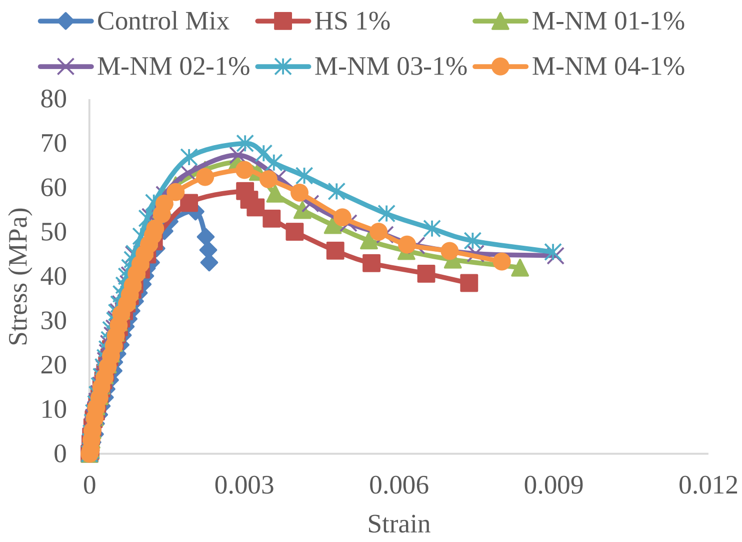


Fig 7.6c Stress-strain curves for metallic - non-metallic HFRC at 1% fiber dosage

Figure 7.6 Stress-strain curves for metallic - non-metallic HFRC for 50 MPa grade of concrete

Table 7.7 Summary of the results for 70 MPa grade of concrete

Mix ID	σ^c_u (MPa)	% Increase	ε^c_u x 10^{-4}	E_s x10^3 (MPa)	D_f	EA^c	T_f
Control Mix	54.55	-	20.5	45.21	2.01	0.1153	1
HS 0.5	54.86	2.4	30.8	46.57	2.61	0.2181	1.89
M-NM 0.5 (1)	63.03	15.3	27.8	52.97	2.72	0.2768	2.40
M-NM 0.5 (2)	65.37	19.6	27.9	53.28	2.95	0.3153	2.73
M-NM 0.5 (3)	66.05	20.9	28.1	56.72	2.85	0.2962	2.57
M-NM 0.5 (4)	63.06	15.4	24.5	57.81	2.78	0.1674	1.45
HS 0.75	54.97	5.0	30.0	47.16	3.12	0.2550	2.21
M-NM 0.75 (1)	64.47	18.0	26.4	55.85	3.16	0.3335	2.89
M-NM 0.75 (2)	67.93	24.3	25.7	56.00	3.24	0.3369	2.92
M-NM 0.75 (3)	68.93	26.1	29.2	56.17	3.32	0.3686	3.20
M-NM 0.75 (4)	65.83	20.5	29.8	54.35	3.12	0.3534	3.06
HS 1	59.82	5.0	30.0	47.16	3.12	0.2550	2.21

M-NM 1 (1)	65.68	20.2	28.5	51.25	3.74	0.3362	2.91
M-NM 1(2)	67.32	23.2	28.8	52.07	3.89	0.3570	3.10
M-NM 1 (3)	70.02	28.1	30.1	61.65	3.92	0.3855	3.34
M-NM 1 (4)	64.01	17.1	30.0	53.63	3.17	0.3271	2.84

From the figure 7.5 to 7.7 it is understood that, fiber hybridization has pronounced impact on both pre-peak and post-peak behaviour. Non-metallic and metallic fibers which are presented in hybridization form significantly improved the pre-peak behaviour of concrete for normal and high strength concretes. In the early stages of concrete PP fibers arrest the formation of plastic shrinkage cracks whereas PO fibers present in concrete bridge the formation of micro-cracks at low-stress levels and hence the ultimate strength of the concrete increases. At high stress-levels these non-metallic fibers pulled-out from the surface or they undergo fracture, at this stage stresses in concrete proximately transfer from non-metallic fiber to metallic fibers. These metallic fibers arrest the propagation of macro-cracks and enhances the toughness at post-crack region. In conclusion combination of both metallic and non-metallic fibers arrest the multi-scale cracks formed at different stress levels in concrete. In totality fibers counter-act the fracture process in the concrete and increases the strength of concrete both at pre-peak and post-crack region.

The peak-strength of the concrete increased significantly through metallic – non-metallic hybridization. The percentage increase in peak-strength achieved maximum at a hybrid combination of 0.85%metallic + 0.15 % non-metallic (M-NM 1 (3)) for all the three grades of concrete. It is 31.1% for 30 MPa grade of concrete, 28.4% for 50 MPa grade of concrete and 28.1% for 70 MPa grade of concrete. There is a slight decrease in strength with the increase in grade of concrete is mainly due to cracks passes throw the aggregate in high strength concrete.

At this stage reinforcement of concrete is not fully utilised. And also composite contains numerous amount of non-metallic fibers which are responsible for the lower workability and improper compaction. Strain at peak-stress is an indication of concrete ductility. There is an increase in strain observed with fiber hybridization compared to mono-FRC. Strain at peak-stress with metallic and non-metallic hybridization in between 0.002 to 0.003. The maximum increase in strain observed at a hybrid combination of 0.9% metallic + 0.1% non-metallic (M-NM 1 (2) for 30 MPa concrete. For 50 and 70 MPa concretes the maximum increase in strain observed at a hybrid combination of 0.85%metallic + 0.15% non-metallic (M-NM 1 (3)) respectively.

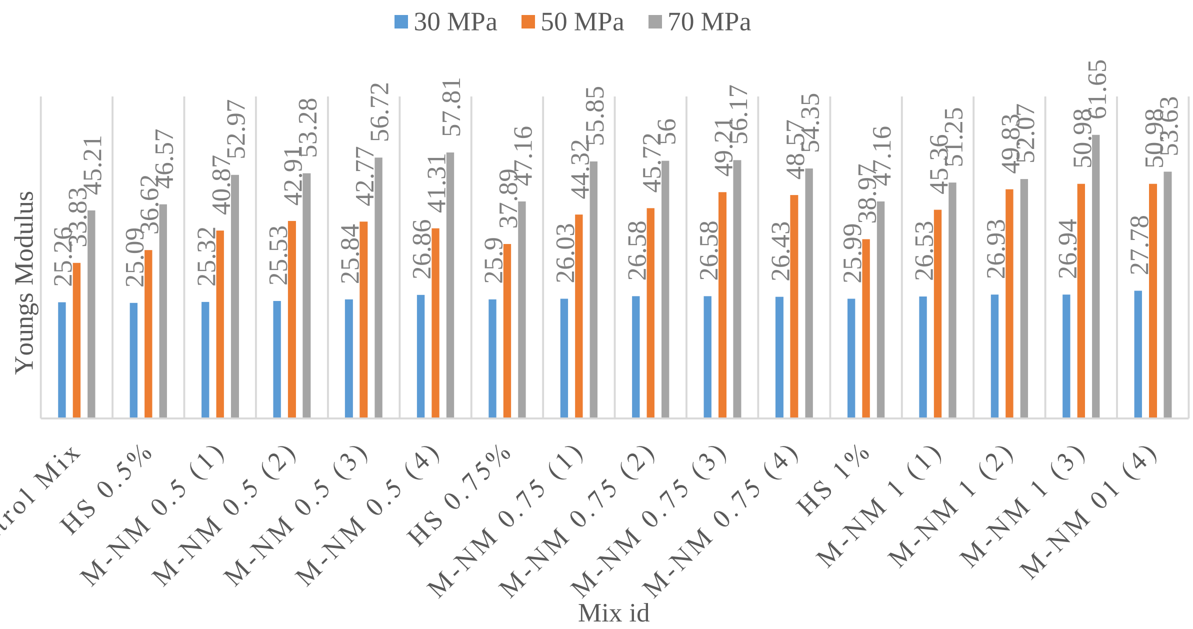


Fig 7.7 Young's modulus of metallic and non-metallic HFRC for 30, 50 and 70 MPa concrete

Figure 7.7 presents the variation of young modulus of metallic and non-metallic HFRC for all the three grades of concrete. It is observed that, for the control mix stiffness of the concrete increases with increase in grade of the concrete. Young's modulus of concrete with the fiber hybridization is more compared to mono-FRC. The maximum stiffness achieved at a hybrid combination of M-NM 1 (3) at a total fiber volume fraction1%.

Ductility factor measured by the ratio of strain at 0.85% peak-stress of ascending potion of stress-strain curve to the strain at 0.85% peak-stress of descending potion of stress-strain curve. Figure 7.8 shows the ductility factor of metallic and non-metallic HFRC for all the grades of concrete. It is observed that ductility ratio increased with fiber hybridization compared to mono-FRC and control Mix. There is decrease in ductility factor is observed with increase in grade of concrete, the maximum ductility factor is achieved at 0.85% metallic + 0.15% non-metallic (M-NM 1 (2)) i.e. 4.58, 4.12 and 3.93 for 30, 50 and 70 MPa concrete respectively.

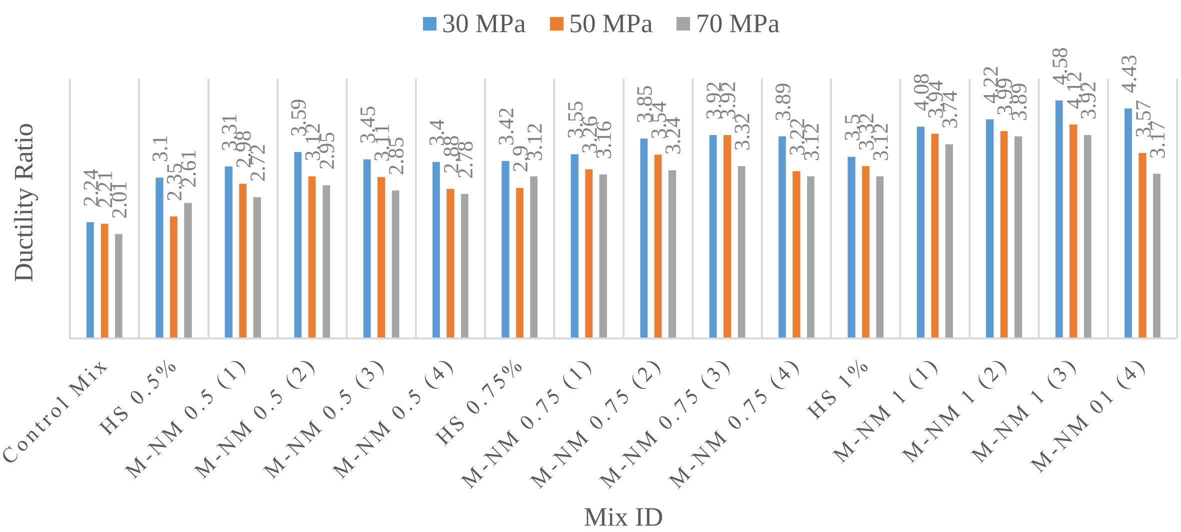


Figure 7.8 Ductility ratio of metallic and non-metallic HFRC for 30, 50 and 70 MPa concrete

Area under stress-strain curve is an indication of energy absorption capacity of concrete. Energy absorption capacity of concrete both at post-peak and post-peak significantly increase with fiber hybridization compared to mono-FRC. The increase in area under stress-strain is because of non-metallic fibers (PP and PO) present in concrete significantly affected the pre-peak behaviour of concrete by bridging the micro-cracks at lower-stress levels and enhanced the pre-peak stress-strain behaviour. At higher stress-levels metallic fibers arrested the propagation of macro-cracks thereby enhanced the post-peak portion of stress-strain curve. The maximum energy absorption capacity of 245% compared to control mix achieved at a hybrid combination of 0.85% metallic + 0.15% non-metallic for all three grades of concrete.

7.2.6 *Stress-strain behaviour of metallic and non-metallic HFRC under uni-axial tension.*

Stress-strain curves of non-metallic and metallic HFRC under uni-axial tension for 30, 50 and 70 MPa concrete are presented in figure 7.9 to 7.10 and the summary of the results are presented in table 7.8 to 7.10 respectively.

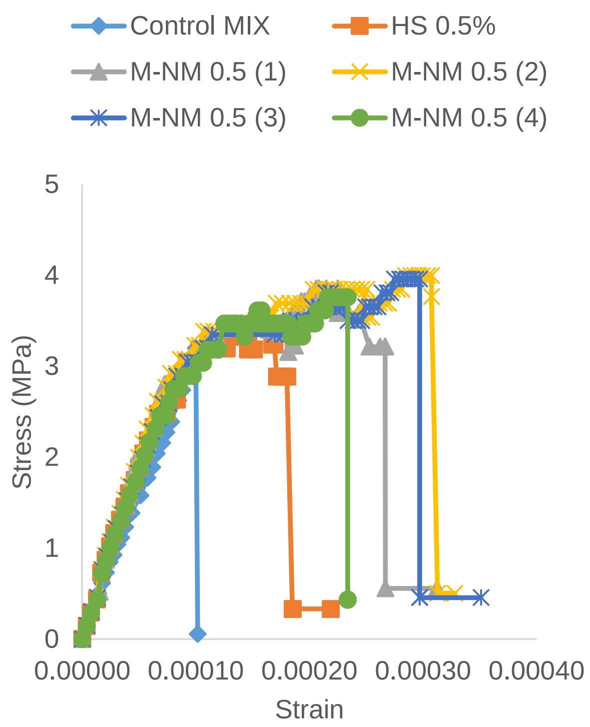


Fig 7.9a Stress-strain curves for metallic - non-metallic HFRC at 0.5% fiber dosage

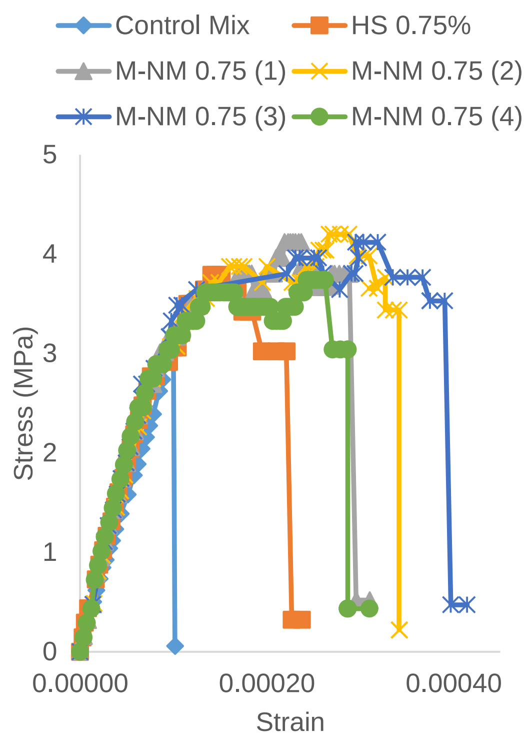


Fig 7.9b Stress-strain curves for metallic - non-metallic HFRC at 0.75% fiber dosage

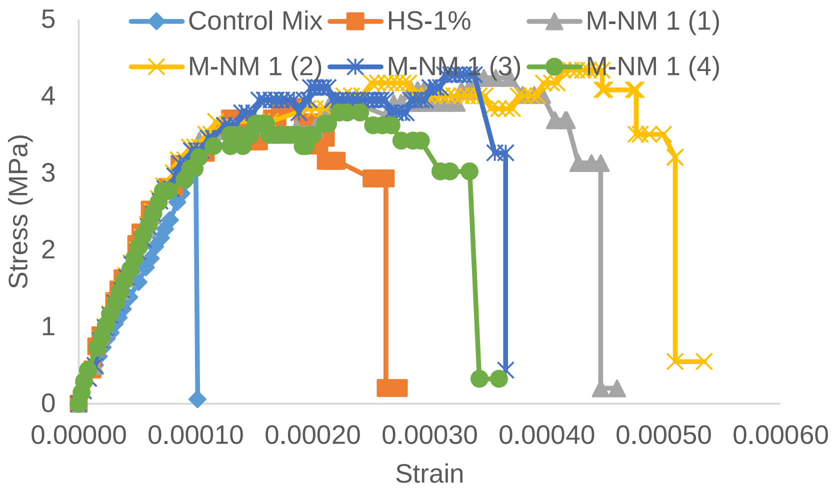


Fig 7.9c Stress-strain curves for metallic and non-metallic HFRC at 1% fiber dosage

Fig 7.9 Stress-strain curves for metallic and non-metallic HFRC for 30 MPa concrete

Table 7.8 Summary of results for 30 MPa grade of concrete

Mix ID	σ^t_f (MPa)	ε^t_f x 10^{-5}	σ^t_u (MPa)	ε^t_b x 10^{-5}	EA^t x 10^{-5} (MPa)
Control Mix	3.20	10.0	3.20	10.2	48.15
HS 0.5	3.19	10.72	3.49	21.9	86.35
M-NM 0.5 (1)	3.21	10.88	3.86	31.21	131.19
M-NM 0.5 (2)	3.24	10.91	4.00	32.80	155.88
M-NM 0.5 (3)	3.26	10.98	3.96	35.11	154.25
M-NM 0.5 (4)	3.18	10.63	3.76	23.37	121.02
HS 0.75	3.21	10.83	3.79	23.8	102.75
M-NM 0.75 (1)	3.27	11.09	4.12	31.01	153.01
M-NM 0.75 (2)	3.29	11.12	4.20	34.20	189.51
M-NM 0.75 (3)	3.32	11.24	4.12	34.19	197.28
M-NM 0.75 (4)	3.24	11.11	3.73	30.99	133.60
HS 1	3.27	10.88	3.86	27.4	128.40
M-NM 1 (1)	3.28	11.52	4.27	46.03	234.2
M-NM 1(2)	3.54	11.61	4.34	53.48	263.34
M-NM 1 (3)	3.32	11.72	4.28	36.51	201.22
M-NM 1 (4)	3.28	11.47	3.77	35.92	156.28

σ^t_f – Stress at inflation point, ε^t_f – Strain at inflation point, σ^t_u – Stress at ultimate point, ε^t_b – Strain at break point, EA^t – Energy absorption capacity, where superscript "t" values in tension.

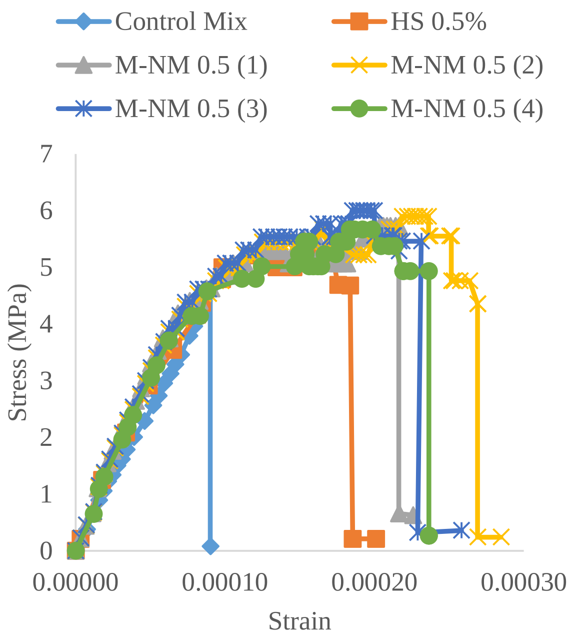


Fig 7.10a Stress-strain curves for metallic - non-metallic HFRC at 0.5% fiber dosage

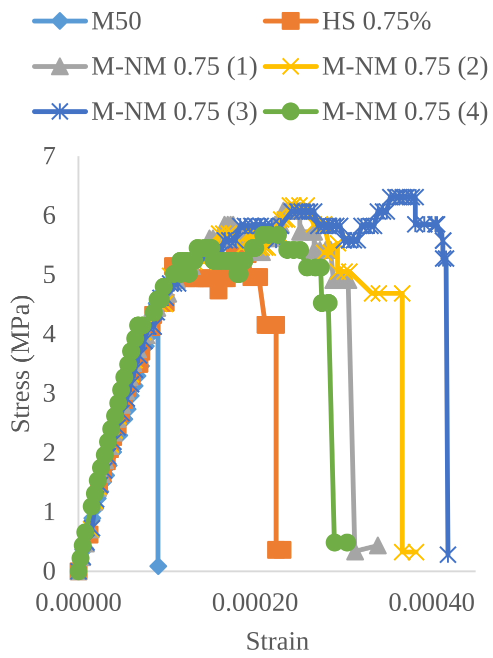


Fig 7.10b Stress-strain curves for metallic and non-metallic HFRC at 0.75% dosage

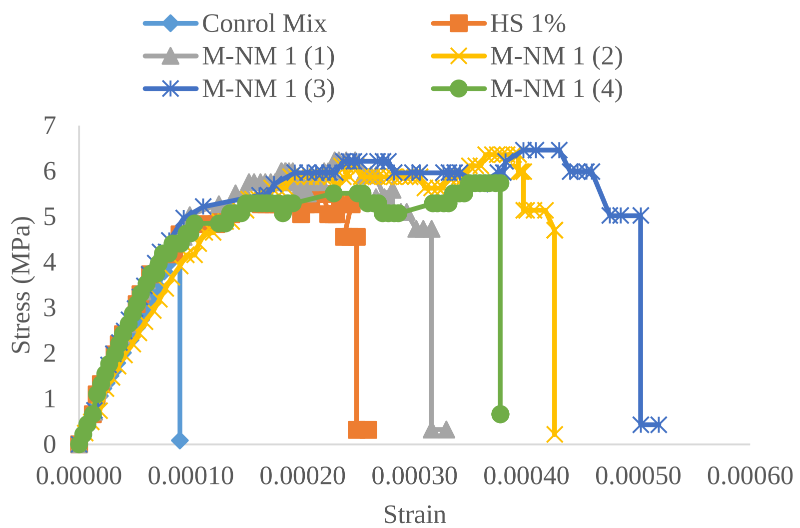


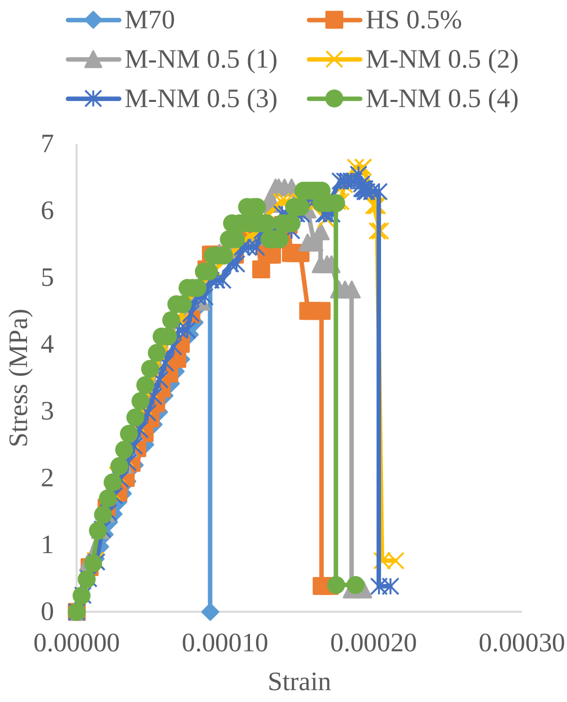
Fig 7.10c Stress-strain curves for metallic - non-metallic HFRC at 1% fiber dosage

Fig 7.10 Stress-strain curves for metallic and non-metallic HFRC for 50 MPa grade of concrete

Table 7.9 Summary of results for 50 MPa grade of concrete

Mix ID	σ^t_f (MPa)	ε^t_f x 10^{-5}	σ^t_u (MPa)	ε^t_b x 10^{-5}	EA^t x 10^{-5} (MPa)
Control Mix	4.63	9.02	4.63	9.02	63.0
HS 0.5	4.79	9.81	5.21	20.1	125.8
M-NM 0.5 (1)	4.81	10.22	5.73	22.6	170.9
M-NM 0.5 (2)	4.90	10.42	5.90	28.5	211.8
M-NM 0.5 (3)	4.92	10.37	6.00	25.8	191.9
M-NM 0.5 (4)	4.85	10.91	5.67	23.6	176.4
HS 0.75	5.12	10.71	5.35	23.1	155.4
M-NM 0.75 (1)	5.22	10.98	6.08	33.9	198.2
M-NM 0.75 (2)	5.34	11.10	6.17	38.2	281.2
M-NM 0.75 (3)	5.62	11.34	6.31	41.8	347.2
M-NM 0.75 (4)	5.27	10.99	5.67	30.4	204.9
HS 1	5.27	11.25	5.49	25.9	181.6
M-NM 1 (1)	5.29	11.29	6.23	32.9	263.2
M-NM 1(2)	5.32	11.36	6.36	42.5	361.4
M-NM 1 (3)	5.34	11.34	6.46	51.8	392.8
M-NM 1 (4)	5.22	11.27	5.95	37.4	276.2

σ^t_f – Stress at inflation point, ε^t_f – Strain at inflation point, σ^t_u – Stress at ultimate point, ε^t_b – Strain at break point, EA^t – Energy absorption capacity, where superscript "t" values in tension.



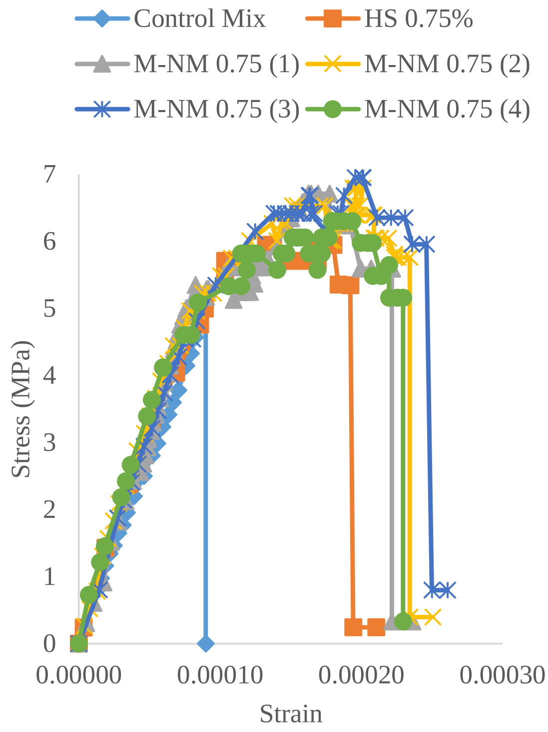


Fig 7.11a Stress-strain curves for metallic - non-metallic HFRC at 0.5% fiber dosage

Fig 7.11b Stress-strain curves for metallic - non-metallic HFRC at 0.75% fiber dosage

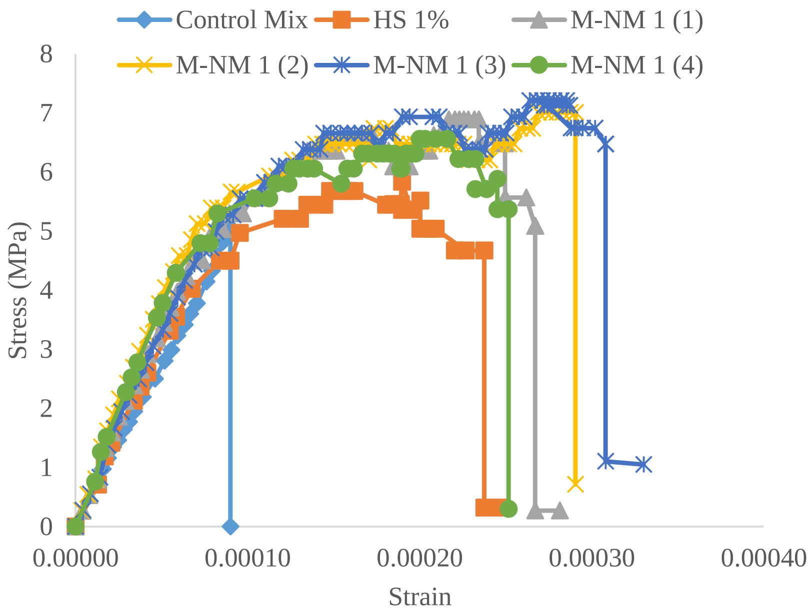


Fig 7.11c Stress-strain curves for metallic - non-metallic HFRC at 1% fiber dosage

Fig 7.11 Stress-strain curves for metallic and non-metallic HFRC for 70 MPa grade of concrete

Table 7.10 Summary of results for 70 MPa grade of concrete

Mix ID	σ^t_f (MPa)	ε^t_f x 10^{-5}	σ^t_u (MPa)	ε^t_b x 10^{-5}	EA^t x 10^{-5} (MPa)
Control Mix	5.05	9.0	5.0	9.0	68.6
HS 0.5	5.12	9.15	5.9	17.0	131.1
M-NM 0.5 (1)	5.26	9.45	6.35	19.3	162.2
M-NM 0.5 (2)	5.29	9.63	6.55	21.1	186.4
M-NM 0.5 (3)	5.32	9.99	6.65	21.5	177.4
M-NM 0.5 (4)	5.19	9.84	6.30	18.8	156.5
HS 0.75	5.46	10.35	6.05	21.1	149.7
M-NM 0.75 (1)	5.55	10.42	6.71	23.6	197.2
M-NM 0.75 (2)	5.59	10.67	6.79	25.0	219.7
M-NM 0.75 (3)	5.64	10.95	6.95	26.2	224.1
M-NM 0.75 (4)	2.38	10.71	6.30	22.9	203.3
HS 1	5.45	10.42	6.15	24.8	178.8
M-NM 1 (1)	5.49	10.69	6.89	28.1	240.9
M-NM 1(2)	5.52	10.74	7.01	29.0	269.8
M-NM 1 (3)	6.01	10.92	7.21	33.0	291.1
M-NM 1 (4)	5.12	10.58	6.56	25.7	221.5

From the figure 7.9 to 7.11 stress-strain curves of metallic and non-metallic HFRC, it is observed that stress in concrete increased with the strain up to the point of inflation and exhibited strain hardening behaviour right up to the ultimate stress and failed suddenly. It is observed that stress at inflation point is increased marginally compared to control mix. This indicates that fibers in concrete active in delaying the crack formation and increasing the first crack stress. The percentage increase in stress at inflation point is 10.6% for 30 MPa concrete at a hybrid combination of 0.9%metallic + 0.1% non-metallic (M-NM 1 (2)), the percentage strength increment at inflation point for 50 and 70 MPa concrete is 15.3% and 19.3% at a hybrid combination of 0.85% metallic+0.15% non-metallic (M-NM 1 (3)) repeatedly. The stress-strain curve after the inflation point exhibited the strain hardening behaviour thereafter little strain softening behaviour at the end of the curve and failed suddenly. This behaviour is observed only in metallic and non-metallic HFRC.

The failure strain of metallic and non-metallic HFRC exponentially increased compared to mono-FRC for the same fiber volume fraction. It is also observed that the strain at failure is decreased with increase in grade of concrete. At higher grades the HFRC could not exhibited much strain hardening behaviour compared to mono-FRC due its brittle nature. The maximum increase in failure strain observed at a hybrid combination of 0.9%metallic + 0.1%non-metllic for 30 MPa grade of concrete is 235% compared to control mix.

Toughness (energy absorption capacity) of concrete increases with metallic and non-metallic hybridization owing to availability of non-metallic fibers in the concrete bridge the micro-cracks at failure region and increased the inflation stress of the concrete, whereas metallic fiber present in the concrete arrested the propagation of macro-cracks. The percentage increase in energy absorption capacity for 30 MPa concrete for non-metallic HFRC at a hybrid combination of M-NM 1 (2) is 447% compared to control mix, for 50 MPa concrete the increment is 522% and for 70 MPa concrete is 327% increase is observed and the results are shown in table 7.8 to 7.10.

The optimum dosage of hybrid combination of 30 MPa concrete is 0.9% metallic + 0.1% non-metallic (M-NM 1 (2)) and for 50 MPa and 70 MPa concrete it is 0.85% metallic + 0.15% non-metallic (M-NM 1 (3)) it is also noticed that higher grades requires more non-metallic fibers because of plastic shrinkage cracks are more.

7.3 Concluding remarks from phase III

In this chapter mechanical behaviour of non-metallic and metallic HFRC has been studied and compared to mono-FRC for the same fiber volume fraction. Compressive strength, direct tensile strength, flexural strength and stress-strain behaviour under uni-axial stresses have been investigated. Following conclusions are drawn from the present experimental investigation.

- Synergy effect was found to be more with the addition of metallic and non-metallic fibers due to inhibition of crack control at different stress levels.
- Optimum dosage of fibers in metallic and non-metallic HFRC achieved at total fiber volume fraction of 1% (0.9% Metallic + 0.1% non-metallic) for 30 MPa (0.85% Metallic + 0.15% Non-metallic) for 50 MPa concrete and for 70 MPa concrete (0.85% Metallic + 0.15% Non-metallic).
- The requirement of non-metallic fibers in hybrid combination increased with the increase in grade of the concrete.
- Improvement in direct tensile strength of HFRC using steel, polyester and polypropylene fibers at a total fiber volume fraction is 36% for 30 MPa, 39% for 50 MPa and 42% MPa 70 MPa concrete compared to the control mix
- Improvement in flexural strength of HFRC at a total fiber volume fraction is 42% for 30 MPa, 43.0% for 50 MPa and 45.2% for 70 MPa compared to the control mix.
- The stress-strain behaviour of concrete under uni-axial compression is significantly improved with the metallic and non-metallic fiber hybridization

- The increase of peak-stress is 31.1% for 30 MPa concrete at an optimum dosage (0.9% metallic + 0.1% non-metallic). For 50 MPa and 70 MPa concrete at an optimum dosage (0.85% metallic + 0.15% non-metallic) is 28.4% and 28.1% respectively.
- The energy absorption capacity of concrete under uni-axial compression is significantly improved with metallic and non-metallic hybridization compared to mono-FRC for the same fiber volume fraction.
- The stress-strain curve of HFRC under uni-axial tension is linear up to inflection point there after exhibited strain Harding behaviour and failed suddenly.
- The maximum increase in toughness under uni-axial tension is achieved at a hybrid combination 0.9% metallic + 0.1% non-metallic (M-NM 1 (2)) for 30 MPa concrete and 0.85% metallic and 0.15% non-metallic (M-NM 1 (3)) for 50 and 70 MPa concrete respectively.

CHAPTER - 8

PHASE IV - VALIDATION OF MECHANICAL PROPERTIES OF HFRC ON NUMERICAL MODELING (ATENA)

8.1 General

In previous chapters 5, 6 and 7 mechanical properties of mono-FRC, non-metallic HFRC and metallic and non-metallic HFRC discussed respectively in detail. To develop a HFRC it is needed to go through number of combinations and trails and it requires sufficient amount of time and energy for the comprehensive experimentations. Non-linear analysis requires particularly for reinforced concrete structures, because of relatively small deformations, serviceability limitations and low tensile strength of the concrete need to be accounted. ATENA is a user-friendly software developed specially for nonlinear analysis of reinforced concrete structures to avoid comprehensives experimentation. In this chapter experimental results are compared with finite element model created using ATENA.

8.2 FEM modelling using ATENA-GID

To generate a complete finite element model for the non-linear analysis is done by ATENA software. The following procedure was adopted

The purpose of the geometrical model is to describe the geometry of the structure, its material properties and boundary conditions. The analytical model for the finite element analysis has been created during the pre-processing stage with the help of mesh generator. The definition of the geometry starts with the creation of geometrical points, these points are later connected into boundary lines. The surfaces are defined by selecting appropriate bounding lines. Volumes can be formed either by extrusion of surfaces or manually by selecting all bounding surfaces.

Three-dimensional regions are modelled by volumes in GID. After creation of the geometry, material properties defined and assigned to individual volumes. Boundary conditions are used to define supports and loads. The boundary conditions and loads are defined in GID with the help of "Intervals". Interval represents a set of boundary conditions and loads that are applied in a specified number of steps. An appropriate definition of intervals used to specify a complete loading history. Then monetary points have been defined, these monitoring points are used to see the evolution of certain quantities during the analysis.

8.3 Material models used in ATENA

The program system ATENA offers a variety of material models for different materials and purposes. For metals, von Mises plasticity can be used, for rock and soil, Drucker-Prager plasticity with associated or non-associated flow rule is available, while for steel, reinforcement multi-linear uniaxial model with cycling is determined. Nonlinear and contact springs for supports can be used, for interfaces Mohr-Coulomb friction is available. In some cases the use of isotropic elastic material law can be advantageous.

Nevertheless, the most important material models in ATENA are the material models for concrete. These advanced models take into account all the important aspects of real material behaviour in tension and compression. Three nonlinear material models for concrete are available in ATENA: crack band model based on fracture energy, fracture-plastic model with non-associated plasticity, and micro plane material model are available.

8.3.1 *Plain Concrete*

For Plain concrete Material type Cementitious2 was used, which is suitable for concrete like materials. Atena name for this nonlinear cementations material is CC3DNonLinCementitious. If cube strength is given as input, the following data can be updated automatically generated values are modified according to our 150 x 150 x 150mm cube details as shown in Table 8.1.

Table 8.2 Modified input data for 30 MPa plain concrete

Input format	Property type	Given Input
Basic	Young's Modulus	27386.12 N/mm2
	Poisson's ratio	0.15
	Direct tensile strength	3.18 N/mm2
	Compressive strength	36.21 N/mm2
Tensile	Fracture Energy	0.000129
	Fixed crack	1
	Activate aggregate interlock	20mm
Compressive	Plastic strain	0.002
	Onset of crushing	0
	Fc Reduction	0.6

8.3.2 ***Fiber reinforced concrete***

For FRC, Material type *Cementitious2user* was used, which is Strain Hardening Cementations Composite material. Material suitable for fiber reinforced concrete. ATENA name for this nonlinear cementations material is *CC3DNon-Lin Cementitious2*. Material properties like basic like Young's modulus, direct tensile strength and compressive strength are defined as input parameters. Input for tensile and compressive properties of FRC as follows.

8.4 FEM model generation

To determine the stress-strain behaviour of concrete under uni-axial compression 200x100x100mm prism was modelled and 500x100x100mm prism was modelled for flexure using ATENA-GID software. The present study shape of the element used is hexahedron for concrete specimen and tetrahedron for supporting steel plates, the boundary conditions used in the analysis was simply supported.The following steps are followed to analyse the model in ATENA-GID [Cervenka V et.al. 2016].

8.4.1 *Modelling of 200x100x100mm Prism for Uniaxial Compression*

Modelling for stress-strain curve for concrete under uni axial compression as shown in figure 8.1 to 8.6.

Step 1: Generating a model

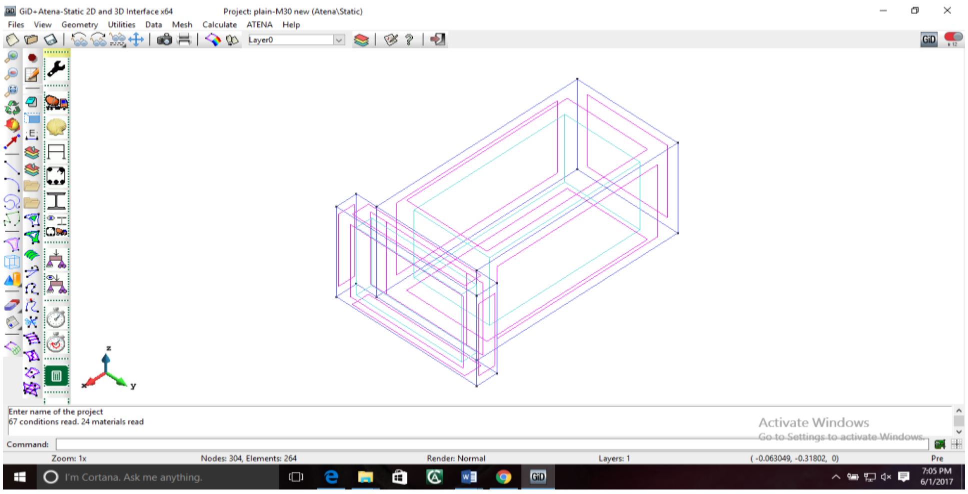


Figure 8.1 Geometric model in ATENA-GID

Step 2: Imposing the boundary conditions and loading on the geometrical model.

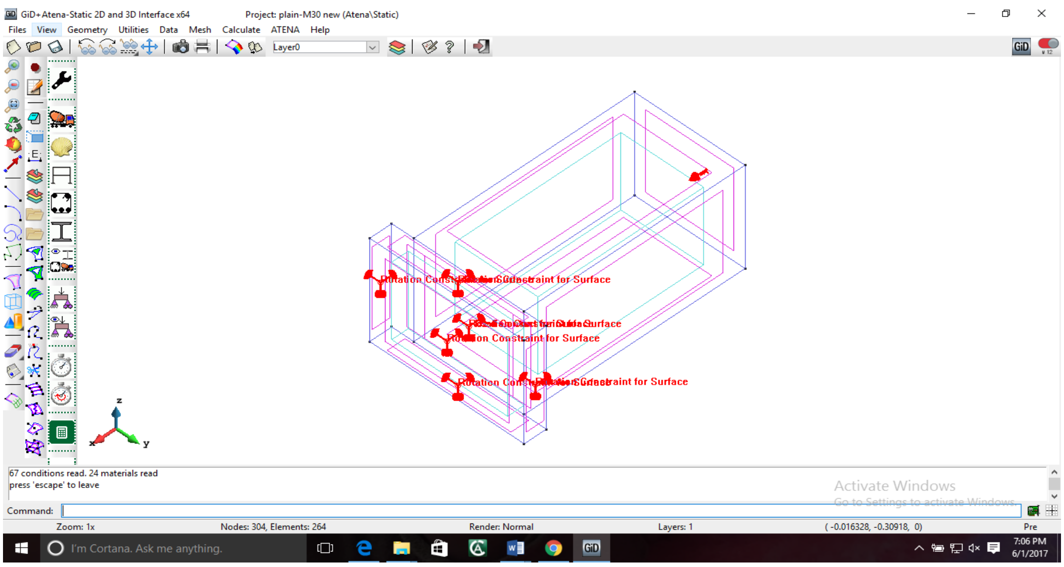


Figure 8.2 After imposing boundary conditions

Step 3: Assigning material properties

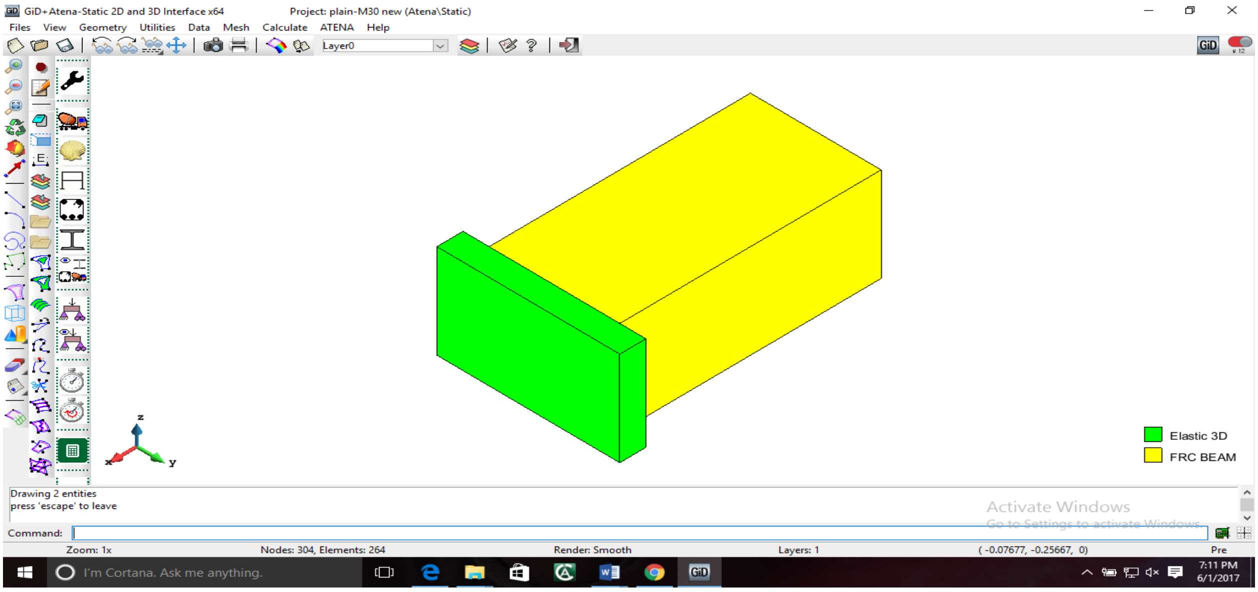


Figure 8.3 Model after assigning material properties

Step 4: Generating finite element mesh.

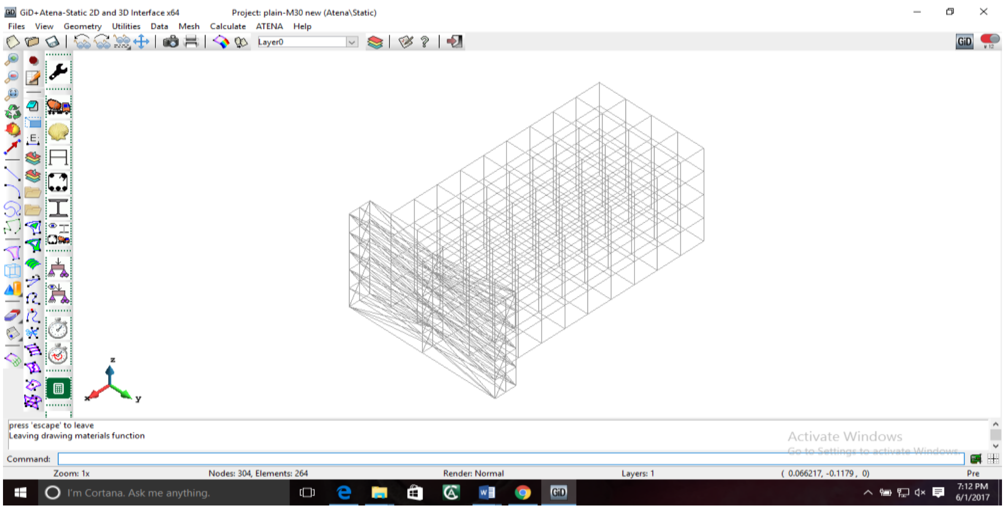


Figure 8.4 Meshing of Prism and Plates

Step 5: Selecting a point where the results are required

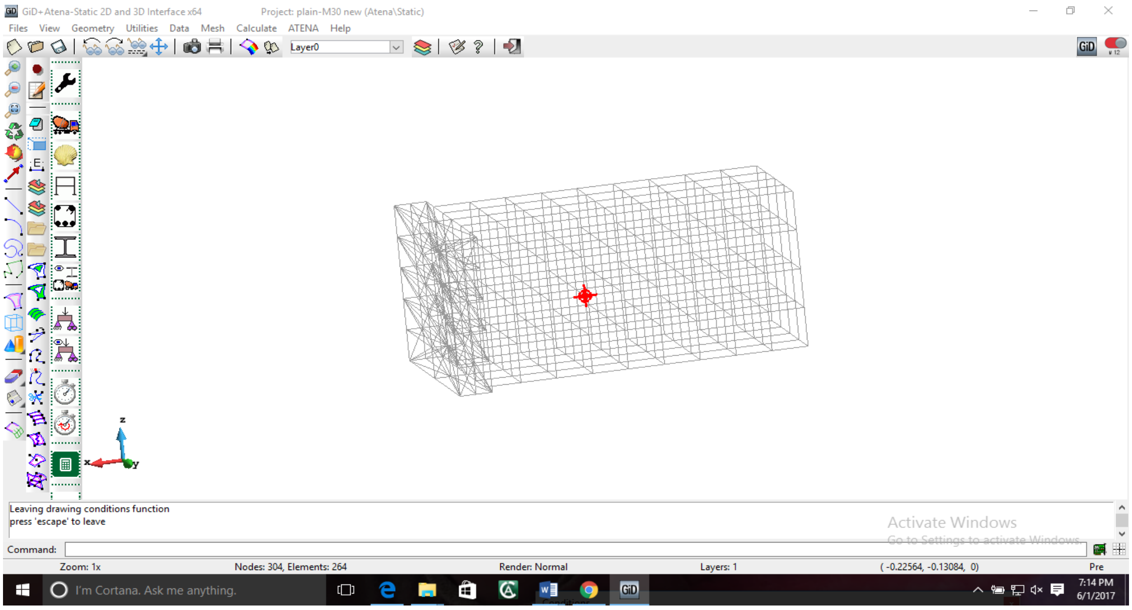


Figure 8.5: Monetary point where the results are taken

Step 6 running the model in ATENA-Studio

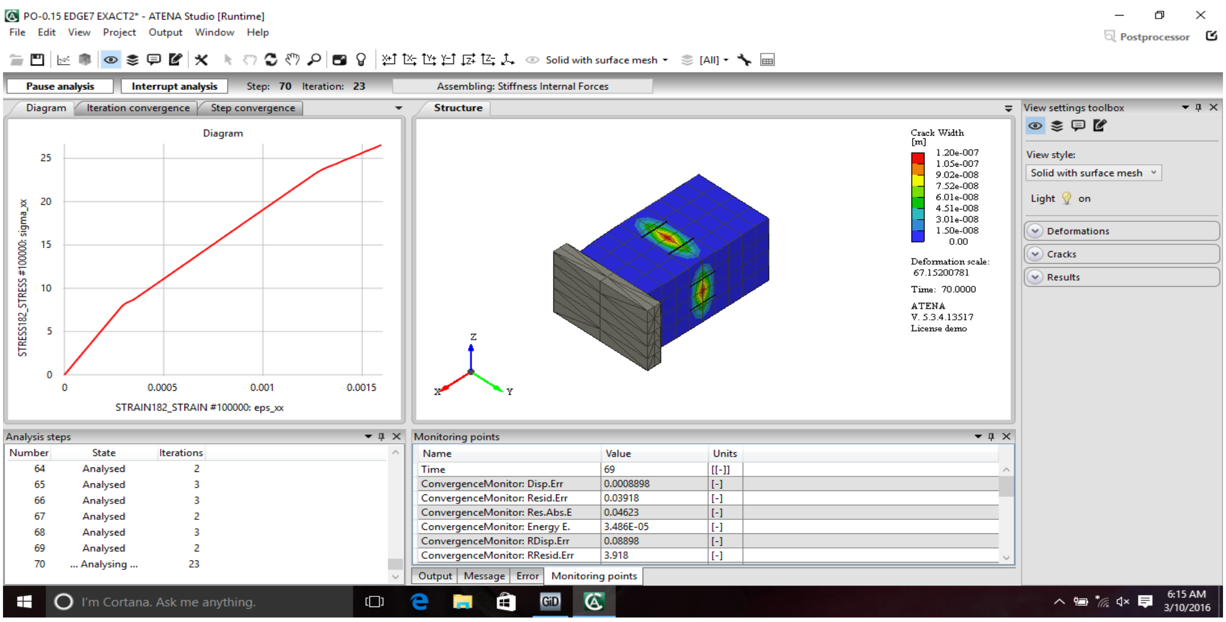


Figure 8.6 Stress contours due to direct compression

8.4.1.1 Comparison of experimental and ATENA results.

For concrete under uniaxial compression, experimental stress-strain curves for 30 MPa concrete and stress-strain curves generated by ATENA model are presented in figures 8.7 and 8.8 respectively. Summary of the results in comparison with experimental and ATENA model for 30MPa, 50MPa and 70MPa concrete are presented in table 8.2 to 8.4 respectively. It is observed that peak-stress values are slightly higher than the experimental results. It is also observed that values obtained through ATENA model are in good agreement with the experimental values the percentage error observed in peak-stress is not more than 15%. Similar trend observed in toughness values also.

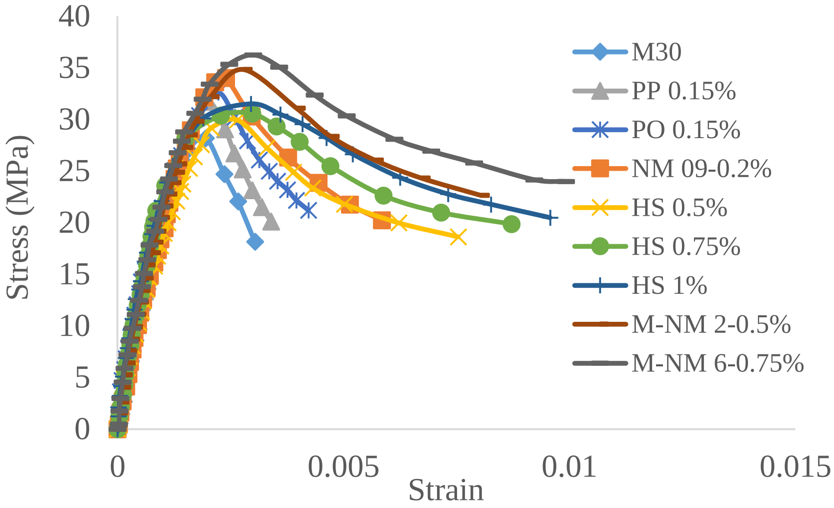


Figure 8.7 Experimental stress strain curves for 30MPa concrete

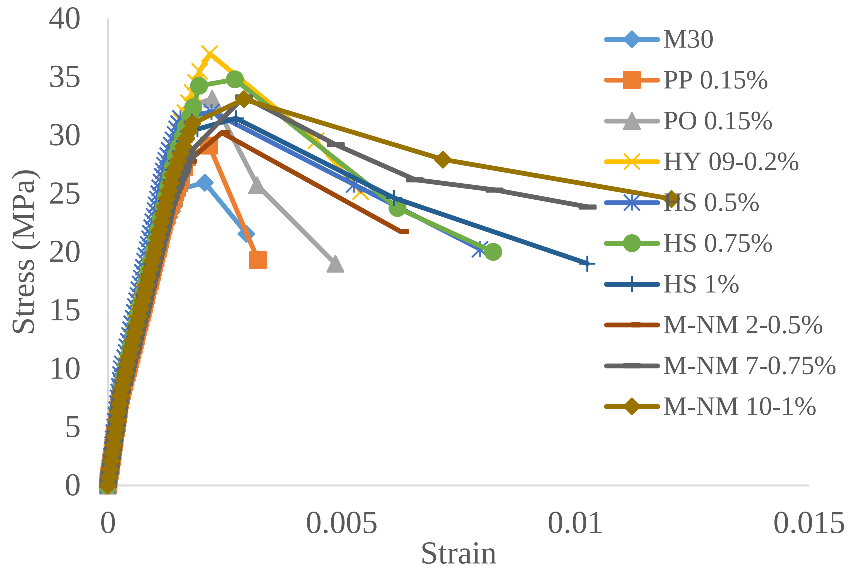


Figure 8.8 ATENA Stress-strain curve

Table 8.2 Comparison of experimental and ATENA for 30 MPa concrete

Mix ID	Peak Stress			Toughness		
	Experimental	Atena	Error in Percentage	Experimental	Atena	Error in Percentage
Control Mix	28.19	31.46	-11.58%	0.0734	0.0652	-11.09%
PP 0.15%	31.7	29.11	8.18%	0.09049	0.0997	10.18%
PO 0.15%	31.96	33.13	-3.65%	0.105511	0.1234	16.95%
NM 0.2 (3)	34.03	36.98	-8.66%	0.1417	0.1463	3.25%
HS 0.5%	29.34	32.00	-9.06%	0.145325	0.1478	1.70%
HS 0.75%	29.94	32.68	-9.15%	0.162618	0.1426	-12.31%
HS 1%	30.87	31.46	-1.90%	0.18453	0.1652	-10.48%
M-NM 0.5 (2)	34.85	30.22	13.30%	0.185	0.1458	-21.19%
M-NM 0.75 (2)	36.24	33.29	8.13%	0.22	0.2073	-5.76%
M-NM 0.75 (2)	36.97	33.08	10.52%	0.25127	0.2351	-6.43%

Table 8.3 Comparison of experimental and ATENA for 50 MPa concrete

Mix ID	Peak Stress			Toughness		
	Experimental	Atena	Error in Percentage	Experimental	Atena	Error in Percentage
Control Mix	42.59	43.25	1.53%	0.098	0.1125	14.91%
PP 0.15%	47.08	49.56	5.00%	0.130	0.1574	21.26%
PO 0.15%	46.8	50.00	6.40%	0.142	0.1452	2.18%
NM 09-0.2%	49.95	53.06	5.86%	0.218	0.2552	17.17%
HS 0.5%	44.03	41.25	-6.74%	0.206	0.2436	18.02%
HS 0.75%	45.18	42.69	-5.83%	0.240	0.2712	12.85%
HS 1%	46.76	52.12	10.28%	0.271	0.3246	19.83%
M-NM 2- 0.5%	51.4	57.16	10.08%	0.251	0.2965	18.27%
M-NM 6-0.75%	55.24	59.92	7.81%	0.349	0.3819	9.58%
M-NM 10 -1%	54.68	54.38	-0.55%	0.298	0.2832	-5.03%

Table 8.4 Comparison of experimental and ATENA for 70 MPa concrete

Mix ID	Peak Stress			Toughness		
	Experimental	Atena	Error in Percentage	Experimental	Atena	Error in Percentage
Control Mix	54.65	58.96	-7.89%	0.115	0.1356	17.61%
PP 0.15%	59.63	64.99	-8.99%	0.161	0.1810	12.69%
PO 0.15%	59.81	68.98	-15.33%	0.186	0.2251	21.22%
NM 09-0.2%	62.97	69.57	-10.48%	0.283	0.3701	30.95%
HS 0.5%	54.86	61.02	-11.23%	0.218	0.2658	21.87%
HS 0.75%	57.94	60.99	-5.26%	0.255	0.3313	29.93%
HS 1%	59.82	64.98	-8.63%	0.279	0.2895	3.91%
M-NM 2- 0.5%	69.16	73.11	-5.71%	0.337	0.4215	24.97%
M-NM 6-0.75%	72.56	75.98	-4.71%	0.427	0.4732	10.79%
M-NM 10 -1%	73.6	72.99	0.83%	0.484	0.5039	4.09%

8.4.2 Modelling of 500x100x100mm Prism for flexure:

To validate the ATENA model with experimental results, flexural model of 500 x 100 x 100 mm developed with the properties obtained from compression model i.e. 200 x 100 x 100 mm specimen. For the flexural model only half of the portion considered and analysed in ATENA because the specimen is symmetry on both the side from the centre of the semen. The steps are considered to develop a model is presented in figure 8.9 to 8.13

Step 1: Generating a model

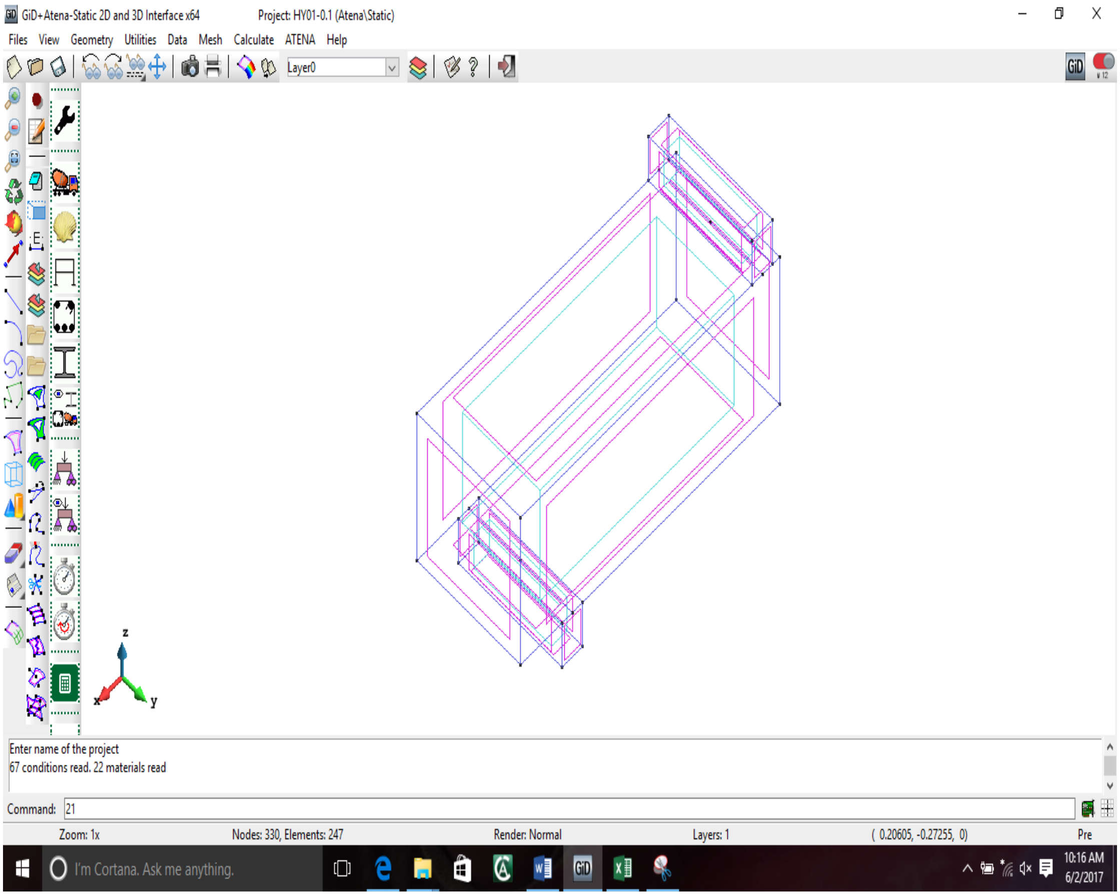


Figure 8.9 Geometric model in ATENA-GID

Step 2: Imposing the boundary conditions and loading on the geometrical model.

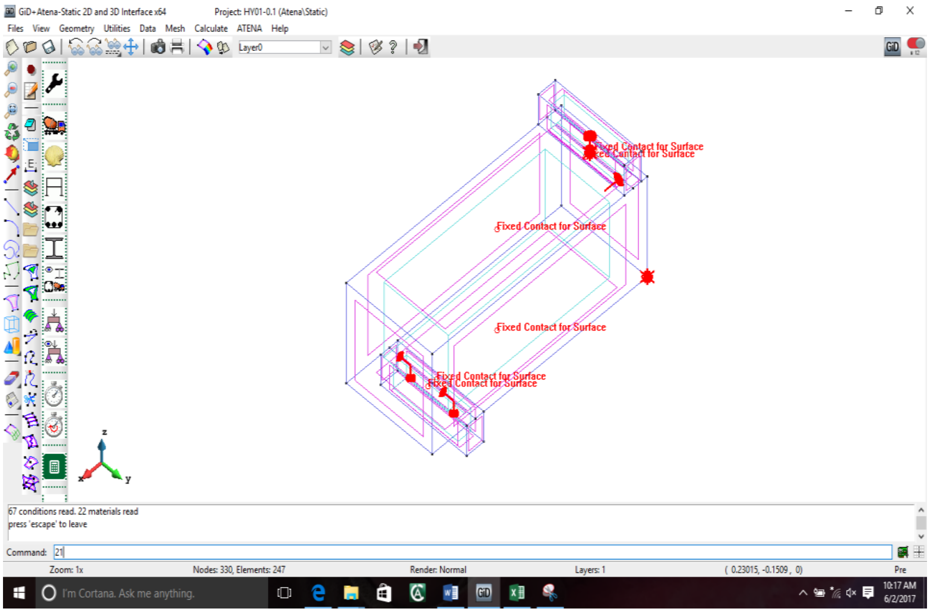


Figure 8.10 After imposing boundary conditions

Step 3: Application of material properties

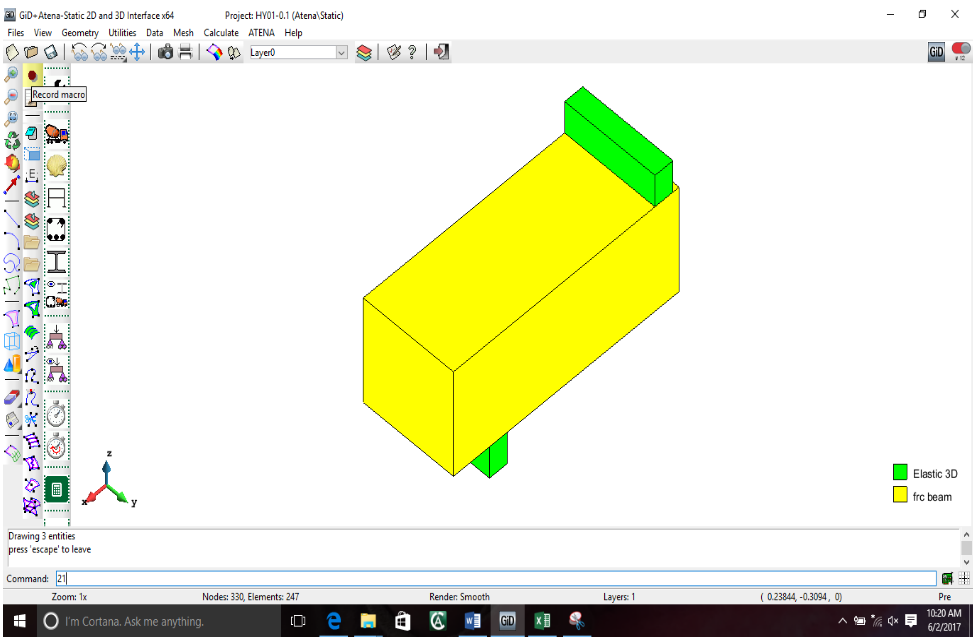


Figure 8.11 Model after assigning material properties

Step 4: Generating finite element mesh.

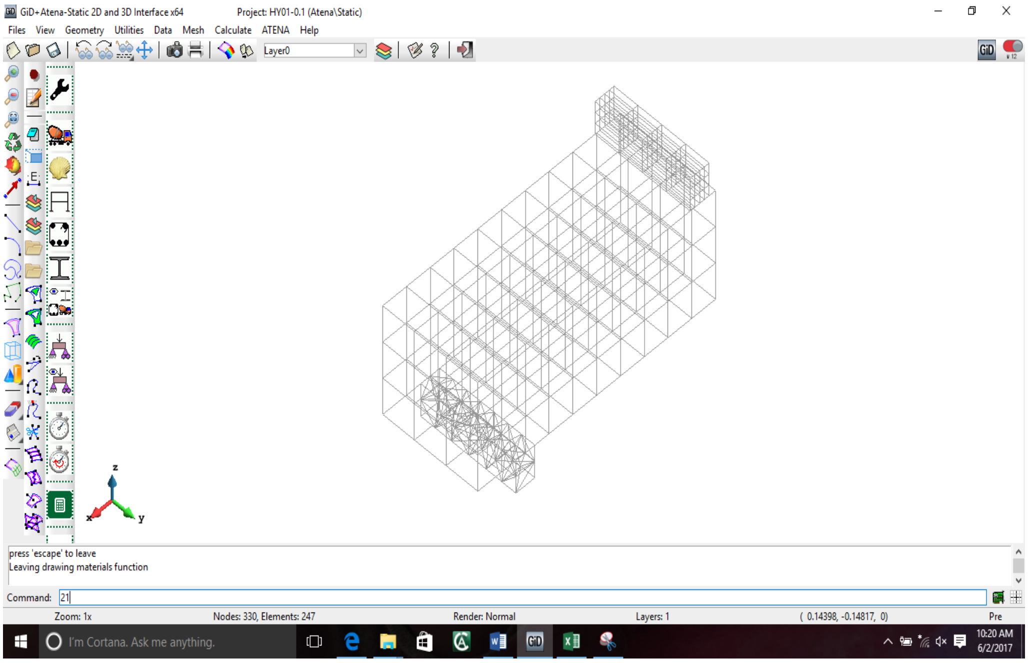


Figure 8.12 Meshing of Prism and Plates

Step 5: Running the model in ATENA-Studio

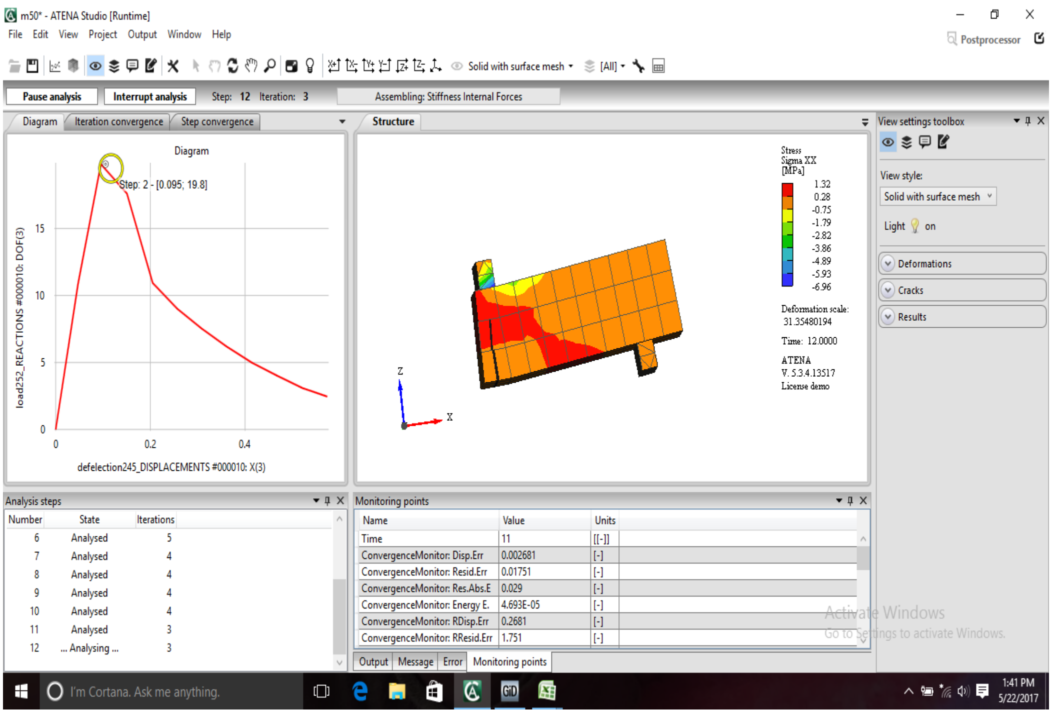


Figure 8.23: Stress contours due to flexure loading

8.4.2.1 Comparison of experimental and ATENA results for concrete specimens under flexure.

To generate the hybrid fiber reinforced concrete model, experimental stress-strain curve obtained for concrete under uni-axial stress are given manually. Flexure model is generated for the same property and compared with the experimental values. Comparison of ATENA results with the experimental results are presented in Table 8.5 to 8.7. From the values it is observed that predicted flexural strength values are in good agreement with the experimental results. The error in percentage is not more than 10%.

Table 8.5 Comparison of experimental and atena flexure strength values 30 MPa

Mix ID	Total Fiber Dosage (%)	Experimental Flexure strength (MPa)	Analytical Flexure strength (MPa)	Error in percentage
Control Mix	-	4.1	4.18	-1.95%
PP 0.15	0.15	4.62	4.99	-8.01%
PO 0.15	0.15	4.73	5.01	-5.92%
M-NM 0.2 (3)	0.2	5.01	5.21	-3.99%
HS 0.5%	0.5	4.6	4.37	5.00%
HS 0.75%	0.75	4.74	5.31	-12.03%
HS 1%	0.1	4.93	4.88	1.01%
M-NM 0.5 (2)	0.5	5.37	4.83	10.06%
M-NM 0.75 (2)	0.75	5.67	5.73	-1.06%
M-NM 1 (2)	1	5.83	5.43	6.86%

Table 8.6 Comparison of experimental and atena flexure strength values 50 MPa

Mix ID	Total Fiber Dosage (%)	Experimental Flexure strength (MPa)	Analytical Flexure strength (MPa)	Error in percentage
Control Mix	-	5.42	5.43	-0.18%
PP 0.15	0.15	6.17	6.48	-5.02%
PO 0.15	0.15	6.36	6.93	-8.96%
M-NM 0.2 (3)	0.2	6.73	6.33	5.94%
HS 0.5%	0.5	6.25	6.38	-2.08%
HS 0.75%	0.75	6.37	6.31	0.94%
HS 1%	0.1	6.59	5.93	10.02%
M-NM 0.5 (3)	0.5	7.38	8.12	-10.03%
M-NM 0.75 (3)	0.75	7.7	7.55	1.95%
M-NM 1 (3)	1	7.93	7.85	1.01%

Table 8.7 Comparison of experimental and atena flexure strength values 70 MPa

Mix ID	Total Fiber Dosage (%)	Experimental Flexure strength (MPa)	Analytical Flexure strength (MPa)	Error in percentage
Control Mix	-	6.02	6.14	-1.99%
PP 0.15	0.15	7.02	6.67	4.99%
PO 0.15	0.15	7.14	8.00	-12.04%
M-NM 0.2 (3)	0.2	7.72	8.72	-12.95%
HS 0.5%	0.5	7.08	7.15	-0.99%
HS 0.75%	0.75	7.26	6.82	6.06%
HS 1%	0.1	7.44	7.14	4.03%
M-NM 0.5 (3)	0.5	8.32	9.24	-11.06%
M-NM 0.75 (3)	0.75	8.8	9.24	-5.00%
M-NM 1 (3)	1	8.92	9.54	-6.95%

8.5 Concluding remarks from PHASE IV

- Experimental results at optimised hybrid combinations in mono-FRC, non-metallic HFRC and HFRC (Metallic and non-metallic) are in good agreement with the values obtained by the ATENA model.
- Peak-strength values of HFRC under uni-axial compression are compared with peak-strength values of ATENA model. The percentage error observed between experimental results and analytical results are within 15%.
- Experimental Flexure strength results are compared with results obtained by the ATENA model and the results are in good agreement.
- The developed ATENA model can be used for different fiber volume fraction and different loading conditions in order to avoid comprehensive experimentations.

CHAPTER 9

OVERAL CONCLUSIONS

9.1 General

From the previous chapters about the influence of hybrid fibers on the mechanical behaviour of metallic and non-metallic fiber reinforced concrete are investigated and following conclusions can be drawn

9.2 Conclusions on mechanical properties of mono-FRC

- Optimum dosage of PP and PO fibers achieved at 0.15% volume fraction. Optimum dosage of hooked end steel fiber achieved at 1% in mono FRC. Thereafter there is decrease in strength characteristics observed due to more number of fibers replaced the cement matrix.

- Strength-effectiveness of metallic fiber is more pronounced compared to the non-metallic fibers at higher dosages.

- Improvement of compressive strength is not significant with the addition of non-metallic fibers, due to presents of numerous fibers leads to improper compaction and unnecessary voids. Whereas strength improvement in compression for metallic fiber is also marginal. But enhancement in direct tensile strength and flexural strength is observed more, this may be due to fibers in concrete controls the formation of crack growth.

- Fiber effect in pre-peak region of stress-strain curve is more significant in addition of non-metallic fibers, whereas metallic fibers improved the load carrying capacity at post-crack region this is due to the stiffness of steel fibers control crack growth even after the crack formation.

- Behaviour of stress-strain curve of PO-FRC and HS-FRC under direct tension is similar up to inflection point and exhibiting strain hardening behaviour their after right up to failure of specimens.

9.3 Conclusions on Mechanical behaviour of non-metallic HFRC

- It is possible to develop non-metallic HFRC using PP and PO fibers combinedly for better mechanical properties compared to mono-FRC and control mix.
- Hybrid combination with 75% PO and 25% PP considered to be the best proportion in the composite for all the strength parameters, among all four fiber volume fractions i.e. 0.1, 0.15, 0.2, 0.25%.
- The percentage increase in direct tensile strength and flexure strength is 20.2% and 22% for 30 MPa concrete, 20.2% and 24.2% for 50 MPa concrete and for 70 MPa concrete it is 24.2% and 28.2% respectively for non-metallic HFRC at a total fiber dosage of 0.2%.
- Peak-stress of non-metallic HFRC under uni-axial compression increased with fiber hybridization. The maximum percentage increase in peak-stress is 20.6% for 30 MPa, 17.3% for 50 MPa concrete and 15.2% for 70 MPa concrete observed at a fiber hybrid combination of 75 % PO + 25% PP in a total fiber volume fraction of 0.2%.
- Energy absorption capacity (toughness) of non-metallic HFRC under uni-axial stresses increased with fiber hybridization. The maximum percentage increase in toughness achieved at a hybrid combination of 75% PO+25% PP in a total fiber volume fraction of 0.2%.

9.4 Conclusions on mechanical behaviour of metallic and non-metallic HFRC

- Synergy effect was found to be more with the addition of metallic and non-metallic fibers due to inhibition of crack control at different stress levels.
- Optimum dosage of fibers in metallic and non-metallic HFRC achieved at total fiber volume fraction of 1% at a hybrid combination of 0.9% Metallic + 0.1% non-metallic 30 MPa concrete. For 50 MPa concrete and 70 MPa concrete is 0.85% Metallic + 0.15% Non-metallic.
- The requirement of non-metallic fibers in hybrid combination increased with the increase in grade of the concrete.
- Improvement in direct tensile strength of HFRC using steel, polyester and polypropylene fibers at a total fiber volume fraction is 36% for 30 MPa, 39% for 50 MPa and 42% MPa 70 MPa concrete compared to the control mix
- Improvement in flexural strength of HFRC at a total fiber volume fraction is 42% for 30 MPa, 43.0% for 50 MPa and 45.2% for 70 MPa compared to the control mix.
- The stress-strain behaviour of concrete under uni-axial compression is significantly improved with the metallic and non-metallic fiber hybridization
- The increase of peak-stress is 31.1% for 30 MPa concrete at an optimum dosage (0.9% metallic + 0.1% non-metallic). For 50 MPa and 70 MPa concrete at an optimum dosage (0.85% metallic + 0.15% non-metallic) is 28.4% and 28.1% respectively.

- The energy absorption capacity of concrete under uni-axial compression is significantly improved with metallic and non-metallic hybridization compared to mono-FRC for the same fiber volume fraction.

- The stress-strain curve of HFRC under uni-axial tension is linear up to inflection point there after exhibited strain Harding behaviour and failed suddenly.

- The maximum increase in toughness under uni-axial tension is achieved at a hybrid combination 0.9% metallic + 0.1% non-metallic for 30 MPa concrete and 0.85% metallic and 0.15% non-metallic for 50 and 70 MPa concrete respectively.

9.5 Conclusions on validation of mechanical behaviour of HFRC on numerical modelling (ATENA)

- Experimental results at optimised hybrid combinations in mono-FRC, non-metallic HFRC and HFRC (Metallic and non-metallic) are in good agreement with the values obtained by the ATENA model.

- Peak-strength values of HFRC under uni-axial compression are compared with peak-strength values of ATENA model. The percentage error observed between experimental results and analytical results are within 15%.

- Experimental Flexure strength results are compared with results obtained by the ATENA model and the results are in good agreement.

- The developed ATENA model can be used for different fiber volume fraction and different loading conditions in order to avoid comprehensive experimentations.

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9.6 Specific contribution made in this work

1) Investigated the potential difference between high- modulus fibers to low-modulus fiber in view point of strength and constitutive stress strain response.

2) A combination of low-modulus polyester and polypropylene (non-metallic HFRC) can enhance the tensile strength of the concrete because of these fibers are having low density and high aspect ratio numerous fibers available through-out the concrete mix effectively arrest the plastic shrinkage cracks and micro-cracks

3) Steel fibres in concrete could be replaced to a small extent with non-metallic fibres to enhance the tensile strength and toughness of the concrete under uni-axial compression and tension.

4) Modelling of HFRC is done using ATENA-GID software to avoid the comprehensive experimentation.

9.7 Scope for the further study

1) Influence of developed metallic and non-metallic HFRC on dynamic characteristics of HFRC need to be studied.
2) Shrinkage and creep characteristics of the HFRC are to be studied.
3) Moment – curvature and stress block parameters are need to be developed for the proposed HFRC.

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2. K.Srikanth, Dr. D. Ravi Prasad. "Mechanical Properties of Polypropylene-Polyester high strength Hybrid Fiber Reinforced Concrete" International Conference on Trends and Recent Advances in Civil Engineering – TRACE 2016 (Amity University).

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