# STUDY OF STRENGTH AND DURABILITY OF HIGH STRENGTH CONCRETE USING CARBON FIBER

A Thesis Submitted
in Partial Fulfilment of the Requirements
for the Degree of

## DOCTOR OF PHILOSOPHY

by

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**Sept, 2024**

# ACKNOWLEDGEMENTS

I would want to express my deepest gratitude to the individuals who have been of the highest assistance to me throughout the course of my research attempts. In the first place, I would like to express my great appreciation to my research supervisor, Dr. Ritu Raj, as well as to my co-supervisor, Dr. Poonam, for giving me with priceless direction, unshakable support, and encouragement along this entire trip. They have been quite helpful in guiding the path that my research will take and in nurturing my academic development through their competence, patience, and mentoring qualities.I am also immensely thankful to the faculty members of Civil Engineering Department, DTU, whose insights, feedback, and constructive criticism have contributed significantly to the refinement of this thesis. Their dedication to teaching and research has been a constant source of inspiration.

I want to thank God, whose favor and assistance have helped me stay strong and on track during this whole ordeal. My academic efforts have been shaped by chances, difficulties, and personal growth, for which I am grateful.

To my family, especially my parents, Mrs. Suresh Kumari, and Mr. I. S. Lamba, I owe an immense debt of gratitude for their unwavering love, support, and sacrifices. Their belief in me and encouragement have been the driving force behind my academic achievements. I am deeply appreciative of their endless support and encouragement.

My sister, Dr. Renu Lamba, deserves a special thank you for her unflinching support, encouragement, and understanding during this entire process. Thank you for being a part of my life because your confidence in me has been a consistent source of inspiration, and I am thankful for your presence.

I am grateful to Mr. Sachin Jain, Director, Ecovision Global Infrastructures pvt ltd. for providing help with arrangement of flyash, Mr. B.R.G. Robert, Assistant Professor, DTU for helping out with certain material tests, my dear friends, Ningaraj Benal, Rahul Kumar, Rajat Gautam, Pooja Rani, Rahul Meena, Prateek Roshan, and Vikas Vashisth for their unwavering support, encouragement, and camaraderie throughout this journey. Your friendship has brought joy, laughter, and invaluable support during both challenging and joyous moments.

I extend my thanks to the laboratories and research facilities that provided the necessary resources, equipment, and infrastructure for conducting experiments and gathering data. Special appreciation goes to the dedicated staff members for their assistance, expertise, and cooperation, which have been essential to the completion of this thesis.

I would like to use this opportunity to express my gratitude to everyone who has helped me along this path, whether it be personally or indirectly provided support. Your contributions, whether big or small, have made a significant impact on my academic and personal growth, and for that, I am truly grateful.

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# CANDIDATE'S DECLARATION

I Nitin Lamba hereby certify that the work which is being presented in the thesis entitled "Study of Strength and Durability of High Strength Concrete using Carbon Fiber" in partial fulfillments of the requirements for the award of the degree of Doctor of Philosophy , submitted in the Department of Civil Engineering, Delhi Technological University is an authentic record of my own work carried out during the period from Aug 2017 to June 2024 under the supervision of Dr. Ritu Raj, Assistant Professor, Department of Civil Engineering, Delhi Technological University, Delhi, and Dr. Poonam, Assistant Professor, Department of Applied Chemistry, Delhi Technological University, Delhi, and being submitted for the award of PhD degree to Delhi Technological University, Delhi, India. The matter presented in the thesis has not been submitted by me for the award of any other degree of this or any other institute.

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This is to certify that the student has incorporated all the corrections suggested by the examiners in the thesis and the statement made by the candidate is correct to the best of our knowledge.

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Certified that **Nitin Lamba** **(2K17/PHD/CE/13)** has carried out their research work presented in this thesis entitled the PhD thesis entitled **"Study of Strength and Durability of High Strength Concrete using Carbon Fiber"** for the award of **Doctor of Philosophy** from Department of Civil Engineering, Delhi Technological University, Delhi, India, under our supervision. The thesis embodies results of original work, and studies are carried out by the student himself and the content of the thesis donot form the basis for the award of any other degree to the candidate or anybody else from this or any other University/Institution.

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# Study of Strength and Durability of High Strength Concrete using Carbon Fiber

**Nitin Lamba, Ritu Raj, and Poonam**

## ABSTRACT

The presented work investigated the mechanical properties, impact resistance (with a modified ACI test setup), and durability of high-strength concrete by reinforcing it with four different aspect ratios i.e., 100, 150, 200, and 250 of carbon fibers with varying dosages of 0.2, 0.4, 0.6, 0.8, and 1% fiber content. Various tests, including flexure tests, impact resistance tests, ultrasonic pulse velocity tests, compression tests, and durability test, were performed on test samples after 28 days of curing period with water. Energy dispersive X-ray spectroscopy along with Powdered X-Ray diffraction analysis was carried on samples to find out various chemical compositions of elements present and mineralogical properties respectively. The surface morphology of concrete samples was determined with the help of Scanning electron microscope (SEM) equipment. Functional groups and metal linkages were confirmed by Fourier Transformed Infrared spectroscopy (FTIR). The presence of atoms or elements were determined by X-Ray Photoelectron spectroscopy (XPS). The mechanical characteristics and impact resistance were connected with an analytical analysis technique. The carbon fiber with the largest aspect ratio of length equivalent to 25mm, showed good growth in the rate of flexural, compressive strength and impact resistance. SEM images revealed that the primary cause of failure in carbon fibers was the debonding of fibers at fracture surfaces. The increase in carbon fibers content or dosages enhances the compressive strength, flexural strength, impact resistance, durability and optimum dose of fibers enhanced the porosity of concrete specimens. Chemical examination showed that silicon and calcium crystalline were the primary components of the concrete matrix, which suggested that calcium silicate hydrate and calcium hydroxide were the primary hydration products of the cement-based matrix.

Keywords: Carbon Fibers, Mechanical Properties, Impact resistance, High Strength Concrete, RCPT, Microstructure Studies

# LIST OF PUBLICATIONS

1. Lamba, N., Raj, R. and Singh, P., (2024). Chopped carbon fibre reinforcement in high-strength concrete: Flexural characteristics. *Materials Science and Technology*. 2024;40(1):47-53. DOI: 10.1177/02670836231212615
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5. Lamba, N., Raj, R. and Singh, P., (2022) Mechanical characteristics of high strength concrete incorporating recycled CFRP fibers." *J. Appl. Polym. Sci.* vol 139, issue 47, DOI: https://doi.org/10.1002/app.53183

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2. Lamba Nitin, Raj Ritu and Singh Poonam, 2022, Flexural Behavior of High strength concrete using recycled carbon fibers, International Conference on scientific computing in innovation (ICSCI-2022), GNIT & GNIET, April 6-8, 2022, GNIT & GNIET.
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| | |
|---|---|
| F.A | Fine aggregate |
| C.A | Coarse aggregate |
| SEM | Scanning electronic microscope |
| OPC | Ordinary Portland Cement |
| XRD | X-ray diffraction |
| C-S-H | Calcium silicate hydrate |
| ASTM | American standard testing materials |
| PCE | Poly-carboxylate ether |
| IS | Indian Standard |
| UPV | Ultrasonic pulse velocity |
| EDX | Energy-dispersive X-ray spectroscopy |
| Ca | Wollastonite |
| CTM | Compression Testing Machine |
| O | $SiO_2$ |
| Al | $Al_2O_3$ |
| Si | $SiO_2$ |
| C | $CaCO_3$ |

| | |
|---|---|
| Al | $Al_2O_3$ |
| Na | Albite |

# CHAPTER 1

# INTRODUCTION

## 1.1 Overview

Natural resources are being consumed at a high rate as a result of the fast-paced modernization of the planet. With the increasing growth of urbanization, industrialization, and other needs, scrap materials are being dumped all over the place, making it a difficult task for humans to deal with this problem. As a result, a sustainable development is critical, and proper disposal of these discarded materials is critical. As a result, recycling and reusing discarded materials may be a viable option for protecting our mother earth and the ecosystem from the detrimental impacts of these materials. Fly ash, silica fume, tyre shreds, recycled carbon fibers, and other scrap materials are employed in the building industry all over the world. Innovative research is being conducted to make high-strength concrete utilizing scrap materials; this way, in addition to achieving high strength, we are also assisting in the recycling and reuse of materials. There have been a lot of studies and investigations done to find ways to use recycled materials in concrete works in environmentally friendly construction methods. Some research introduced an innovative electric field-induced manipulation method for recycling short-chopped carbon fibers (SCCFs), offering a pollution-free, cost-effective, and efficient approach with broad applications in sustainable manufacturing (Ma et al., 2022) . Researchers looked at the possibility of employing recycled carbon fiber reinforced polymer (CFRP) in rubberized concrete, which showed improved mechanical qualities and a considerable decrease in carbon dioxide emissions, making it an attractive sustainable building material. (Xiong et al., 2021). In a study that critically examined the incorporation of carbon fiber reinforced polymers (rCFRP) in cementitious composites as a sustainable solution to address environmental concerns and enhance mechanical properties, the researchers discovered that 0.25-1% rCFRP has a positive influence on impact resistance and mechanical properties while simultaneously promoting sustainable development. However, further investigation is required to investigate durability aspects (Danish et al., 2022). The potential of short pyrolyzed carbon fibers (rCF) from waste carbon fiber reinforced plastic (CFRP) to improve the mechanical properties of fiber-reinforced concrete (FRC) was investigated by some researchers. The results of this investigation showed that rCF could achieve a significant 31% increase in flexural strength at a fiber volume content of 0.5 vol.-% and improved elongation at break through $O_2$ plasma treatment (Kimm M et al., 2021). Some research showed that there are financial benefits to recycling, but also detrimental environmental effects (Ghernouti et al., 2015). According to the amended recommendations of ACI Committee 363 (ACI Committee 363, 2010), concrete with a compressive strength of exceeding 8000 psi (55 MPa) is often referred to as high-strength concrete. Several researchers have benefited the construction industry by raising public awareness of incorporating recycled fibers in the generation of high-strength concrete (Ghernouti et al., 2015; Khaloo et al., 2015; Mastali et al., 2016; Mastali & Dalvand, 2016a, 2016c; Meddah & Bencheikh, 2009; Yang et al., 2015). In addition, studies have been conducted to see if the addition of other fibers to regular concrete will improve its functionality (Foti, 2011, 2013; Kim et al., 2010; Ochi et al., 2007; Ogi et al., 2005). The researchers discovered that adding fibers to normal and high-strength concrete enhances impact resistance and overall mechanical characteristics. The performance of concrete is heavily dependent on a number of factors, including the fiber doses, fiber type, aspect ratio, and qualities of the concrete itself. CFRP fibers are rigid, durable, have a great tensile strength, and can withstand extreme temperatures(Guo et al., 2021; Li, Wang, et al., 2021) . Due to the prominent qualities of CFRP-based materials, reinforcing carbon fibers in plain ordinary concrete could be an intriguing study. There is relatively little research on the possibility of using carbon fiber fragments to achieve high strength concrete, according to the authors (Li et al., 2022; Li, Lee, et al., 2021; Liu et al., 2020; Mastali & Dalvand, 2016a; Ogi et al., 2005; Patchen et al., 2023; Soupionis & Zoumpoulakis, 2021). The effects of carbon fiber reinforced plastic (CFRP) fiber on the fresh and hardened characteristics of reinforced specimens were investigated by Mastali et al. (Mastali & Dalvand, 2016a)(Mastali et al., 2017). To enhance the mix compositions, several fiber doses ranging from 0.25 percent to 1.25 percent were applied. A drop-weight setup to measure impact resistance was incorporated of the developed mix design samples. Carbon fibers in plain ordinary concrete have a substantial impact on mechanical properties and impact resistance, according to the studies (Mastali & Dalvand, 2016a). A modified drop weight test arrangement has been used by certain researchers to assess the impact resistance of concrete. (Abid, Abdul-Hussein, et al., 2020; Abid, Abdul Hussein, et al., 2020). After adding crushed CFRP pieces, Ogi et al. investigated the compressive and flexural properties of regular concrete. (Ogi et al., 2005). Pull-out and peel tests are important methods for evaluating the adhesion strength or bond strength that exists between carbon fiber and concrete to understand the adhesion features of carbon fibers (Yang et al., 2015). To evaluate the adhesion characteristics of plain standard concrete, varied carbon fiber doses of 5 to 10 percent and fiber lengths ranging from 3 to 20 millimeters were added. (Ogi et al., 2005). The findings demonstrated that the study's CFRP components have a substantial adhesive strength as a result of anchoring effects.

Consequently, due to the unique qualities of carbon fibers, when they are reinforced in plain, ordinary concrete, they can strengthen impact resistance, improve mechanical properties, and produce concrete with high strength properties. The purpose of this investigation was to examine the concrete's mechanical characteristics and impact resistance of varying carbon fiber doses (0.2, 0.4, 0.6, 0.8, and 1%) with lengths (10mm, 15mm, 20mm and 25mm), along with durability study of high strength concrete. The need for research on developed high-strength concrete was empowered by the implementation of a modified drop-weight setup that was different from ACI recommended test setup. In addition, the test equipment greatly shortened the time duration for experimentation; this is a critical factor for rapidly drawing comparisons in different concrete mixes and a novel approach. Compression, flexure, impact resistance, durability and tests with ultrasonic pulse velocities were performed to determine the quality of carbon fiber-reinforced specimens' strength. 252 samples in total, 15 of each fiber length, were cast and experimentally tested for compressive strength, flexure strength, impact resistance and durability. An analytical analysis was performed following the destructive and non-destructive tests using the huge quantity of experimental data collected. Energy dispersive X-ray spectroscopy was performed along with the Powdered X-Ray diffraction analysis on concrete samples in order to find out various chemical compositions of elements present and mineralogical properties respectively. The surface morphology of concrete samples was determined with the help of Scanning electron microscope (SEM) equipment. Functional groups and metal linkages were confirmed by Fourier Transformed Infrared spectroscopy (FTIR). The presence of atoms or elements were determined by X-Ray Photoelectron spectroscopy (XPS).

## 1.2 Research Gaps/Findings from Literature Survey

- While there is a substantial body of research on high-strength concrete and separately on carbon fiber reinforcement, there is a noticeable gap in the literature concerning the combined effects of high-strength concrete with carbon fibers. This study aims to bridge this gap by providing a comprehensive examination of the synergistic interactions between these two materials.
- Many existing studies focus on the short-term mechanical properties of high-strength concrete, but there is a gap in understanding its long-term performance. This research seeks to address this gap by conducting extended exposure tests to simulate real-world conditions and evaluate the durability over an extended period.
- Research needs to be done on strength and durability studies in concrete with the addition of different dose and aspect ratios of carbon fibers in high strength concrete.
- Research needs to be done on high-strength concrete to optimize the fiber content and different fiber lengths, and the concrete’s mechanical properties need to be assessed.

## 1.3 Research Objectives

The aims of the research are:

- To study durability and strength properties of High strength concrete using carbon fibers.
- To standardize an optimized carbon fiber reinforced concrete mix for the development of High strength concrete.
- To analyze and study the response of fiber size, and fiber content on the physical and mechanical properties of High strength concrete.
- To compare the results of carbon fiber reinforced High strength concrete with the existing study.
- To Provide recommendations for future research based on the study carried out.

## 1.4 Significance of the study

The significance of this research comes in the fact that it has the ability to make significant contributions to the field of building and engineering materials by providing the field with vital insights and developments. The investigation into the strength and durability of high-strength concrete using carbon fibers addresses critical concerns in the construction industry. Firstly, the study aims to enhance the understanding of the mechanical properties and long-term performance of high-strength concrete, which is vital for ensuring the structural integrity of buildings and infrastructure. By incorporating carbon fibers, known for their reinforcing capabilities, the research seeks to identify ways to improve the material's strength, durability, and resistance to various environmental factors.

Furthermore, the findings of this study may have practical implications for engineers, architects, and construction professionals, providing them with evidence-based guidelines for the selection and optimization of high-strength concrete mixes with carbon fibers in real-world applications. This could lead to the development of more resilient and sustainable construction practices, addressing the increasing demand for durable structures capable of withstanding diverse environmental challenges.

Moreover, the study contributes to the broader academic and scientific community by adding to the existing body of knowledge on advanced construction materials. The insights gained from this research can potentially inform future studies and innovations in materials science and engineering. Ultimately, the significance of this study extends beyond the immediate scope, influencing the way high-strength concrete is conceptualized, designed, and implemented in the construction industry.

## 1.5 Thesis Arrangement

The thesis is organized into several interconnected chapters to provide a systematic exploration of the research on the strength properties and durability charecteristics of high-strength concrete employing carbon fibers. The chapters are as follows:

**Chapter 1:** The journey begins with the 'Introduction' chapter, setting the stage by outlining the research background, research gaps, objectives, significance of the study, thesis arrangement, and the methodology incorporated in the study.

**Chapter 2:** The 'Literature Review' chapter critically reviews relevant literature, establishing a foundation by examining existing knowledge gaps and highlighting key findings in the field.

**Chapter 3:** The 'Materials and Experimental Program' chapter details the materials employed, experimental procedures, and testing methodologies, providing a comprehensive insight into the research methodology.

**Chapter 4:** 'Results and Discussion' is the chapter that gives the empirical findings, illuminating trends and facilitating a rigorous discussion on the outcomes that were seen.

**Chapter 5:** The 'Microstructure and Analytical Study' chapter delves into microscopic analyses, unraveling the intricate details of the material structure, correlation regression technique was incorporated to produce correlation between mechanical properties and impact resistances and compared the results with existing literature.

**Chapter 6:** The 'Conclusions, Future Scope and Social Impact ' chapter consolidates the study's key findings, discusses their implications, and suggests avenues for future research.

## 1.6 Methodology

The following methodology was used to examine the mechanical properties of carbon fiber-reinforced high-strength concrete:

1. Material selection: Selecting the right type and grade of cement, aggregate, and carbon fiber to achieve the necessary qualities of high-strength concrete.

2. Mix design: Considering the strength properties when designing the mix proportions for high-strength concrete using carbon fibers.

3. Sample preparation: Shape and size the concrete specimens as desired, then apply the appropriate procedure to evenly include the carbon fibers into the concrete mix.

4. Testing: Performing a variety of mechanical tests on the concrete sample to determine its strength. Compressive strength, flexure, impact resistance, ultrasonic pulse velocity, XRD, SEM, XPS, FTIR, and EDX analysis were among the tests performed.

5. Data examination: Analysing test findings and comparing them to the specified design parameters and requirements to guarantee that the high-strength concrete made with carbon fibers has the appropriate mechanical properties.

6. Conclusion: Document the entire research process, including methodologies, results, discussions, and conclusions. Provide recommendations for future research in the field.

The mechanical properties of high-strength concrete incorporating carbon fibres were established using this methodology, and optimised mix designs for specific applications were developed. Fig. 1.1 depicts the flow chart of the test process.

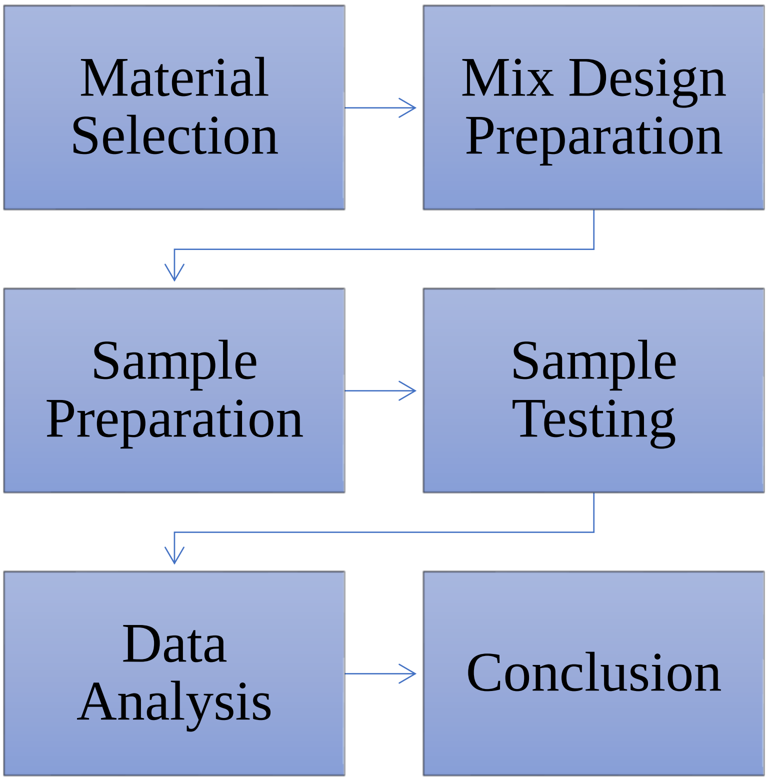


**Fig.1.1** Flow chart of test methodology

# CHAPTER 2

# LITERATURE REVIEW

The purpose of this chapter is to conduct a literature evaluation on the current body of knowledge that is relevant to the subject of this investigation. A brief description is presented in addition to some key points that govern concrete properties and behaviour to show a fundamental understanding of the technology of concrete. This chapter presents a comprehensive review of carbon fiber reinforced high strength concrete to highlight the main advantages of this material alongside its drawbacks, the results obtained were unpredictable, necessitating more research on developed high strength concrete. In order to find a solid base of information on materials, mechanical, impact, and durability properties were studied in order to carry out the research work, the following literature survey was done for the current research.

The viability of utilizing carbon fiber reinforced plastic (CFRP) fibers in self-compacting concrete was examined by **Mastali, Dalvand, and Sattarifard (2022).** In the course of assessing the hardened and fresh qualities of the self-compacting concrete (SCC), various fiber volume fractions ranging from 0.5% to 2% were considered. Additionally, different fiber lengths of 10, 20, and 30 mm were also taken into consideration. The qualities of the reinforced mix compositions in their fresh state were tested in terms of their viscosity and flowability. For the purpose of acquiring the hardened specimen properties, several tests like the impact resistance, ultrasonic pulse velocity, flexural strength, and compressive strength were also employed. A total of 130 specimens were subjected to experimental testing in order to determine their mechanical properties and impact resistance. They used elemental maps and images from back-scattered electron (BSE) research to figure out the matrix's crystal structure, which is based on cement. Using energy-dispersive X-ray spectroscopy (EDX), the chemical constituents of the cementitious mix were also determined, either qualitatively or to a semi-quantitative degree. This was either done qualitatively or quantitatively. The scanning electron microscopy (SEM) and atomic force microscopy (AFM) techniques were applied simultaneously in order to investigate the surface topography and morphology of the carbon fiber reinforced plastic (CFRP) fibers that were embedded in the cement-based matrix. The use of linear regression analysis in conjunction with the massive experimental database allowed for the establishment of a link between the impact and mechanical properties of reinforced SCC. This was done while taking into consideration the various carbon fiber concentrations and lengths. The findings shown that increasing the volume fraction and length of carbon fiber in reinforced mix compositions results in an improvement in the mechanical characteristics and impact resistance of the mixtures, while simultaneously reducing their workability.

Reinforced self-compacting concrete made from recycled steel fiber was tested by **Mastali and Dalvand (2016)** to see what happens when cement is substituted with silica fume. They also studied the concrete's mechanical qualities and its resistance to impact. The experimental tests were carried out on 144 specimens that had fiber volume fractions ranging from 0.25 percent to 0.75 percent. The objective of the investigations was to provide a description of the material's mechanics, including its impact resistance and mechanical characteristics. In order to determine the mechanical attributes of the specimens, the compressive, splitting tensile, and flexural strengths of the specimens were evaluated. Regarding the massive research dataset that was obtained, an analytical investigation was carried out by employing regression analysis in order to study the connection between the impact and mechanical properties of self-compacting concrete that was reinforced with recycled steel fibers. This was done in order to determine whether or not there was a relationship between the two. This was done in order to find out whether or not there was a relationship between the two. During the same time period, an investigation was carried out to determine whether or not there was a correlation between the mechanical qualities of the specimens and the quantity of silica fume that was used to substitute the cement. This was done to determine whether or not there was a relationship between the two. This improvement was brought about as a result of the combination of these two factors. Moreover, linear equations were developed in order to create a correlation between the mechanical characteristics and impact resistance of specimens when the coefficient of determination was high. This was done in order to determine whether or not there was a relationship between the two.

**Caggiano et al. (2016)** reported the findings of experimental tests that were carried out on concrete specimens that were internally reinforced with polypropylene and steel fiber particles. To be more specific, samples of five distinct combinations, together with a reference plain concrete, were subjected to compression and bending tests. The total volume of fibers in these combinations was the same, but the proportions of polypropylene and steel fibers were different. This was the distinct characteristic of these mixtures. This study set out to better understand how various combinations of these fibers affect the fracture behavior of hybrid fiber-reinforced concrete (HyFRC) by identifying specific examples. It was not surprising that the results of the compression tests showed that the fibers had no effect on the strength. Thus, in comparison to the reference specimens, the FRC ones showed a more ductile post-peak response. Because of the preceding sentence, this came to pass. However, the stress-crack-opening-displacement curves of HyFRC that were tested in bending were significantly affected by the type of fibers. These curves were analyzed while the material was being bent. When it came to the small fracture opening ranges that were significant for the Serviceability Limit State, FRC specimens that were constructed entirely of polypropylene fibers demonstrated an excellent post-cracking toughness. An apparent degradation, on the other hand, was found in terms of the post-cracking reaction, particularly at fracture apertures that were quite large. This was the situation with crack holes that were greater. On the other hand, the post-cracking behavior of specimens that had a greater percentage of steel fibers exhibited a considerable re-hardening reaction. This happened after the specimens had been cracked. Nevertheless, at the same time, the data that related to this response displayed a significant amount of dispersion.

**Martinelli, Caggiano, and Xargay (2015)** evaluated the mechanical behavior of FRC that was manufactured using both recycled steel fibers and industrial steel fibers that were collected from waste tires. Both compression and bending tests were performed on specimens of a variety of mixes. These combinations were distinguished by the fact that they contained the same volume proportion of fibers, but they contained varying percentages of industrial and recycled reinforcing. In terms of compressive strength, the findings indicated that the influence of fibers was very insignificant. On the other hand, specimens that had a greater proportion of recycled fibers exhibited a considerable decline in their post-cracking behavior. The bending response, on the other hand, was found to be significantly improved in comparison to the case of plain concrete, and this was observed even for specimens that were merely reinforced by recycled fibers.

When discussing the feasibility of using polymer fibers into high performance concrete (HPC), **Khaloo et al. (2015)** highlighted the possibility. Recycled automobile timing belts were used to recover the fibers that were used in this investigation. In order to explore the various features of the concrete specimens, a number of destructive and non-destructive tests were carried out. These tests included compressive strength, modulus of rupture, flexural toughness, ultrasonic velocity, and electrical resistance tests. In addition to that, tests of slump flow were carried out on the relatively fresh concrete. Experimental findings from the research indicated that the utilization of waste fibers in low percentages (up to 0.5%) resulted in an improvement in both the modulus of rupture and the flexural toughness of the material. According to the findings of ultrasonic and electrical resistance tests, a rise in the proportion of fibers also resulted in an increase in the pore volume and electrical resistance of the fiber-reinforced concretes in comparison to a control mixture.

**Yang et al. (2015)** executed an analysis that focused on self-compacting lightweight concrete (SCLC), which was the subject of examination. The researchers were interested in understanding how the introduction of modified polypropylene (PP) plastic particles affected the physical properties of the concrete, including its workability and its mechanical performance. It was decided to replace ten percent, fifteen percent, twenty percent, and thirty percent of the amount of sand with plastic. Any increase in the amount of sand substitution results in an improvement in the slump flow value. The viscosity of fresh SCLC is reduced when the replacement amount is increased to up to 15%, and the ability to flow through is improved as a result. When there is a greater quantity of sand replacement, there is a corresponding reduction in the dry bulk density of SCLC, as well as a decrease in the elastic modulus of the material. When the replacement amount is increased by up to fifteen percent, the material's flexural tensile strength, splitting tensile strength, and compressive strength all experience an increase. This is because higher replacement amounts result in higher material strength. A research study into the interface between plastic and paste was carried out for the purpose of microscopic examination.

The researchers **Gupta, Sharma, and Chaudhary (2015)** did an investigation into the impact resistance of concrete by assessing how the material was changed by the substitution of waste rubber fibers for small particles. It has also been hypothesized that silica fume could serve as a substitute for cement. There are three various levels of silica fume replacements (0%, 5%, and 10%) and six distinct degrees of rubber fiber replacement (0%, 5%, 10%, 15%, and 25%) that have been taken into consideration for each of the three distinct water-cement ratios. None of these substitutions have been explored. The procedure of conducting impact testing on concrete has been carried out using three various methods: the drop weight test, the flexural loading test, and the rebound test. Each of these tests has been applied in their own unique way. When it comes to the outcomes of the impact, drop weight, flexural loading, and rebound tests, there are also established correlations among their respective outputs. In order to assess the experimental data of the drop weight test, a two-parameter Weibull distribution is utilized. This is done since there is a significant amount of variation in the impact values. The findings of the study indicate that residual rubber fiber has the potential to be exploited as a sustainable material for the purpose of strengthening the impact resistance and ductility capacities of concrete. This is the conclusion that can be drawn from the data of the study. The research also reveals that the presence of silica fume contributes to an increase in the impact resistance of rubber fiber concrete while simultaneously reducing its ductility.

**Ghernouti et al. (2015)** documented the characteristics of SCC including plastic bag waste fibers (PBWF). These qualities were presented both fresh and hardened. The recycling of waste materials, such as plastic bags, was used to successfully prepare fibers. Among the many SCC mixtures investigated in the study were fourteen with a water-to-cement ratio of 0.40, twelve with plastic bag waste fiber (WFSCC) of varying lengths (2 to 6 cm) and the amount of formation (1 to 7 kg/m$^3$), and two more with polypropylene fibers (1 kg/m$^3$) and one without (RSCC) serving as a control. All of these types of mixtures were investigated. All of these mixtures were analyzed in the research. There were a number of additional sorts of stability experiments that were carried out in order to evaluate the fresh qualities of the mixtures that were generated. These tests included slump flow, L-box stability, and sieve stability. The compressive strength, splitting tensile strength, and flexural strength of the concrete were evaluated in order to ascertain the qualities of the concrete after it had been subjected to the process of hardening. The results of the tests showed that mixes based on PBWF with a length of 2 centimeters were able to satisfy the requirements of self-compaction, regardless of the amount of fibers that were included in the mixture. This was the case regardless of the length of the PBWF. These findings were highly intriguing; they suggested that PBWF could be used for structural reinforcement of SCC. The results that were obtained were quite intriguing. In addition to this, the presence of these fibers in concrete slowed down the development of micro fractures. However, the integration of PBWF did have a significant impact on 28 days attained split tensile strength, despite the fact that it did not have a significant impact on the compressive and flexural strengths of the material. When it came to the development of the improvement, which varied from 4% to 74% and was based on the number of fibers, there was no association between the length of the PBWF and the advancement of the improvement.

Through the use of experimental testing and numerical simulations, **Naghibdehi (2014)** was able to explore the reinforcement of the cross-section by employing either steel fibers, PP fibers, or both. These experiments were carried out in two distinct layers. When it came to the reinforcing of beams, steel and polypropylene fibers were utilized at volumes fractions of 0.5%, 1%, and 2%, respectively. Due to the fact that they had a reinforced cross-section with either one or two different types of fiber, the beams that had been tested for flexural loading were investigated. The findings revealed that the load-carrying capacity of the cross-section was enhanced when steel fibers were used to reinforce the entire cross-section. This was in contrast to the situation in which the cross-sectional was reinforced with two separate kinds of fibers.

In light of the outstanding features that High Performance Fiber Reinforced Cement Composites (HPFRCC) possess, **Fakharifar et al. (2014)** conducted a comprehensive set of experimental tests on these construction materials. The majority of the statistical research that has been done has concentrated on Fiber Reinforced Concrete (FRC). During the course of this study, two hundred and forty specimens were put through a thorough analysis that encompassed both an experimental and statistical approach to addressing essential mechanical properties of high-performance composites. Strength in both compressive and flexural directions, as well as resistance to impact, were among these characteristics. During the course of the experiment, different amounts of fibers were incorporated into the composition. According to the results of this inquiry, it was found that the normal distribution is followed by the compressive and flexural strength of HPFRCC, in addition to its impact resistance. This was observed based on the findings of your investigation. In high-performance fiber reinforced composites (HPFRCC), a higher percentage of fibers led to higher values for the mechanical properties and impact resistance. This was proved by statistical data analysis, which included both parametric and non-parametric methods. The findings of the tests that were conducted were used to build equations that were constructed to connect the mechanical properties of HPFRCC materials with their impact resistance. These equations were developed based on the results of the tests were obtained.

Recent research published by **Foti (2013)** details the results of a series of experiments that were conducted on concrete specimens that were reinforced with fibers derived from waste polyethylene terephthalate (PET) bottles. For the purpose of making the concrete samples more robust, such fibers were utilized. What is necessary to separate the fibers from the bottles is nothing more than a simple cutting of the bottles into smaller pieces. Subsequently, these fibers are either included in the concrete mixture or utilized as separate reinforcements for samples and smaller beam placed on top of bars of steel. Both of these operations are carried out. Both of these choices are open to consideration. An extra in-depth investigation into the use of PET as a form of reinforcement for both masonry and concrete projects is going to be carried out, and the results of the tests will be taken into consideration as a second approach to the research that is being conducted. The findings that have been obtained are highly intriguing, particularly with regard to the adhesion that exists between PET and concrete. These findings point to the possibility of employing this material for structural reinforcement in the shape of flat or circular bars, or networks.

To conduct an approach to a more extensive testing on the possibilities of employing fibers from polyethylene terephthalate (PET) bottles to raise the ductility of the concrete, **Foti (2011)** published the findings of various tests that were carried out for the reason of researching the likelihood of carrying out so. The purpose of these tests was to determine whether or not it would be possible to use PET bottles as a source of fibers for the concrete. The fibers were made by just cutting old plastic bottles, which resulted in a reduction in the expenses connected with the production of recycled PET fiber-reinforced concrete. This was accomplished by merely cutting the bottles. The purpose of this piece was to investigate the possibility of recycling a waste material that is currently being created in vast amounts, with the eventual goal of creating an improvement in the ductility of the concrete (which was the main aim of this work). The purpose of this piece was to investigate the possibility of recycling a waste material that is currently being created in vast amounts, with the eventual goal of creating an improvement in the ductility of the concrete (which was the main aim of this work).

A discussion was held by **Seddik and Bencheikh (2009)** regarding the possibility of incorporating metallic and polypropylene by-product fibers into regular concrete as a kind of reinforcement. An investigation into the effects of introducing various types of waste metallic fibers (WMF) and polypropylene fibers (WPF) into fiber-reinforced concrete was carried out through the use of experimental research. The examination regarding the concrete's ability to mechanical characteristics turned out to be the result of the investigation. For the purpose of the control combination, a normal concrete with a compressive strength of thirty megapascals was utilized. This concrete was used. An investigation is carried out in order to ascertain the manner in which the compressive and flexural strengths, in addition to the toughness, of fiber-reinforced concrete (FRC) are influenced by the type, volume, and length of the wall thickness (WF). When long fibers with a high volume % are utilized in the construction of WFRC, the data that were collected revealed that the WPF has a detrimental impact on the compressive strength of the structural fiber reinforced composite (WFRC). It was also noticed that the composites that contained more than 2% of the WMF had a minor drop in their compressive strength. Nevertheless, the flexural strength of the WFRC is increased when the WPF and hybrid fibers are included in the composition. It was recently noticed that hybrids that are strengthened with the WPF prove more beneficial than hybrids that are strengthened with the WMF in terms of post-cracking behavior and load-carrying capabilities. This is because the WPF is superior to the WMF in respect of structural integrity. This is the case when comparing the two types of reinforcement; the WPF is more advantageous. When specific conditions are met, the WPF can even yield results that are superior to those produced by the multifunctional hybrids. The usage of multifunctional composites has been shown to result in a significant improvement in the post-cracking behavior of the WFRC, as indicated by the findings of the comparison between the hybrids augmented with the mono-fibers system and the application of multifunctional hybrids. This improvement is especially noticeable in terms of ductility and toughness. An additional topic of discussion was the findings about the orientation and distribution of fibers inside the cement matrix, as well as porosity and the impact it has on the performance of the WFRC.

**Aiello et al. (2009)** reported the findings that were gained from the experimental work that has been carried out up to this point. Initially, pull out studies were conducted out for the purpose to investigate the characteristics of the relationship that exists among the concrete and the fibers, in addition to to determine the fibre length that is particularly important. In addition, the compressive property of concrete was evaluated according to a number of different volume proportions of extra RSF. Furthermore, flexural investigations were performed out with the aim to explore the behavior of RSFRC after it had fractured. In order to facilitate comparisons, samples that had been reinforced with industrial steel fibers (ISF) were also taken into consideration. On the other hand, the compressive property of concrete appeared to be unchanged by the existence of fibers, regardless the reality that fibers contain irregular geometric features. The findings that were obtained pertain to the bond that exists between steel fibers and concrete, and they were found to be adequate. In conclusion, flexural tests demonstrated, in certain instances, results that were equivalent to those obtained through the utilization of ISF in terms of the post-cracking behavior.

A discussion was held by **Seddik and Bencheikh (2009)** regarding the possibility of incorporating metallic and polypropylene by-product fibers into regular concrete as a kind of reinforcement.. An investigation into the effects of introducing various types of waste metallic fibers (WMF) and fibers made from polypropylene (WPF) into concrete with fiber reinforcement was carried out through the use of experimental research. The examination of the concrete's ability to strength turned out to be the result of the investigation. For the purpose of the control combination, a normal concrete with a compressive strength of thirty megapascals was utilized. This concrete was used. An analysis was carried out to establish the extent to which the compressive and flexural strengths, as well as the toughness, of fiber-reinforced concrete (FRC) were influenced by the type of reinforcement fibers

(WF), the volume of reinforcement fibers, and the length of reinforcement fibers. When long fibers with a high volume % are utilized in the construction of WFRC, the data that were collected revealed that the WPF has a detrimental impact on the compressive strength of the structural fiber reinforced composite (WFRC). The composites that contained more than 2% of the WMF were also shown to have a slight decrease in their compressive strength. This was another observation that was made. On the other hand, the incorporation of WPF and hybrid fibers into the formulation results in an increase in the flexural strength of the WFRC. When compared to composites reinforced with WMF, hybrids strengthened with WPF had superior post-cracking performance and load-carrying capacity, according to the observations that were made. On occasion, the WPF is superior to the multifunctional hybrids in terms of performance. In general, the findings have demonstrated the overall elasticity, rigidity, and post-cracking behavior of the WFRC were greatly enhanced when multifunctional combinations were utilized as opposed to combinations which have been strengthened with only one kind of fiber. This improvement can be attributed to the utilization of multimodal composites. Another subject of conversation revolved around the discoveries regarding the alignment and arrangement of fibers inside the cement matrix, as well as the presence of pores and its influence on the effectiveness of the WFRC.

A study that was conducted by **Ogi, Shinoda, and Mizui (2005)** demonstrated the strength of concrete that was strengthened with fragments of crushed carbon fiber reinforced plastic (CFRP). In this study, the fracture behavior of carbon fiber reinforced plastic reinforced concrete (CFRPRC) was studied, and its mechanical parameters, including compressive and flexural strength, were analyzed. Initially, compressive and flexural testing of CFRPRC were carried out in order to investigate the influence that the compositions and size of fiber had on the flexure and compression strength of the material, as well as the work of fracture in the flexural tests correspondingly. This was done in order to examine the impact that the size and composition of CFRP pieces had on the material. Pull-out and peel tests were carried out in the second step of the process in order to ascertain the adhesion strength at the interface. These tests were carried out simultaneously. With the purpose of gaining an understanding of the behavior of fractures and the adhesion that takes place at the interface between carbon fiber reinforced plastic (CFRP) with cement, the surfaces of fractures were investigated with the use of an electron probe micro analyzer and an optical microscope. Both the flexural strength and the compressive strength of the material dramatically improve as the amount of carbon fiber reinforced plastic (CFRP) increases. After the maximum load, a significant amount of displacement is seen in the load-displacement curves that are produced by the flexural tests performed on CFRPRC specimens. As a direct result of this relationship, the amount of work required to fracture reinforced specimens is very much greater than the amount of work required to fracture blank specimens. Through the use of pull-out and peel tests, as well as microscopic examination, it was shown that the anchoring effect was responsible for the good bonding that occurred at the interface. As a result of the bridging effect, it has been determined that the incorporation of CFRP pieces of the proper size into concrete results in an increase in both the flexural strength and the work of fracture.

## 2.1 Summary

This chapter reviews research published that is relevant to the scope of this thesis. Thefollowing points summarise the main conclusions from this literature:

- Many existing studies focus on the short-term mechanical properties of high-strength concrete, but there is a gap in understanding its long-term performance. This research seeks to address this gap by conducting extended exposure tests to simulate real-world conditions and evaluate the durability of high strength concrete over an extended period with the addition of different dose and aspect ratios of carbon fibers.
- Research needs to be done on high-strength concrete to optimize the fiber content and different fiber lengths, and the concrete's mechanical properties need to be assessed.
- An optimized carbon fiber reinforced concrete mix is to be standardized for the development of High strength concrete.
- Recommendations for future research based on the study carried out should be provided.

# CHAPTER 3

# MATERIALS AND EXPERIMENTAL PROGRAM

This chapter details the materials employed, experimental procedures, and testing methodologies, providing a comprehensive insight into the research methodology.

Additionally, the tests that have been carried out to assess hardened properties of high strength concrete including non-destructive tests, and destructive tests such as compression test, flexure tests, impact resistance, and durability properties have been thoroughly explained.

## 3.1 Materials

As per ACI Committee 363R -92 (ACI 363R-92, 1997), the major raw materials utilized to prepare concrete mix designs for high-strength concrete were cement (OPC 43), fly ash, silica fume, fine aggregates (F.A), coarse aggregates (C.A), carbon fibers, superplasticizer (water reducer), and water. According to the instructions provided by numerous code standards, several preparatory tests were conducted on the materials required to create concrete mix designs.

### 3.1.1. Cement

It was selected to carry out the experiment using OPC 43 grade cement, which complies with IS 8112-2013 code criteria and has a minimum compressive strength of 43MPa (IS 269 : 2015, 2015). Table 3.1 displays the results of the essential cement tests that were performed prior to casting, with comparisons made to the specifications for typical OPC 43 grade cement (IS-8112 & 2013, 2013). Table 3.2 shows the chemical qualities of the cement used (OPC 43 grade) in the study.

**Table 3.1** Standard specification of OPC 43 cement and test results for cement used.

| Characteristics | IS 8112-2013 | Cement used (Lamba et al., 2022, 2023a, 2023b, 2024a, 2024b) |
|---|---|---|
| Setting time (mins) (IS 4031- Part V, 1988) | | |
| Final Setting Time | 600 | 255 |
| Initial Setting Time | 30 | 50 |
| Compressive strength (MPa) (IS: 4031 (Part 6), 2005) | | |
| 7 Days | 33 | 37 |
| 28 Days | 43 | 46 |
| Soundness (IS: 4031(Part 3), 1988) | | |
| Le-chatelier (mm) | 10 | 1 |
| Autoclave (%) | 0.8 | 0.1 |

**Table 3.2** Fly ash and OPC 43 cement: a comparison of their physical and chemical qualities

| Chemical qualities (%) | Fly ash | OPC 43 Cement |
|---|---|---|
| C3S | <0.1 | 50.5 |
| C2S | | 22.6 |
| C3A | | 5.7 |
| C4AF | | 11.3 |
| $SiO_2$ | 65.7 | 22.7 |
| $Al_2O_3$ | 29.8 | 4.82 |
| $Fe_2O_3$ | 2.20 | 3. 44 |
| MgO | 0.43 | 1. 38 |
| $K_2O$ | 0.35 | 0.56 |
| $Na_2O$ | 0.1 | 0.52 |
| CaO | 1.39 | 62.32 |
| Physical qualities | | |
| Specific gravity | 2.22 | 3.15 |
| Specific surface ($cm^2 g^{-1}$) | 3328 | 2955 |
| Loss on Ignition (%) | 3.58 | |
| Retention on 45µm Sieve size (%) | 26 | |
| Strength activity index test value (%) | 76.3 | |

### 3.1.1 Admixtures

An Indian thermal coal power station called NTPC Jhajjar supplied the fly ash additive used to make pozzolan. Grade 1 fly ash that complied with IS 3812 (IS:3812, 1999) code standards was used in the mix design. IS 456 2000 mentions that fly ash could be used as a partial replacement for cement. Table 3.2 shows the mineral composition of this type of fly ash. Silica fume, which is generally recognized for the construction of high strength concrete, was included in the mix design in line with IS 5388: 2003 (IS:15388, 2003). The results of the tests conducted in accordance with AASHTO M307, ASTM C-1240, and the IS Code (AASHTO Designation: M 307-13 (2021), 2021; ASTM C1240, 2020; IS:15388, 2003) are presented in Table 3.3 with the physical and chemical specifications for silica fume admixture. The chemical admixture ACI WR-1010 Polycarboxylate ether (PCE), which is a potent slump retention and water content reduction, was used. The marsh cone test (Shetty, 2000) was able to lower the water content requirement in the design of the mix by 30 percent. As a result, the suitable dose of the chemical admixture or super plasticizer (S.P.) was determined to be1.1 percent. The specifications complied with IS 9103: 1999 (IS 9103, 1999) and Table 4.4 lists the physical characteristics of the superplasticizer.

**Table 3.3** Standard specifications of silica fume and test results of silica fume used

| Chemical and Physical requirements | Specification | Result |
|---|---|---|
| Appearance | Gray Powder | Gray Powder |
| $SiO_2$ | >85% | 92.1% |
| Activity Index | >90% | 100% |
| Loss on Ignition (%) | < 6.0% | 1.0% |
| Chloride Content | <0.1% | 0.96% |

| | | |
|---|---|---|
| Moisture (%) | <3.0% | 0.23% |
| Specific Gravity | 2.20-2.40 | 2.25 |
| Retention on 45µm Sieve size (%) | < 10% | 2.5% |
| Deviation from mean retention (%) | < 5% | 0.7% |
| Alkalies (as equivalent $Na_2O$) | <0.4% | 0.18% |
| Bulk Density (Kg $m^{-3}$) | < 400-600 | 495 |

**Table 3.4** Physical properties and specification of super plasticizer used

| Physical properties | Specifications |
|---|---|
| Appearance | Yellowish to Brownish |
| Viscosity (CPS) | < 1,000 |
| Specific gravity | 1.12 |
| Non-Volatile matter (%) | 55.5 |
| pH | 4.5 |

### 3.1.3 Aggregates

According to IS 383: 1970 (IS:383, 1970) , The fine aggregates utilized in this project were made up of Zone II Badarpur sand, which was imported from a location close to New Delhi, India. The pit sand utilized in the experiments was filtered using a 4.75mm sieve. The results of the sieve analysis test indicated that the fineness modulus of the Badarpur sand employed in the investigation was 2.80. All of the particle size aggregates present in the sample are listed in Table 3.5 along with their percentages. Table 3.6 describes the properties of the F.A. The water absorption and specific gravity of the sand was calculated using the pycnometer method, and the values were 1.21 percent and 2.72, respectively (IS: 2386- Part I, 1963; IS 2386- Part III, 1963; IS: 2386 (Part IV), 2016). The grain size distribution curve for fine and coarse aggregates, as determined by sieve analysis, is shown in Fig.3.1. For the design mix, coarse aggregates with a nominal size of 10 mm were employed, and a sieve analysis test revealed that the coarse aggregates' fineness modulus was 7.29. By using the wire basket method, the specific gravity and water absorption of the coarse aggregates were calculated. The results were 2.70 and 0.19 percent, respectively (IS: 2386- Part I, 1963; IS 2386- Part III, 1963; IS: 2386 (Part IV), 2016).

**Table 3.5** Sieve Analysis of Sand/Stone Dust

| **Sieve Size** | **Weight Retained (gm)** | **% Weight Retained** | **Cumulated % Weight Retained** | **% Finer** | **Remarks** |
|---|---|---|---|---|---|
| 4.75 mm | 0 | 0 | 0 | 100 | Sand falls in zone II |
| 2.36 mm | 106 | 10.6 | 10.6 | 89.4 | |
| 1.18 mm | 300 | 30 | 40.6 | 59.4 | |
| 600 µm | 212 | 21.2 | 61.8 | 38.2 | |
| 300 µm | 132 | 13.2 | 75 | 25 | |
| 150 µm | 129 | 12.9 | 87.9 | 12.1 | |
| 75 µm | 36 | 3.6 | 91.5 | 8.5 | |
| pan | 85 | 8.5 | 100 | 0 | |

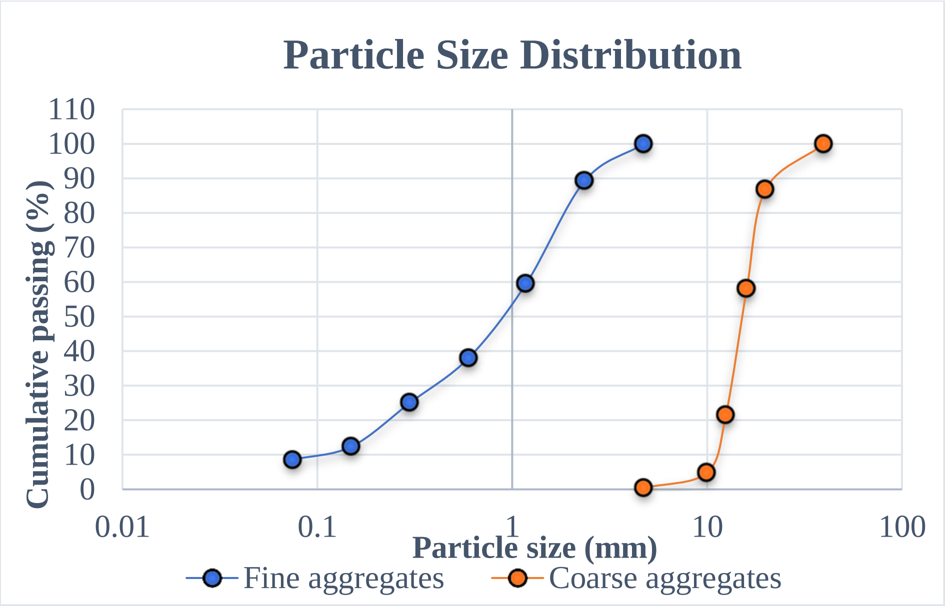


**Fig.3.1** Sieve analysis results of aggregates

The stone dust sand is classified as grade II. $D_{10}$=0.1, $D_{30}$=0.4, and $D_{60}$=1.2 are determined by the gradation curve.

$$C_u = \frac{D_{60}}{D_{10}}$$

$$C_u = \frac{1.2}{0.1} = 12 > 6$$

$$C_c = \frac{D_{30}^2}{D_{10}D_{60}}$$

$$C_c = \frac{0.4^2}{0.1X1.2} = 1.33\ (Range\ 1 - 3)$$

Thus the sand is well graded sand.

**Table 3.6** Characteristics of fine aggregate

| S. No. | Test | Result |
|---|---|---|
| 1 | Grade | Well graded |
| 2 | Zone | Zone II |
| 3 | Silt content | 12.5 % |
| 4 | Bulk density | 1610 kg/m$^3$ |
| 5 | Water absorption | 2.46 % |
| 6 | Fineness modulus | 2.76 (medium sand) |
| 7 | Specific gravity | 2.72 |

### 3.1.4 Coarse Aggregate

In order to determine the characteristics of coarse aggregate, preliminary quality tests are carried out. These tests include the elongation index, , los angeles abrasion value, impact value, flakiness index, water absorption, crushing value, fineness modulus, and specific gravity. Another source of crushed rock, also known as coarse aggregate, is obtained from a material shop in Delhi that is located locally. Two different kinds of aggregate are utilized in the design mix of the CA. These are 10 mm and 20 mm aggregate. In the different mix designs, the locally accessible CA sample material is utilised. All of the particle size aggregates present in the sample are listed in Table 3.7 along with their percentages and the CA's fineness modulus. Table 3.8 describes the properties of the CA [82, 83, 91–96]. Before the raw materials were utilised in the study project, all the necessary tests were carried out to evaluate their quality.

**Table 3.7** Sieve analysis experiment result of coarse aggregate

| Sieve size (mm) | 20 | 16 | 12.5 | 10 | 4.75 | 2.36 | 1.18 | .6 | .3 | .15 |
|---|---|---|---|---|---|---|---|---|---|---|
| Weight retained (gm) | 264 | 573 | 732 | 334 | 89 | 8 | 0 | 0 | 0 | 0 |
| Cumulative Wt Retained | 264 | 837 | 1569 | 1903 | 1992 | 2000 | 2000 | 2000 | 2000 | 2000 |
| Cumulative % wt. retained | 13.2 | 41.85 | 78.45 | 95.15 | 99.6 | 100 | 100 | 100 | 100 | 100 |
| % Cumulative Passing | 86.8 | 58.15 | 21.55 | 4.85 | 0.4 | 0 | 0 | 0 | 0 | 0 |
| % Passing of Nominal Size IS-383 | - | - | - | 0-20 | 0-5 | - | - | - | - | - |

$$\text{Fineness modulus} = \frac{(5X100\ + 99.6 + 95.15 + 78.45 + 41.85 + 13.2\,)}{100} = 7.29$$

**Table 3.8** Properties of coarse aggregate

| S. No. | Test | Result |
|---|---|---|
| 1. | Los Angeles Abrasion Value | 36.6% |
| 2. | Elongation index | 32.2% |
| 3. | Impact value | 26.6% |
| 4. | Flakiness index | 9.25% |
| 5. | Water absorption | 0.2% |
| 6. | Crushing value | 24% |
| 7. | Specific gravity | 2.70 |
| 8. | Fineness modulus | 7.29 |

### 3.1.5 Carbon fibers

For the preparation of fiber reinforced high strength concrete, carbon fiber strands cut from 12k filaments were employed. Table 3.9 shows some of the physical parameters of the carbon fibers utilized in the research. The average length of a carbon fiber piece was determined by averaging the lengths of 100 fibers, and this methodology has been published in various research works (Caggiano et al., 2016; Martinelli et al., 2015). Fig. 3.2 shows the 25mm long carbon fibers employed in the experiment.

**Table 3.9** Data from physical property tests on the carbon fiber

| **Physical qualities** | **Results** |
|---|---|
| Elongation (%) | 1.82 |
| Bulk density (g $lt^{-1}$) | 558 |
| Tensile Strength (MPa) | 3800 |
| Chop length (mm) | 10,15,20,25 |
| Volume resistivity (cms) | $2*10^3$ |
| Carbon content (%) | 93.5 |
| Specific heat (cal $g^{-1}$ $c^{-1}$) | 0.16 |
| Diameter (mm) | 0.1 |
| Aspect ratio | 100,150,200,250 |
| Elastic modulus (GPa) | 240 |

**Fig.3.2** Carbon fiber with 25 mm length

## 3.2 Mix Design (IS 10262:2019)

After the material samples have been tested for concrete control, the mix design calculations are completed. The concrete mixes were prepared with a w/c ratio of 0.24 by reinforcing it with four different aspect ratios i.e., 100, 150, 200, and 250 of carbon fibers with varying dosages of 0.2, 0.4, 0.6, 0.8, and 1% fiber content Mix design was made for $M_{60}$ grade concrete. The concrete mix design was prepared with IS 10262:2019 code guidelines comprising following steps:

### Target strength for mix proportioning

$F'ck = f_{ck} + 1.65s$

or

$F'ck = f_{ck} + X$, whichever is higher.

where

F'ck = Target average compressive strength at 28 days

f ck = characteristic compressive strength at 28 days,

s = standard deviation, and

X = factor based on grade of concrete.

From Table 2 of IS code, standard deviation, S = 5.0 N/mm$^2$.

Therefore, target strength using both equations, that is,

a) F’ck = f ck+1.65 S = 60 +1.65 × 5.0 = 68 N/mm$^2$

b) F’ck = f ck + 6.5 (The value of X for M 60 grade as per Table 1 is 6.5 N/mm$^2$)

= 60 + 6.5 = 66.5 N/mm$^2$, The higher value is to be adopted. Therefore, target strength will be 68 N/mm$^2$ as 68 N/ mm$^2$ > 66.5 N/mm$^2$.

### Approximate Air Content

According to Table 6 of the IS code, the approximate quantity of air that is predicted to be entrapped in normal (non-air-entrained) concrete is 0.5 percent for aggregates with a nominal maximum size of 20.0 millimeters.

**Selection of water-cement ratio**

According to Table 8, the ratio of water to cementitious materials that is necessary to achieve the desired strength of 68 N/mm$^2$ for OPC 43 grade cement is adjusted to be 0.26. This adjustment is based on previous experience with aggregates that have a maximum nominal size of 20 mm. The highest possible value is 0.45, although this is lower than that.

Since 0.26 is less than 0.45, it is acceptable.

**Selection of water content**

Using Table 7, we can determine that the water content of 20 mm aggregate is equal to 186 kg/m$^3$ (for a slump of 50 mm without the use of superplasticizer).

Water content estimation for a slump of 120 millimeters

$=186 + \frac{8.4}{100} * 186$ = 202 kg/m$^3$

When a superplasticizer that is based on polycarboxylate ether is utilized, the amount of water that is present can be decreased by thirty percent.

Hence, the reduced water content = 202 × 0.70 = 141.4 kg/m3 ≈ 141 kg/m$^3$

**Calculation of cement content**

Water content = 141 kg/m$^3$

Water–cement ratio = 0.26

Cement content = 141 / 0.26 ≈ 535 kg/m$^3$

In such circumstances, it may be appropriate to increase the amount of cementitious material that is present in the mixture. It is proposed that 18 percent fly ash be added to the mixture. Experience and trial and error may be used to make a judgment on the increase in cementitious material content and the percentage of that material.

The cementitious material content = 535 × 1.10 ≈ 589 kg/m$^3$

Fly ash at about 18 percent by weight of cementitious material = $589 \times \frac{18}{100}$ = 106 kg/m$^3$

Silica fume content at 7 percent by weight of revised cementitious material =

$589 \times \frac{7}{100}$ = 41 kg/m$^3$

Cement content = 589 – 106 – 41 = 442 kg/m$^3$

Revised w/cm = $\frac{141}{589}$ = 0.24

Verify that the minimum cementitious materials content is 320 kg/m$^3$, which is less than 589 kg/m$^3$ (442 kg/m$^3$ of organic matter content, 41 kg/m$^3$ of silica fume, and 106 kg/m$^3$of fly ash). As a result, okay. Verify that the maximum cement content (OPC) is 450 kg/m$^3$ , which is greater than 442 kg/m$^3$. Therefore, that is OK.

**The proportion of the volume of CA and FA content**

According to Table 10, the amount of coarse aggregate that corresponds to aggregate with a size of 20 millimeters and fine aggregate grading Zone II equals 0.66 per unit volume of total aggregate. A ratio of 0.30 between water and cementitious materials is appropriate for this. Due to the fact that the ratio of water to cementitious material is actually 0.24, the ratio is taken to be 0.667.

With a water-cement ratio of 0.50, the volume of fine aggregate content is equal to 0.333 per unit volume of total aggregate and FA (Zone II). This is calculated by subtracting 0.667 from 1.

**Mix calculations**

The mix calculations per unit volume of concrete shall be as follows:

a) Volume of concrete = 1 $m^3$

b) Volume of entrapped air in wet concrete = 0.005 $m^3$

c) Volume of cement= $\frac{[Mass\ of\ cement]}{\{[Specific\ Gravity\ of\ Cement] X\ 1000\}}$

$$=\frac{[442]}{\{3.15 X\ 1000\}} = 0.140\ m^3$$

d) Volume of water = $\frac{[Mass\ of\ water]}{\{[Specific\ Gravity\ of\ water] X\ 1000\}}$

$$=\frac{[141]}{\{1 X\ 1000\}} = 0.141\ m^3$$

e) Volume of silica fume= $\frac{[Mass\ of\ silica\ fume]}{\{[Specific\ Gravity\ of\ silica\ fume] X\ 1000\}}$

$$=\frac{[41]}{\{[2.2] X\ 1000\}} = 0.0186\ m^3$$

f) Volume of fly ash= $\frac{[Mass\ of\ fly\ ash]}{\{[Specific\ Gravity\ of\ fly\ ash] X\ 1000\}}$

$$=\frac{[106]}{\{[2.2] X\ 1000\}} = 0.048\ m^3$$

g) Volume of chemical admixture (By marsh cone apparatus used 1.1% by the weight cement, mass of admixture is 0.5% by mass of cementitious material) =

$$\frac{[Mass\ of\ \text{chemical admixture}]}{\{[Specific\ Gravity\ of\ \text{chemical admixture}] X\ 1000\}}$$

$$=\frac{[2.95]}{\{[1.1] X\ 1000\}} = 0.0027\ m^3$$

h) Volume of all in aggregate = [(a-b) - (c+d+e+f+g)]

= [(1-0.005) -(0.140+0.141+0.0186+0.048+0.0027)] = 0.645 $m^3$

i) Mass of CA = h X volume of CA X Sp. Gr. of CA X 1000

= 0.645 X 0.67 X 2.70 X 1000 = 1167 kg/$m^3$

j) Mass of FA = h X Volume of FA X Sp. Gr. of FA X 1000

= 0.645 X 0.33X 2.72 X 1000 = 580 kg/$m^3$

**Mix Proportions on Aggregate in ssd condition**

Cement = 442 kg/$m^3$

Water = 141 kg/$m^3$

Silica fume = 41 kg/$m^3$

Fly ash = 106 kg/$m^3$

w/cm = 0.24

Fine aggregate = 580 kg/$m^3$

Chemical admixture = 2.95 kg/$m^3$

Coarse aggregate = 1167 kg/$m^3$

### 3.3 Mix design proportion and sample preparation

For the purpose of conducting experiments, a total of 252 samples in total, 15 of each fiber length, were cast and experimentally tested for compressive strength, flexure strength, impact resistance, and durability. Concrete was mixed with carbon fibers with lengths of 10mm, 15mm, 20mm and 25mm, as well as varied dosages of carbon fibers (0.2, 0.4, 0.6, 0.8, and 1 percent fiber content). The concrete mix design was prepared with the help of IS 10262: 2019 2019. Table 3.10 shows the various mix design compositions that were generated. After batching the raw materials, mixing the raw materials in a concrete mixer, then pouring them into moulds, and then compacting the concrete in the moulds, they were allowed to dry for around twenty-four hours before reaching their final setting. After spending twenty-four hours in the moulds, the samples were taken out of the moulds and stored in water for about twenty-eight days, they were prepared for ultrasonic pulse velocity tests after a 28-day curing time in water, and these tests were done prior to flexure test, compressive strength test and impact resistance test as per IS 456-2000, IS 516-1959 and ACI Committee 544 (Committee, n.d.; IS 456:2000, 2000; IS 516, 1959). Slump values for freshly prepared concrete right after the mixing of raw materials in concrete mixer was calculated to check the workability of the concrete mixes along with densities of concrete samples prepared after 28 days curing as shown in Table 3.11.

**Table 3.10** Concrete mix design composition of raw materials used for the experiment

| Types of Mixes | Cement kg $m^{-3}$ | Fly ash kg $m^{-3}$ | Silica fume kg $m^{-3}$ | F.A kg $m^{-3}$ | C.A kg $m^{-3}$ | S. P kg $m^{-3}$ | Water lt | Carbon fibers | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Dose (%) | Length (mm) |
| N1F1L0 | 442 | 106 | 41 | 580 | 1167 | 1.10 | 141 | 0 | 0 |
| N1F2L10 | 442 | 106 | 41 | 580 | 1167 | 1.10 | 141 | 0.2 | 10 |
| N1F3L10 | 442 | 106 | 41 | 580 | 1167 | 1.10 | 141 | 0.4 | 10 |
| N1F4L10 | 442 | 106 | 41 | 580 | 1167 | 1.10 | 141 | 0.6 | 10 |
| N1F5L10 | 442 | 106 | 41 | 580 | 1167 | 1.10 | 141 | 0.8 | 10 |
| N1F6L10 | 442 | 106 | 41 | 580 | 1167 | 1.10 | 141 | 1 | 10 |
| N1F2L20 | 442 | 106 | 41 | 580 | 1167 | 1.10 | 141 | 0.2 | 20 |
| N1F3L20 | 442 | 106 | 41 | 580 | 1167 | 1.10 | 141 | 0.4 | 20 |
| N1F4L20 | 442 | 106 | 41 | 580 | 1167 | 1.10 | 141 | 0.6 | 20 |
| N1F5L20 | 442 | 106 | 41 | 580 | 1167 | 1.10 | 141 | 0.8 | 20 |
| N1F6L20 | 442 | 106 | 41 | 580 | 1167 | 1.10 | 141 | 1 | 20 |
| N1F2L15 | 442 | 106 | 41 | 580 | 1167 | 1.10 | 141 | 0.2 | 15 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| N1F3L15 | 442 | 106 | 41 | 580 | 1167 | 1.10 | 141 | 0.4 | 15 |
| N1F4L15 | 442 | 106 | 41 | 580 | 1167 | 1.10 | 141 | 0.6 | 15 |
| N1F5L15 | 442 | 106 | 41 | 580 | 1167 | 1.10 | 141 | 0.8 | 15 |
| N1F6L15 | 442 | 106 | 41 | 580 | 1167 | 1.10 | 141 | 1 | 15 |
| N1F2L25 | 442 | 106 | 41 | 580 | 1167 | 1.10 | 141 | 0.2 | 25 |
| N1F3L25 | 442 | 106 | 41 | 580 | 1167 | 1.10 | 141 | 0.4 | 25 |
| N1F4L25 | 442 | 106 | 41 | 580 | 1167 | 1.10 | 141 | 0.6 | 25 |
| N1F5L25 | 442 | 106 | 41 | 580 | 1167 | 1.10 | 141 | 0.8 | 25 |
| N1F6L25 | 442 | 106 | 41 | 580 | 1167 | 1.10 | 141 | 1 | 25 |

**Table 3.11** Slump and density values of different mix compositions

| Types of mix | Slump (mm) | Density (Kg $m^{-3}$) |
|---|---|---|
| N1F1L0 | 100 | 2450 |
| N1F2L10 | 90 | 2440 |
| N1F3L10 | 80 | 2435 |
| N1F4L10 | 75 | 2436 |
| N1F5L10 | 70 | 2438 |
| N1F6L10 | 65 | 2441 |
| N1F2L15 | 85 | 2435 |
| N1F3L15 | 70 | 2430 |
| N1F4L15 | 65 | 2431 |
| N1F5L15 | 60 | 2433 |
| N1F6L15 | 55 | 2436 |
| N1F2L20 | 80 | 2430 |
| N1F3L20 | 70 | 2424 |

| | | |
|---|---|---|
| N1F4L20 | 65 | 2429 |
| N1F5L20 | 65 | 2433 |
| N1F6L20 | 60 | 2434 |
| N1F2L25 | 80 | 2426 |
| N1F3L25 | 65 | 2420 |
| N1F4L25 | 60 | 2423 |
| N1F5L25 | 55 | 2427 |
| N1F6L25 | 50 | 2429 |

## 3.4 Experimental Test Procedure

### 3.4.1 Compressive Test

In order to ascertain the compressive strength of various mix compositions, 66 cubic specimens with measurements of 150x150x150 specimens were prepared, cured, and evaluated in accordance with the IS-456:2000 (IS 456:2000, 2000) code, as illustrated in Fig.3.3a. Using common equipment with a capacity of 2000kN, the compression test was carried out on cubic concrete samples to evaluate compressive strength. 5.18 kN $s^{-1}$ was the constant rate of sample loading. The compressive strength values for each kind of mixture proportions were computed after getting an average of three replicated cube specimens.


COMPRESSION TESTING MACHINE
CAPACITY - 2000 kN

(a)


FLEXURE TESTING
MACHINE

**(b)**

(c)

**(d)**

**Fig.3.3** Equipment for (a) compressive tests, (b) flexure tests, (c) casting of concrete cubes and prism beams, and (d) curing of test specimens in water

### 3.4.2 Ultrasonic Pulse Velocity Test

It is observed that the density and void ratio of concrete are altered when carbon fiber bits are added to the mix (Gehlot et al., 2016). As a result, this is a type of test that is used to determine the compactness of concrete prior to destructive tests like compressive and flexure tests. The pulse velocity of the cast samples was calculated using the following equation, which is based on the direct transmission approach (IS 13311 (Part 1), 1992), as illustrated in Fig.3.4.

$$\mathbf{V = L/T} \tag{3.1}$$

Here, L stands for the length between two transducers (m m), which is approximately 150mm, V stands for pulse velocity (k m $sec^{-1}$), and T stands for transmission time (μsec).

**Fig.3.4** Ultrasonic Pulse Velocity Test Setup

### 3.4.3 Four-point bending test

33 samples of 500*100*100mm prism beams were cast with 11 different mix compositions and examined for flexure. According to ASTM C78 (ASTM, 2010), four-point bending tests were conducted on prismatic beam samples using a flexure machine with a 100kN capacity. The samples were loaded in the center of the test beam. Under displacement control, four-point bending tests were conducted at a deflection rate of 0.6mm min$^{-1}$. Flexural strengths were determined by using the following equation on samples of prismatic beams(IS 516, 1959).

$$\mathbf{f = FL/bh^2} \tag{3.2}$$

where F, is the flexural force at which the sample fails, f the flexural strength, b the width of the test specimen (here, 100 mm), L is the span length, and h the height of the test specimen (here, 100 mm). The flexural strength test was conducted using the four-point bending test equipment depicted in Fig. 3.3b.

### 3.4.4 Impact drop weight test

Fig.3.5 shows the modified drop weight test setup that was used to evaluate the impact resistance of the sample. The impact test was created using a modified version of the impact test setup described in the ACI Committee 544 report (ACI Committee, 1986). As shown in Fig.3.5, a steel hammer weighing 14 kg is dropped from a height of 355 mm into a steel ball of 40 mm in diameter resting in the center of a cylinder disc specimen. Sixty-six-disc samples, each measuring 100mm in diameter and 50mm in height, were previously cast, and an impact test was conducted on them. Impact resistance was evaluated by testing three specimens of each mix composition for factors including fiber length and dosage, surface roughness, and loading position. Each mix composition's impact resistance was calculated as the mean of four replicated discs. The amount of energy taken in was estimated using this equation.

$$\boldsymbol{En = N.m.g.H} \tag{3.3}$$

Impact energy is denoted by En, the number of strikes by N, the mass of the 14-kilogram steel hammer is denoted by m, the acceleration of gravity is denoted by g, and the height of fall, H, was determined to be 355 mm.

### 3.4.5 Rapid Chloride Permeability Test

Compared to normal concretes, concretes that contain silica fume or fly ash are more durable because they are less susceptible to the penetration of harmful substances from the environment. The Rapid Chloride-ion Permeability Test, often known as the RCPT, was developed with the purpose of determining the degree to which concrete is resistant to the diffusion of chloride ions, which is a measure of its permeability. The purpose of this test method is to observe the quantity of electric current that is passed through cores or cylinders with a nominal diameter of 102 millimeters and slices that are 50 millimeters thick during a period of six hours. Between the two ends of the specimen, a potential difference of sixty volts direct current (V DC) is maintained. One of the ends is submerged in a solution of sodium chloride, while the other is submerged in a solution of sodium hydroxide. There is a correlation between the total charge that is passed, measured in coulombs, and the resistance of the specimen to the penetration of chloride ions, as was discovered. The procedure was performed in accordance with the

American standards ASTM C1202-12. Fig.3.6 illustrates the RCPT Test setup used for the study.

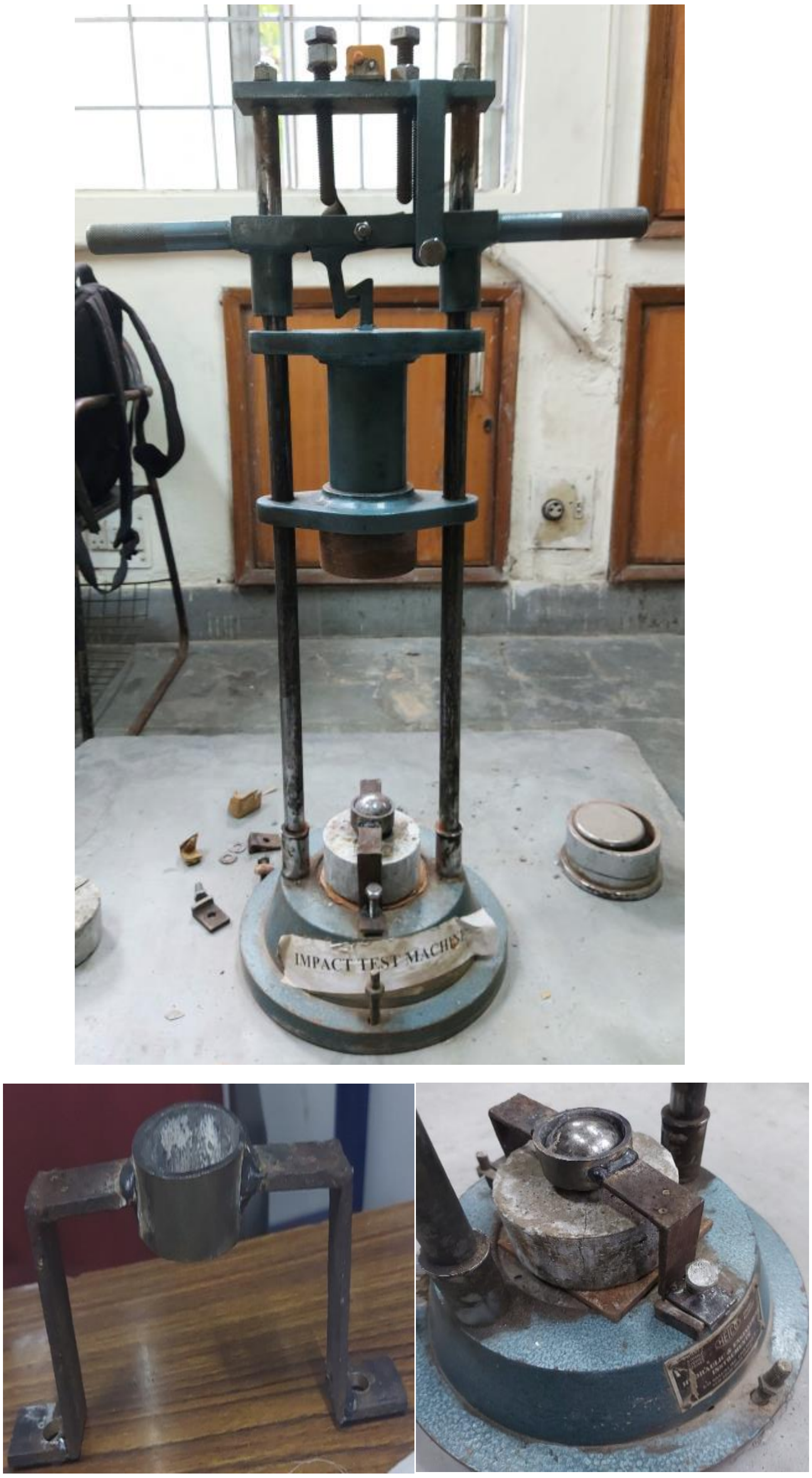


**Fig.3.5** Adapted Instrumentation for the Drop Weight Impact Test

**Fig.3.6** RCPT test setup

## 3.5 Mixing, Casting, and Curing

The mixing process involved combining the ingredients to create a homogenous high-strength concrete mixture. The materials used included cement, fine aggregates, coarse aggregates, silica fume, fly ash, super plasticizer, water, and carbon fibers with varying aspect ratios and dosages. The aspect ratios of the carbon fibers used were 100, 150, 200, and 250, with fiber contents of 0.2%, 0.4%, 0.6%, 0.8%, and 1%. Ordinary Portland Cement (OPC) was used as the binder, while sand conforming to grading zone II of IS: 383-1970 served as the fine aggregate. Crushed granite stones of 20 mm nominal size were employed as the coarse aggregate, and potable water was used for mixing. Carbon fibers of various aspect ratios and dosages were prepared for incorporation into the concrete mix. The dry materials (cement, fine aggregates, and coarse aggregates) were first mixed thoroughly in the concrete mixer to ensure uniform distribution. Carbon fibers were then gradually added to the dry mix to ensure even dispersion and prevent clumping. Water was added incrementally while continuously mixing to achieve the desired workability and consistency of the concrete mix.

For the casting process, standard molds of appropriate dimensions were cleaned and coated with a release agent to facilitate easy demolding. The molds were then assembled securely to prevent leakage during casting. The mixed concrete was placed into the molds in layers, with each layer being compacted using a table vibrator to remove air bubbles and achieve a dense concrete structure. Care was taken to ensure that the carbon fibers were evenly distributed throughout the concrete matrix during placement. The surface of the concrete in the molds was leveled and smoothed using trowels to achieve a uniform finish, and the molds were then covered with plastic sheets to prevent moisture loss and contamination.

In terms of curing, the concrete specimens were kept in the molds for 24 hours at room temperature to allow initial setting. After 24 hours, the specimens were demolded carefully to avoid damage. The demolded concrete specimens were then immersed in a curing tank filled with potable water, where they were cured under water for 28 days to ensure proper hydration and development of strength and durability. During the curing period, the water temperature was maintained at approximately 27°C to simulate standard curing conditions. After 28 days of water curing, the specimens were removed from the curing tank, the surface moisture was wiped off, and the specimens were allowed to air dry for a short period before conducting the tests.

# CHAPTER 4

# RESULTS AND DISCUSSION

The results and discussion section presents a comprehensive analysis of the mechanical properties, impact resistance, and durability of high-strength concrete reinforced with carbon fibers of varying aspect ratios and dosages. This section synthesizes the findings from multiple tests conducted after 28 days of water curing, including flexure tests, compression tests, impact resistance tests, durability tests, and ultrasonic pulse velocity tests. The results reveal how varying the aspect ratios and dosages of carbon fibers influence the performance and structural integrity of the concrete. The primary focus is on how these variations enhance or impair the compressive strength, flexural strength, impact resistance, durability, and porosity of the concrete samples, providing insights into the optimal use of carbon fibers in high-strength concrete applications. The discussion interprets these results in the context of existing literature, elucidating the mechanisms behind observed behaviors and suggesting practical implications for construction practices.

## 4.1 Compressive strength

Concrete cracks are slowed down by fibers. The porosity of the matrix was also improved by the carbon fibers. The existence of these two factors has a substantial impact on compressive strength growth or loss. The compressive strengths of the various types of mixes cast are shown in Fig.4.1a and Fig.4.2a. Compressive strength rose consistently as fiber content with longer lengths were increased, according to the results. As a result of the increase in fiber dose, specimen N1F3L25 exhibited a maximum compressive strength of around 81 MPa, nearly 19% higher than the N1F1L0 (reference specimen), which was around 68 MPa. Additionally, when the carbon fiber aspect ratio was increased while maintaining the fiber content, specimen N1F3L25 (81 MPa) had a maximum improvement in compressive strength of about 7% as compared to specimen N1F3L15 (76 MPa). Specimen N1F3L25 (81MPa) showed a maximum improvement in compressive strength of roughly 10% over Specimen N1F2L25 (73.5 MPa) when the aspect ratio was held constant while the fiber content was altered. Statistical analysis was also conducted for compressive strength of different samples as shown in Table 4.1 to quantify the variability within their data sets. This is important for understanding the inherent uncertainty associated with impact resistance measurements.

**Table 4.1** Statistical analysis of compressive strengths of different concrete mixes

| Types of composition | Compressive strength (MPa) | |
|---|---|---|
| | Mean | COV (%) |
| N1F1L0 | 68 | 7.352 |
| N1F2L15 | 71.5 | 6.99 |
| N1F3L15 | 76 | 6.57 |
| N1F4L15 | 73.5 | 6.802 |
| N1F5L15 | 72 | 6.944 |
| N1F6L15 | 71 | 7.04 |
| N1F2L25 | 73.5 | 6.802 |
| N1F3L25 | 81 | 6.17 |
| N1F4L25 | 75.5 | 6.622 |
| N1F5L25 | 74.5 | 6.711 |
| N1F6L25 | 72.5 | 6.89 |

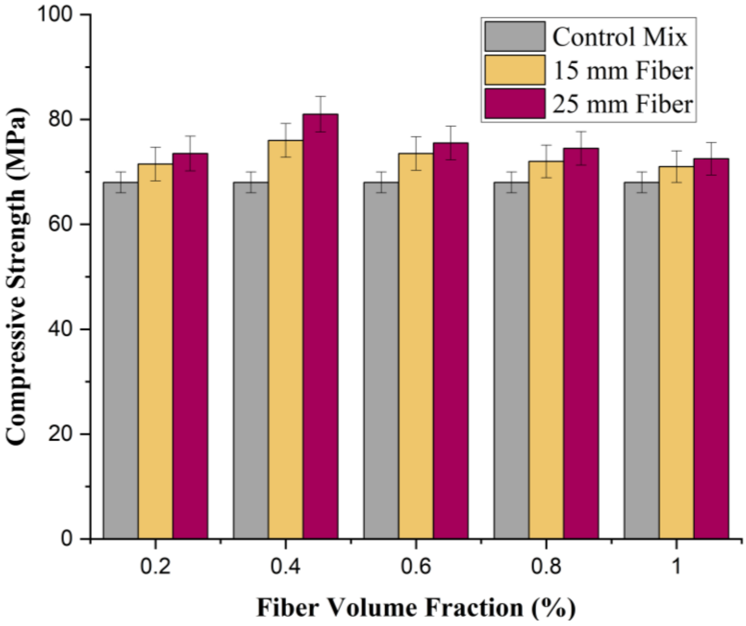
## 4.2 Flexural Strength

Fig.4.1b and Fig.4.2b exhibits the flexural performance of carbon fibers by varying its lengths and dosages in high strength concrete with the help of a four-point bending tests. Experiments revealed that boosting the dosages and aspect ratio of carbon fibers boosted the test sample's flexure resistance. When compared to the reference specimen (N1F1L0), which had a flexure strength of 6 MPa, sample N1F3L25's (9 MPa) flexural strength improved by about 50%. Maximum improvement of roughly 29% was seen when comparing N1F3L25 flexure test samples to N1F2L25; this was attributed to an increase in fiber content while maintaining a consistent fiber aspect ratio. When fiber dose was held constant, there was a highest increase in flexure strength of around 16% in the N1F3L25 compared to the N1F3L15. Later, the failure mechanism resulting from fiber failure to sustain loads would be investigated, and it was proposed that the benefit of longer fiber length comes from the increased friction which gets created by itself. When three-dimensional fiber orientation was kept, mechanical properties of shorter fibers improved more than those of longer fibers (Mastali et al., 2015; Naghibdehi, 2014; Naghibdehi et al., 2014).

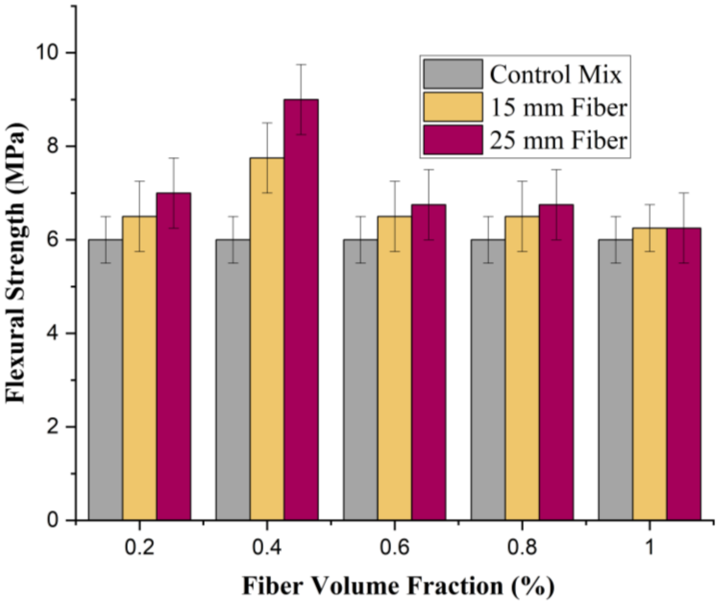
## 4.3 Ultrasonic Pulse Velocity Test

Carbon fibers were added to the mixes to make them more porous. Fig.4.1c and Fig.4.2c illustrate the compacted results of using carbon fibers in concrete. Porosity values for the concrete mixtures rose as expected with increasing aspect ratios of carbon fibers and fiber dosages, with the highest porosity found in the N1F3L25 sample. Sample N1F3L25 (4557 m $s^{-1}$) was found to have the largest decrease in pulse velocity value (approximately 8%) when compared to the standard sample N1F1L0 (around 4800 m $s^{-1}$) (4950 m $s^{-1}$). The results showed that the pulse velocity shifted between 4557 and 4950 meters per second. The pulse velocity in specimen N1F3L15 drops by the most (about 4 percent) of any reinforced sample when doses were increased and the aspect ratio is held constant. Furthermore, when the aspect ratio was raised while the carbon fiber dose remained constant, sample N1F5L25 showed the greatest decline in pulse velocity (approximately 5%) when compared to sample N1F5L15. When carbon fiber dosage was increased from 0.2 percent to 0.4 percent, ultrasonic pulse velocity dropped continuously (average 3.5%) while fiber lengths remained unchanged.

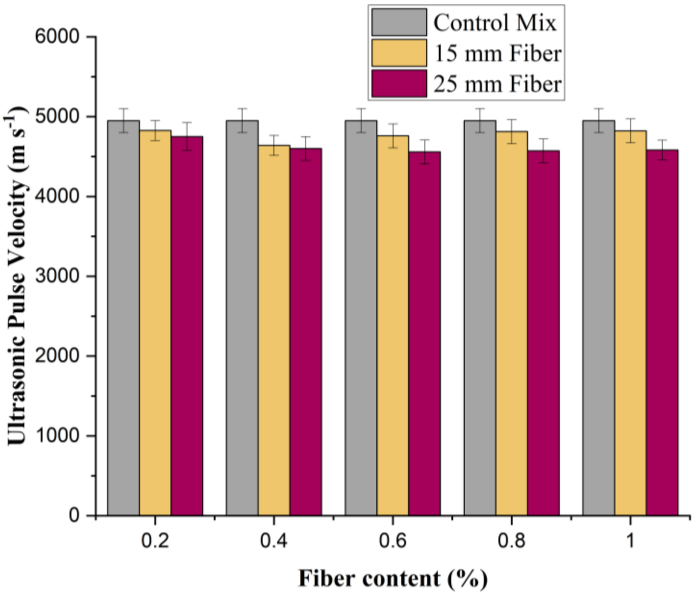
As the porosity of the models decreased with an increase in fiber dose, the compressive strength values increased because the fibers significantly slowed the spread of cracks formed under compressive loads. This was an interesting limitation of the study.



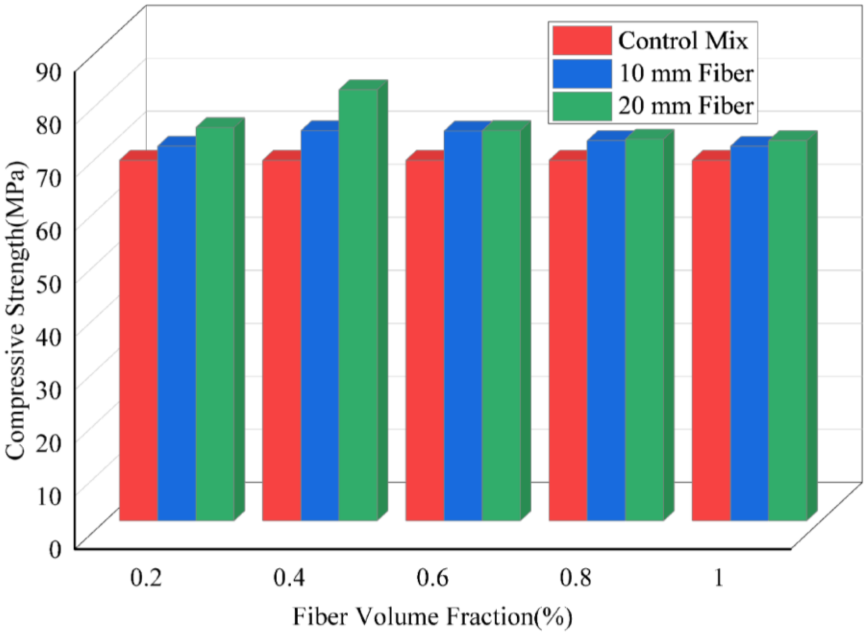
**(a)**



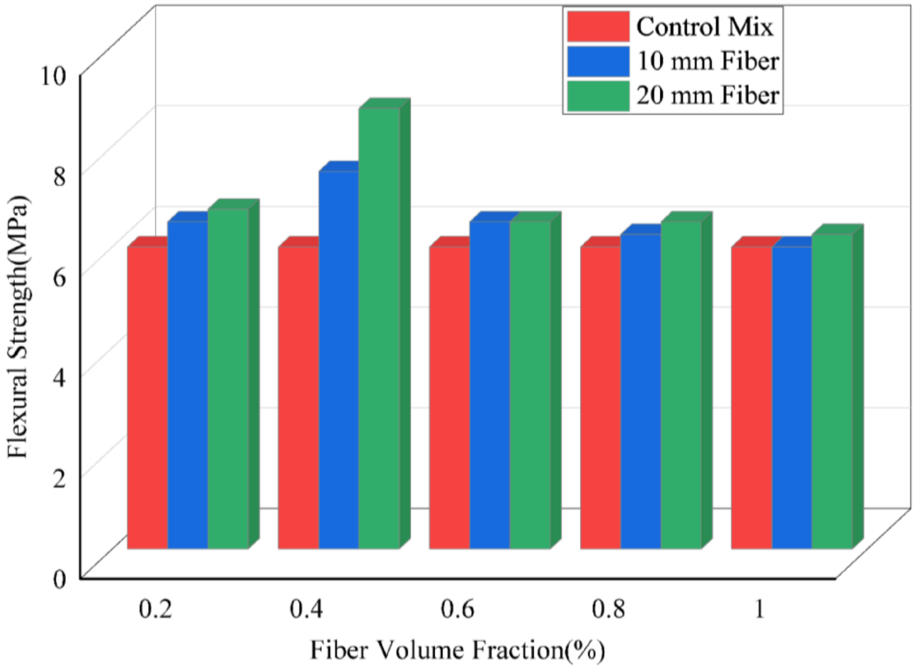
**(b)**


Control Mix
15 mm Fiber
25 mm Fiber
Ultrasonic Pulse Velocity (m s$^{-1}$)
0
1000
2000
3000
4000
5000
6000
0.2
0.4
0.6
0.8
1
Fiber content (%)

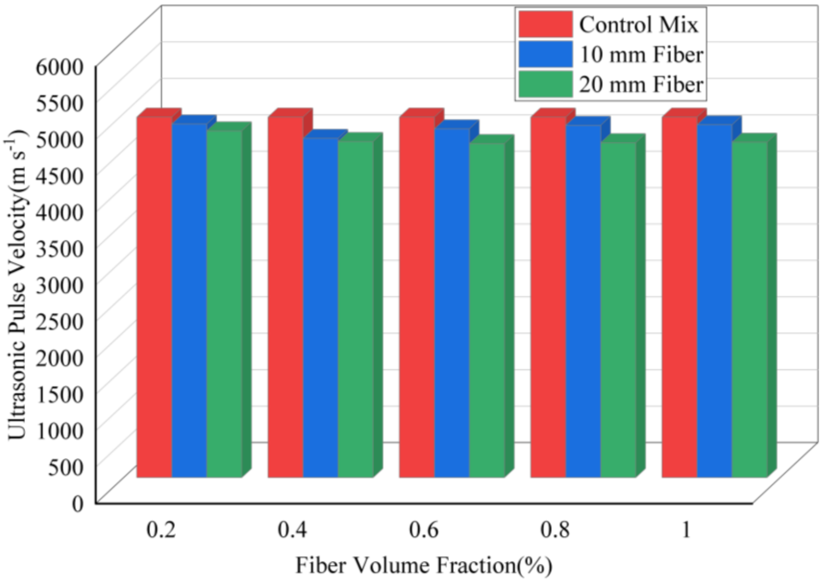
**(c)**


Control Mix
10 mm Fiber
20 mm Fiber
Compressive Strength(MPa)
0
10
20
30
40
50
60
70
80
90
0.2
0.4
0.6
0.8
1
Fiber Volume Fraction(%)

**(a)**

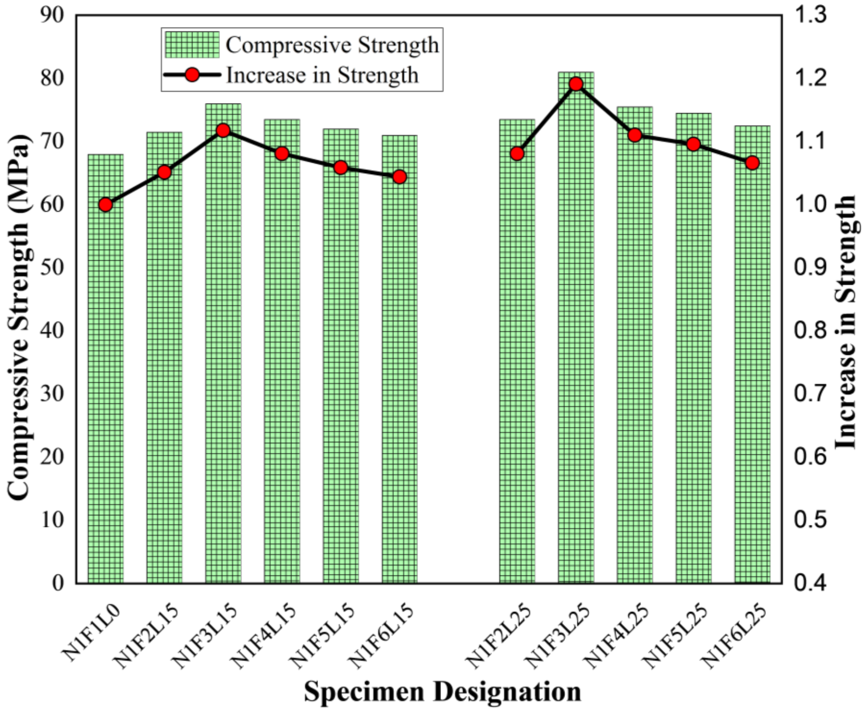


**(b)**

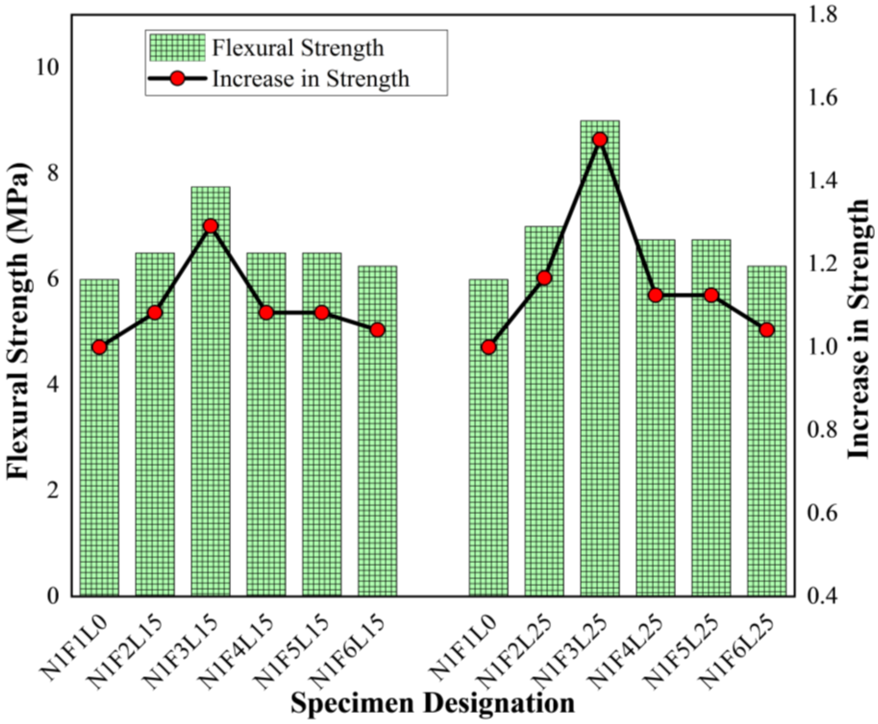


**(c)**

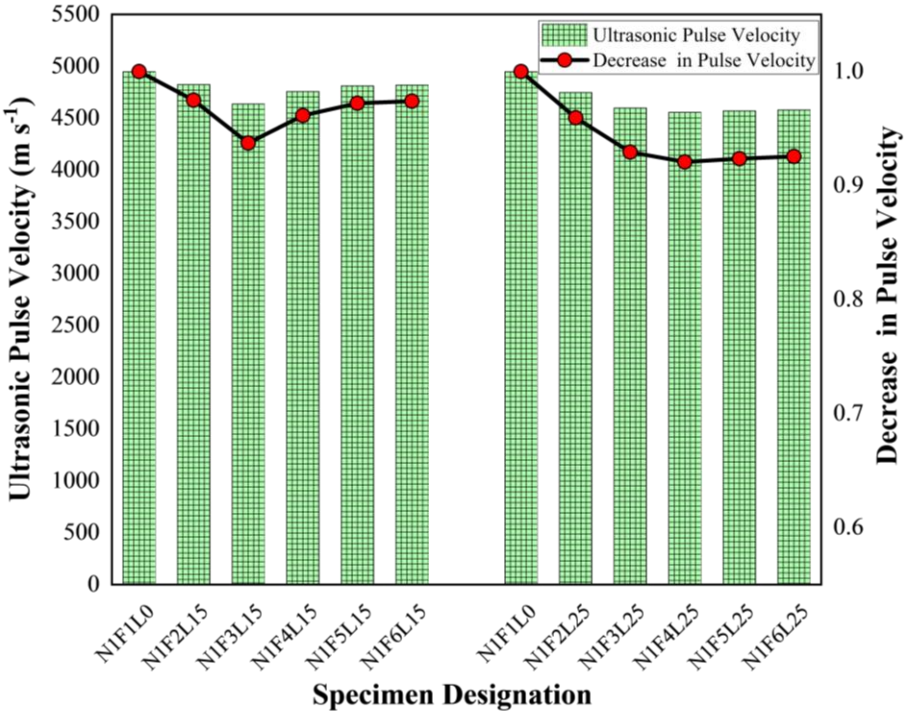
**Fig.4.1** Fiber dose's impact on (a) compression strength, (b) flexure strength, and (c) UPVT test


Compressive Strength
Increase in Strength
Compressive Strength (MPa)
Increase in Strength
0
10
20
30
40
50
60
70
80
90
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
N1F1L0
N1F2L15
N1F3L15
N1F4L15
N1F5L15
N1F6L15
N1F2L25
N1F3L25
N1F4L25
N1F5L25
N1F6L25
Specimen Designation

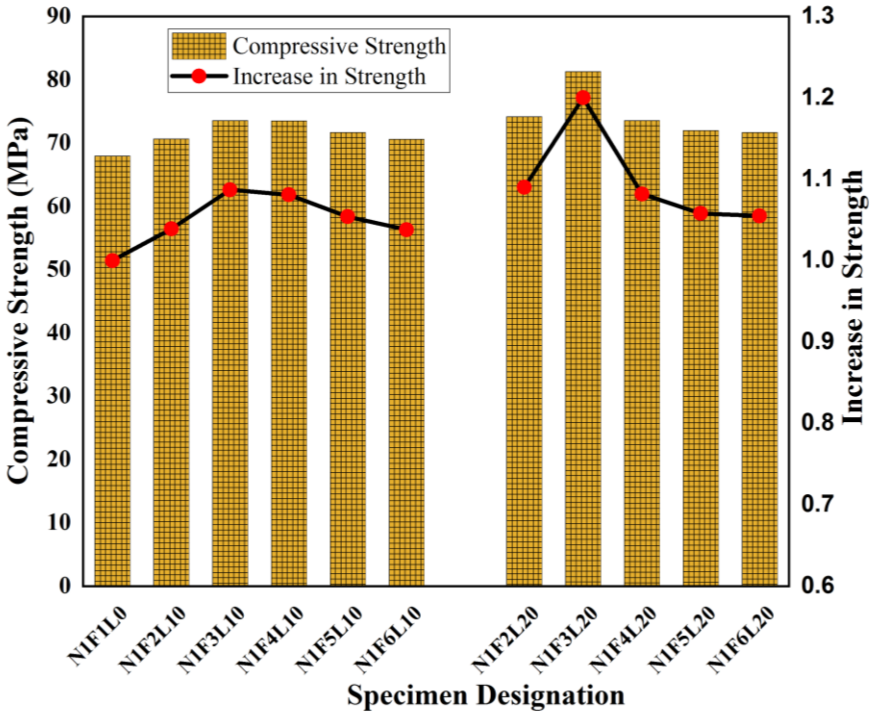
**(a)**


Flexural Strength
Increase in Strength
Flexural Strength (MPa)
Increase in Strength
0
2
4
6
8
10
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
N1F1L0
N1F2L15
N1F3L15
N1F4L15
N1F5L15
N1F6L15
N1F1L0
N1F2L25
N1F3L25
N1F4L25
N1F5L25
N1F6L25
Specimen Designation

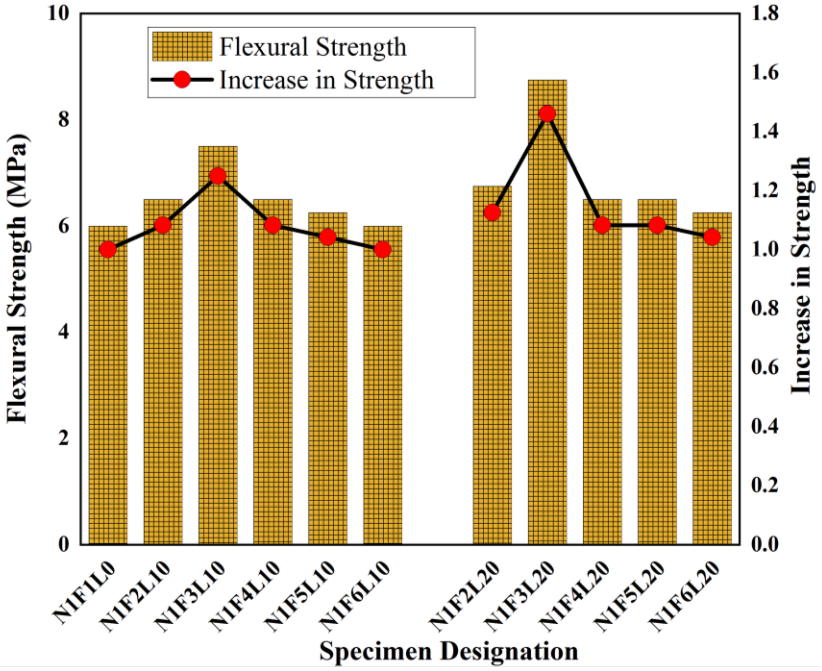
**(b)**


Ultrasonic Pulse Velocity
Decrease in Pulse Velocity
Ultrasonic Pulse Velocity (m s$^{-1}$)
Decrease in Pulse Velocity
Specimen Designation
5500
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
1.0
0.9
0.8
0.7
0.6
N1F1L0
N1F2L15
N1F3L15
N1F4L15
N1F5L15
N1F6L15
N1F1L0
N1F2L25
N1F3L25
N1F4L25
N1F5L25
N1F6L25

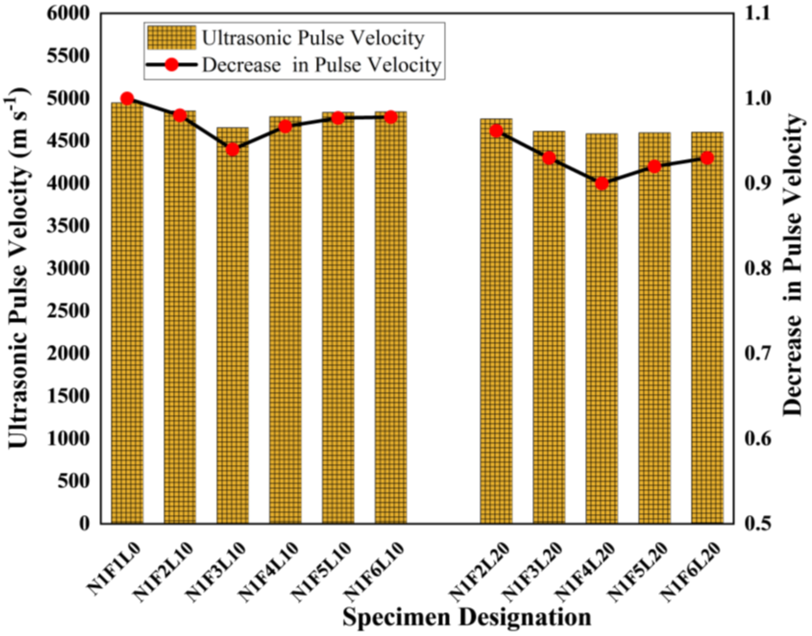
**(c)**


Compressive Strength
Increase in Strength
Compressive Strength (MPa)
Increase in Strength
Specimen Designation
90
80
70
60
50
40
30
20
10
0
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
N1F1L0
N1F2L10
N1F3L10
N1F4L10
N1F5L10
N1F6L10
N1F2L20
N1F3L20
N1F4L20
N1F5L20
N1F6L20

**(a)**



**(b)**

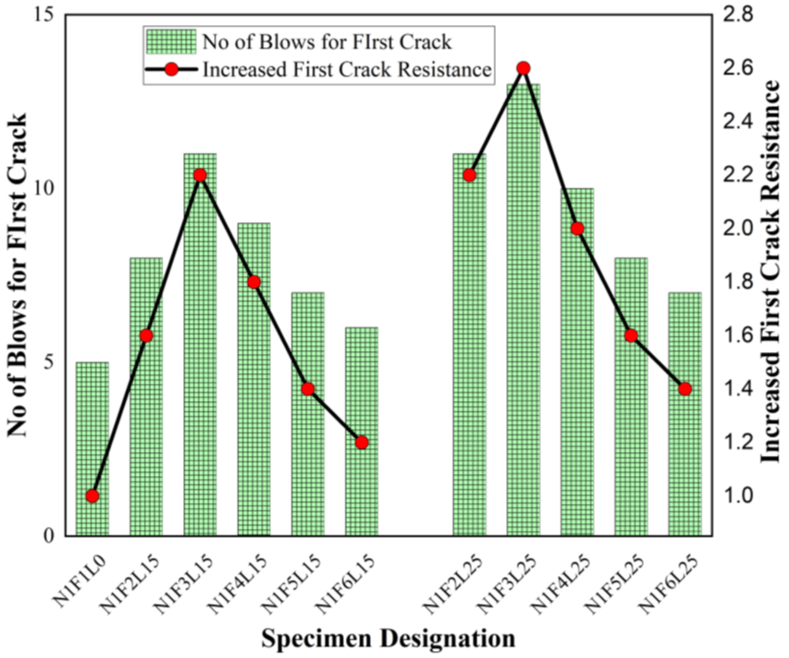


**(c)**

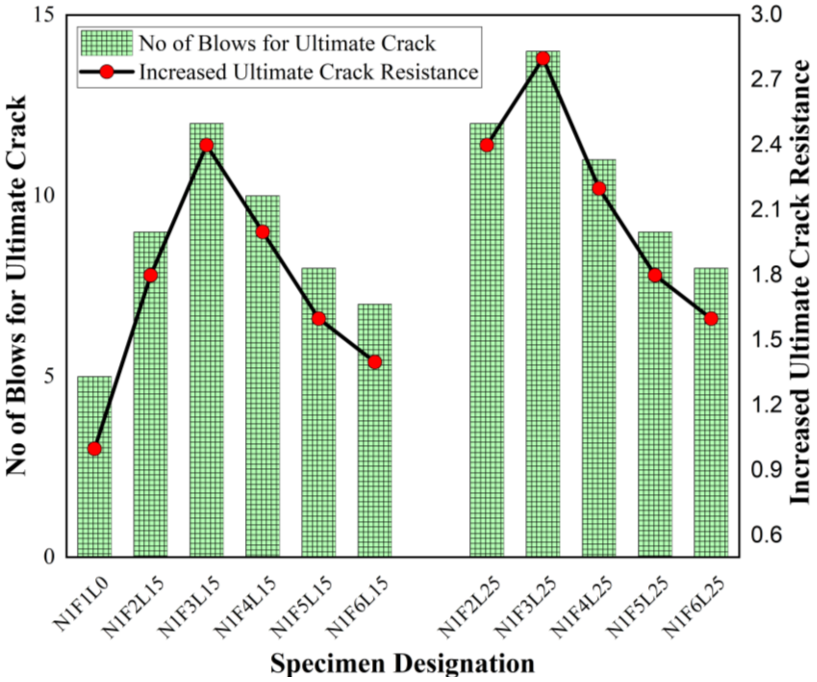
**Fig.4.2** Different fiber content’s effects on **(a)** compression strength, **(b)** flexure strength, and **(c)** UPVT test

## 4.4 Impact Resistance

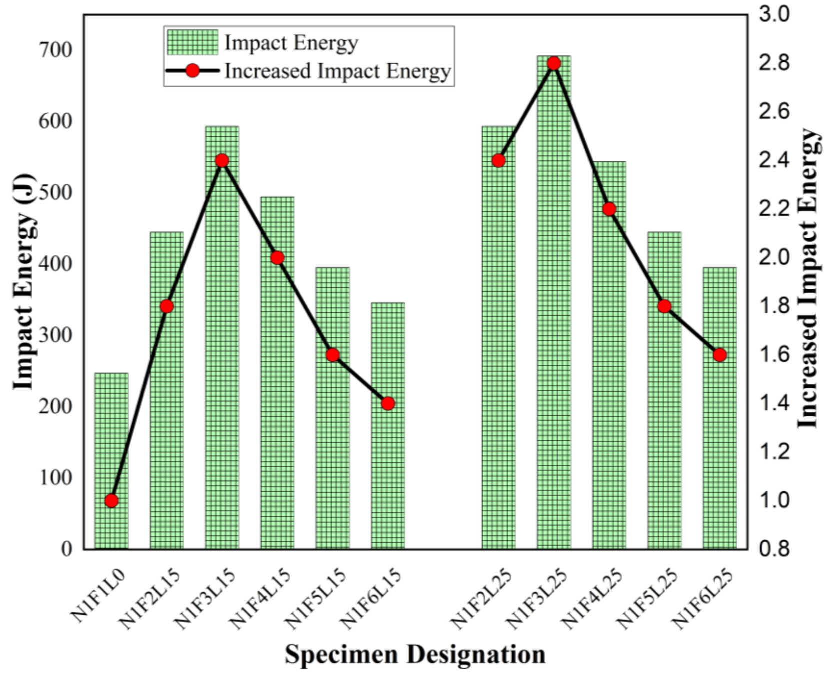
Fig.4.3a and Fig.4.3b depict the number of initial crack blows and the number of ultimate crack blows with the impact resistance test setup, respectively. Results showed that both the first and final crack impact resistances were improved by including carbon fiber in the reinforced specimens, with the latter demonstrating a higher improvement. The first and final crack impact resistances of N3F3L25 were nearly 2.8 times those of the reference specimen (N3F1L0). Specimen N3F3L15 showed a 38% and 34% improvement in first crack resistance and final crack impact resistance over N3F2L15 due to a higher fiber dose. The improvement in impact resistance strength of specimens as a function of fiber length and dosage may be explained by the fiber's planar orientation and efficient bridging action. Fig.4.3c depicts the computed impact energy taken using equation (3.3) by the test samples, which represents the global ultimate fracture impact resistance. The data showed that the impact energy of the fortified samples was between 247 J and 692 J. It was found that the lowest impact energy was measured for N3F1L0 and the highest for N3F3L25. These carbon fibers were also found to be uniformly dispersed across the fracture surface, which boosted the bridging action's efficiency. After being subjected to a drop weight impact test, cylindrical disc specimens showed a wide range of failure patterns, as shown in Fig.4.4. More uniformity in crack patterns was observed upon an increment of fiber dose from 15mm to 25 mm. Statistical analysis was also conducted for first crack and ultimate crack resistance as shown in Table 4.2 to quantify the variability within their data sets. This is important for understanding the inherent uncertainty associated with impact resistance measurements.


No of Blows for FIrst Crack
Increased First Crack Resistance
No of Blows for FIrst Crack
Increased First Crack Resistance
Specimen Designation
0
5
10
15
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8
N1F1L0
N1F2L15
N1F3L15
N1F4L15
N1F5L15
N1F6L15
N1F2L25
N1F3L25
N1F4L25
N1F5L25
N1F6L25

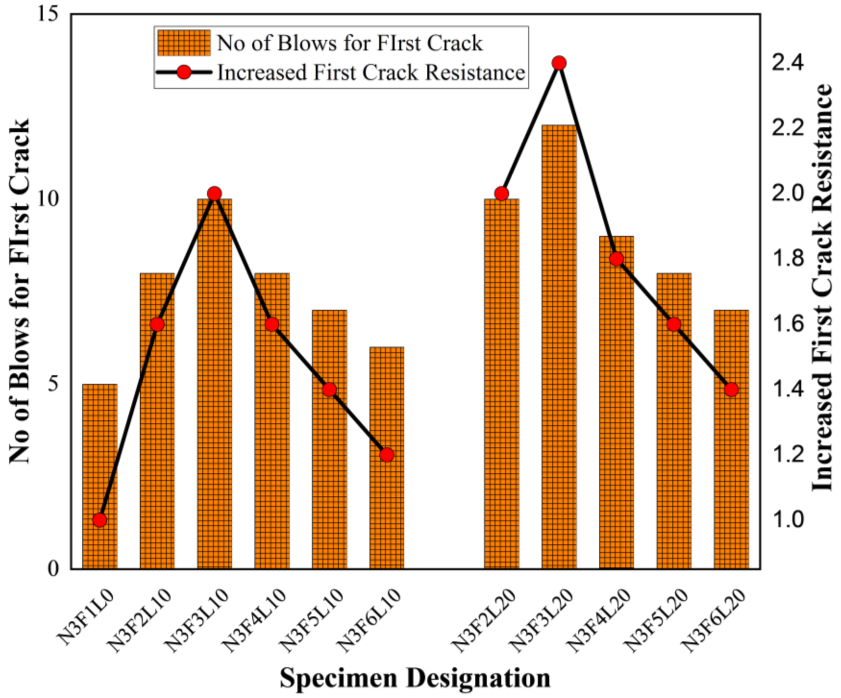
**(a)**


No of Blows for Ultimate Crack
Increased Ultimate Crack Resistance
No of Blows for Ultimate Crack
Increased Ultimate Crack Resistance
Specimen Designation
0
5
10
15
0.6
0.9
1.2
1.5
1.8
2.1
2.4
2.7
3.0
N1F1L0
N1F2L15
N1F3L15
N1F4L15
N1F5L15
N1F6L15
N1F2L25
N1F3L25
N1F4L25
N1F5L25
N1F6L25

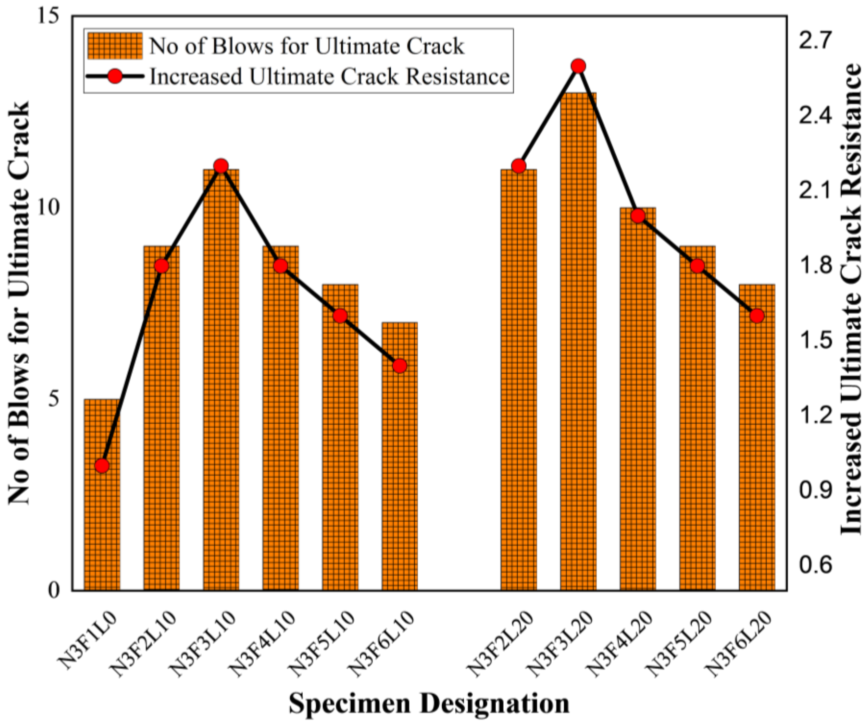
**(b)**


Impact Energy
Increased Impact Energy
Impact Energy (J)
Increased Impact Energy
0
100
200
300
400
500
600
700
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8
3.0
N1F1L0
N1F2L15
N1F3L15
N1F4L15
N1F5L15
N1F6L15
N1F2L25
N1F3L25
N1F4L25
N1F5L25
N1F6L25
Specimen Designation

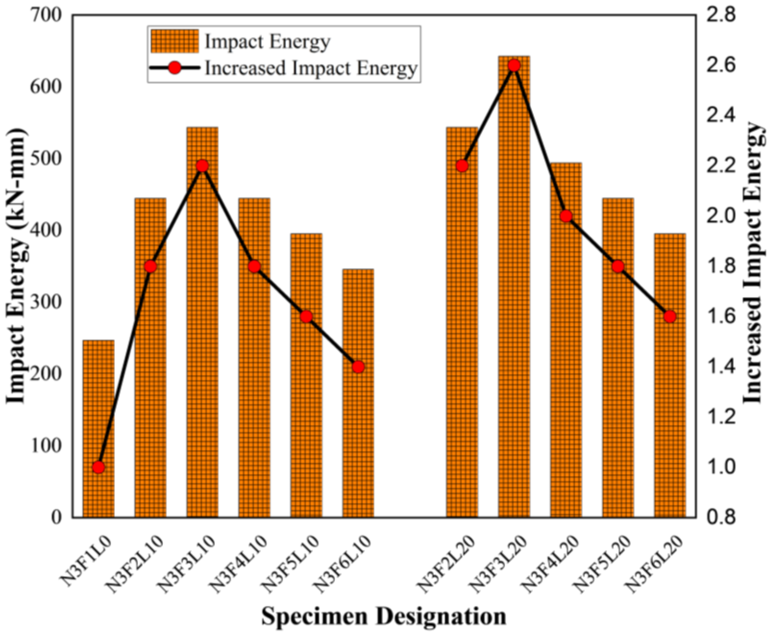
(c)


No of Blows for FIrst Crack
Increased First Crack Resistance
No of Blows for FIrst Crack
Increased First Crack Resistance
0
5
10
15
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
N3F1L0
N3F2L10
N3F3L10
N3F4L10
N3F5L10
N3F6L10
N3F2L20
N3F3L20
N3F4L20
N3F5L20
N3F6L20
Specimen Designation

(a)



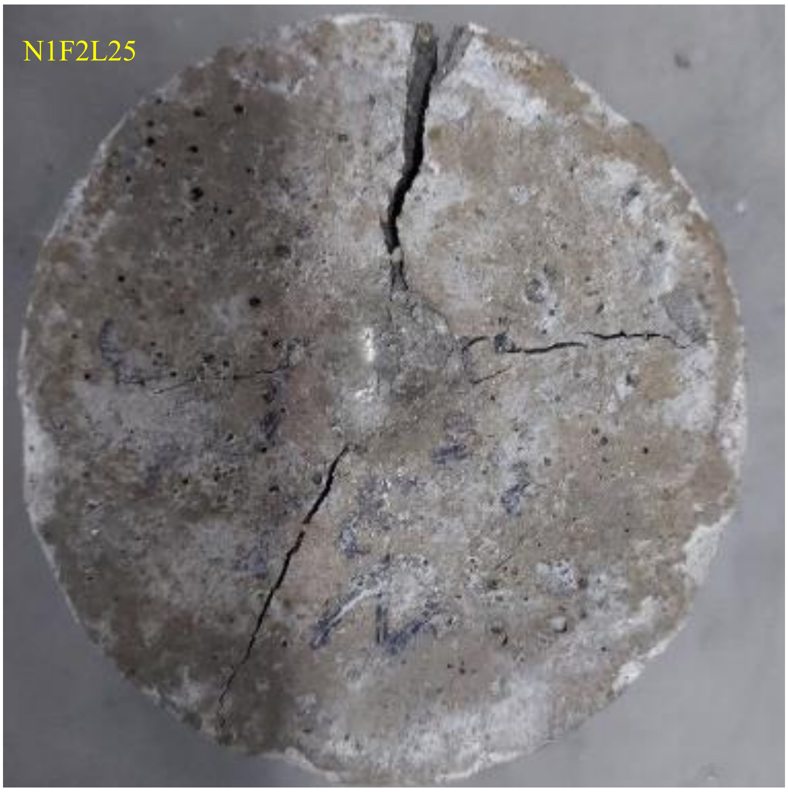
**(b)**



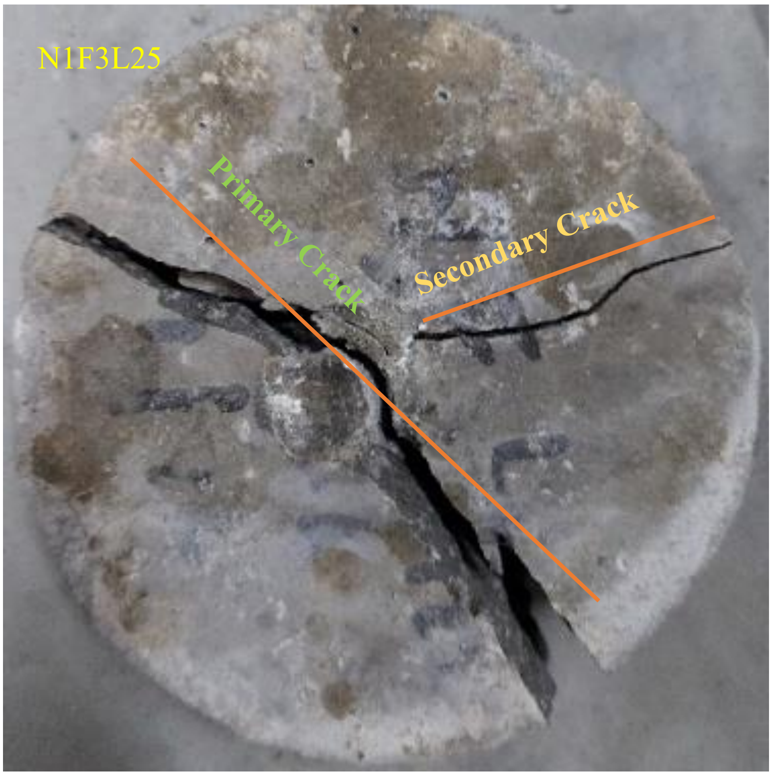
**(c)**

**Fig.4.3** Fiber dose response to: **(a)** first crack blows**(b)** ultimate crack blows **(c)** impact energy


N1F1L0


N1F2L25


N1F4L25
More Uniform Cracks


N1F3L25
Primary Crack
Secondary Crack

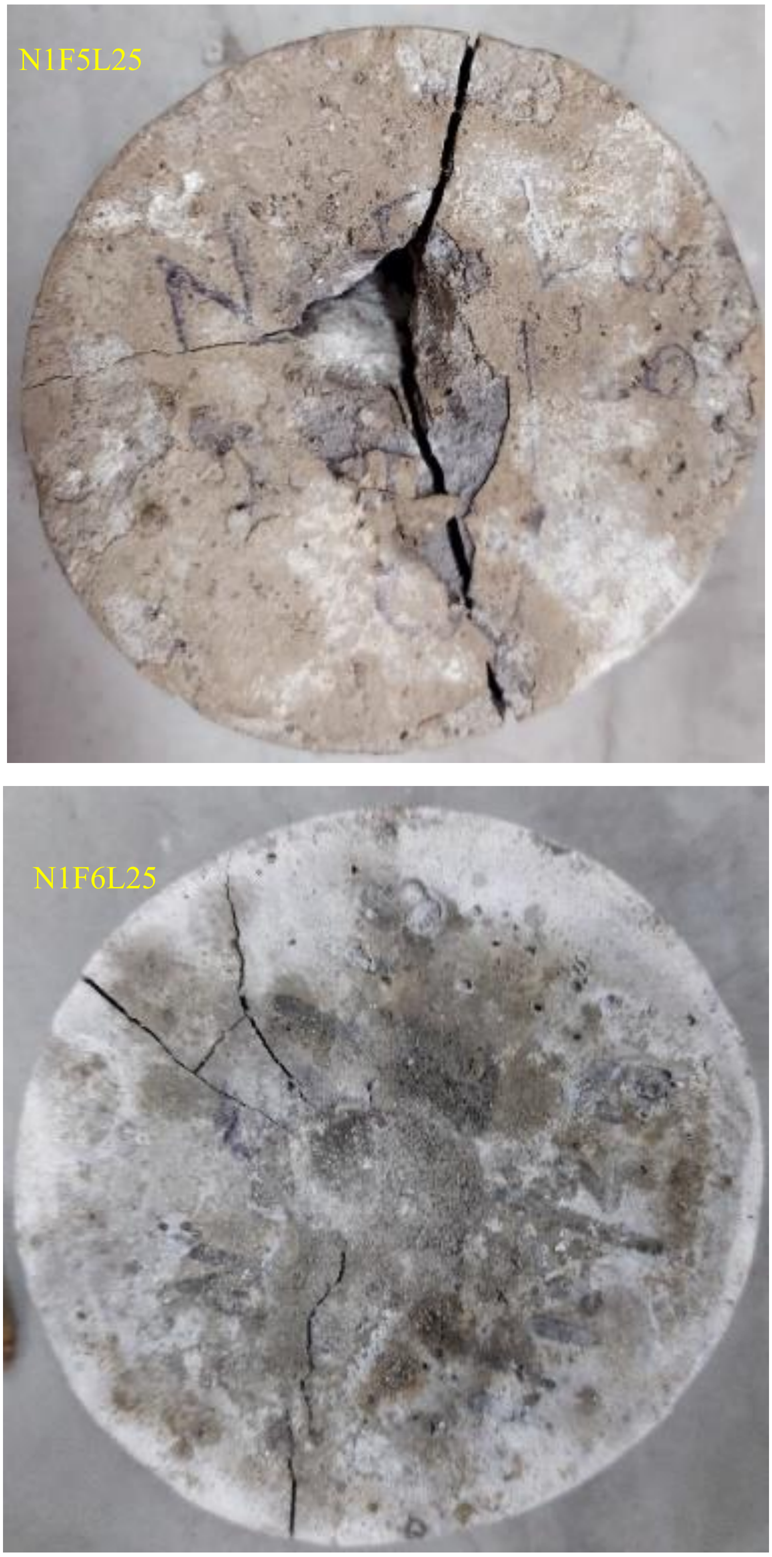


**Fig.4.4** Crack patterns of concrete from impact test.

**Table 4.2** Statistical analysis of Impact resistance

| Types of composition | First crack impact resistance (Blows) | | | Ultimate crack impact resistance (Blows) | | |
|---|---|---|---|---|---|---|
| | Mean | Standard Deviation | COV (%) | Mean | Standard Deviation | COV (%) |
| N1F1L0 | 5.53 | 0.471 | 8.517 | 5.42 | 0.51 | 9.409 |
| N1F2L15 | 8.22 | 0.816 | 9.92 | 9.11 | 1.12 | 12.29 |
| N1F3L15 | 11.11 | 2.121 | 19.09 | 12.11 | 2.31 | 19.07 |
| N1F4L15 | 9.25 | 0.829 | 8.96 | 10.2 | 1.82 | 17.84 |
| N1F5L15 | 7 | 0.707 | 10.1 | 8.23 | 0.96 | 11.66 |
| N1F6L15 | 5.66 | 0.472 | 8.33 | 7.16 | 0.789 | 11.01 |
| N1F2L25 | 11.28 | 2.31 | 20.47 | 12.23 | 2.41 | 19.705 |
| N1F3L25 | 13.08 | 2.11 | 16.13 | 14.27 | 3.12 | 21.86 |
| N1F4L25 | 10.3 | 1.82 | 17.66 | 11.32 | 1.95 | 17.22 |
| N1F5L25 | 8.1 | 0.908 | 11.209 | 9.15 | 1.31 | 14.31 |
| N1F6L25 | 7.05 | 0.721 | 10.22 | 8 | 0.86 | 10.75 |

## 4.5 RCPT

The Rapid Chloride Penetration Test (RCPT) results for carbon fiber reinforced concrete indicate an impressive performance with less than 100 coulombs charge for all types of mixes prepared for the study, suggesting very low chloride ions permeability in the concrete matrix. The low charge transfer is indicative of the enhanced durability and resistance to chloride ingress attributed to the incorporation of carbon fibers. This outcome aligns with the theoretical expectations that the use of carbon fibers in concrete can act as an effective barrier against chloride penetration, mitigating the risk of corrosion in reinforced structures. The discussion of these RCPT results underscores the potential of CFRC as a sustainable and durable construction material. The reduced chloride permeability is critical in preventing the corrosion of embedded steel reinforcements, a common cause of structural degradation in conventional concrete. The reinforcing role of carbon fibers not only improves the mechanical properties of the concrete but also serves as a protective measure against environmental aggressors, thereby extending the service life of the structure. These findings contribute to the growing body of evidence supporting the efficacy of carbon fiber reinforcement in enhancing the durability and performance of concrete structures in chloride-rich environments. Further research and long-term monitoring will provide valuable insights into the practical application and longevity of CFRC in real-world scenarios. Fig.4.5 illustrates the RCPT results of different fiber dose mixes conducted in the study.

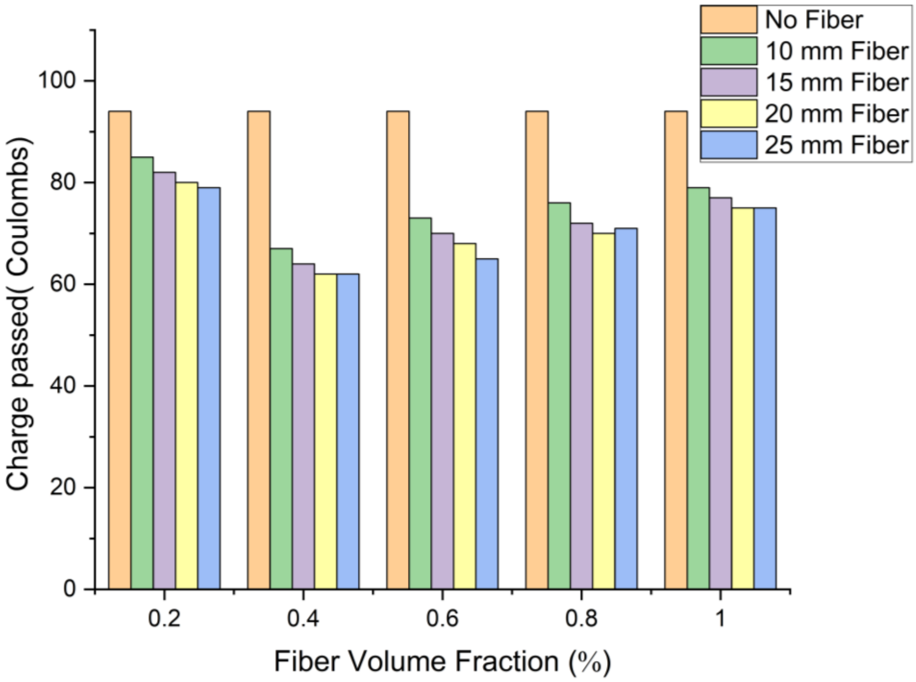


**Fig.4.5** RCPT result of different fiber dose mixes

# CHAPTER 5

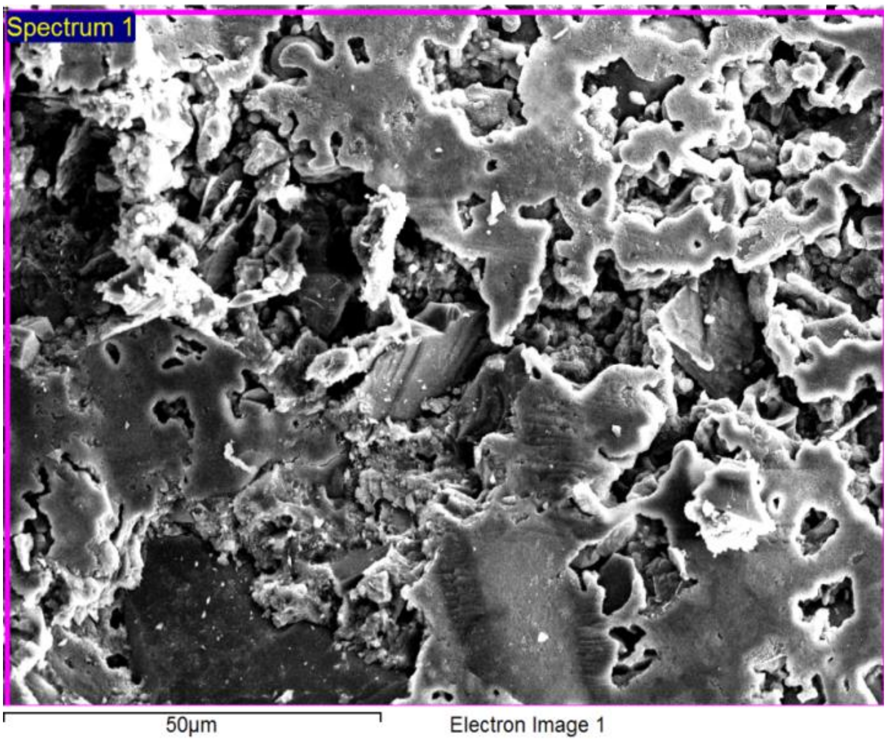
# MICROSTRUCTURE AND ANALYTICAL STUDY

This section delves into the microstructural and analytical examination of high-strength concrete reinforced with carbon fibers. Understanding the microstructure is crucial for comprehending the mechanisms behind the enhanced mechanical properties, durability, and impact resistance observed in the experimental tests. Advanced characterization techniques such as Scanning Electron Microscopy (SEM), Energy Dispersive X-ray Spectroscopy (EDS), Powder X-ray Diffraction (XRD), Fourier Transformed Infrared Spectroscopy (FTIR), and X-ray Photoelectron Spectroscopy (XPS) were employed to analyze the concrete samples. These techniques provided detailed insights into the morphology, chemical composition, mineralogical properties, and the distribution of functional groups and elements within the concrete matrix. By correlating these microstructural features with the observed macroscopic properties, this section aims to elucidate the role of carbon fibers in enhancing the performance of high-strength concrete. The analytical study not only helps in validating the experimental results but also in identifying the underlying factors that contribute to the material's behavior, thereby offering a comprehensive understanding of carbon fiber-reinforced concrete. This section delves into the microstructural and analytical examination of high-strength concrete reinforced with carbon fibers. Understanding the microstructure is crucial for comprehending the mechanisms behind the enhanced mechanical properties, durability, and impact resistance observed in the experimental tests. Advanced characterization techniques such as Scanning Electron Microscopy (SEM), Energy Dispersive X-ray Spectroscopy (EDS), Powder X-ray Diffraction (XRD), Fourier Transformed Infrared Spectroscopy (FTIR), and X-ray Photoelectron Spectroscopy (XPS) were employed to analyze the concrete samples. These techniques provided detailed insights into the morphology, chemical composition, mineralogical properties, and the distribution of functional groups and elements within the concrete matrix. The analytical study not only helps in validating the experimental results but also in identifying the underlying factors that contribute to the material's behavior, thereby offering a comprehensive understanding of carbon fiber-reinforced concrete.

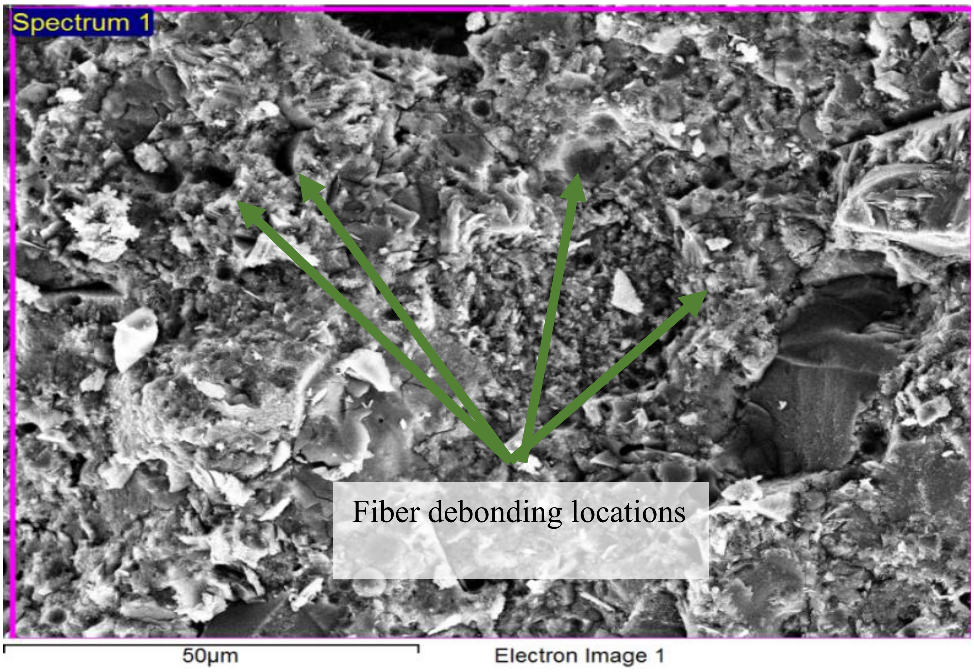
## 5.1 Microstructure studies (PXRD, SEM, EDX), XPS and FTIR

Using a high-resolution Bruker D8 advanced diffractometer, the powder X-ray diffraction (PXRD) trends were captured. The radiation used was Cu Ka radiation with a wavelength of 1.5418 Å, which was obtained by a Gobel mirror. The scan rate was set at 1.0 second per step, and the step size was set at 0.02 degrees. The temperature was set at 298 degrees Kelvin. The range of 2theta was from 5 to 70 degrees. A Zeiss GeminiSEM was used for field emission-SEM with EDX analysis to investigate the morphological properties of PANI-intercalated Zn/Cu LDH. An examination of the surface morphology of the carbon fibers that were utilized in the research was carried out with the assistance of scanning electron microscopy (SEM), as shown in Figure 5.1. In order to visualize the microstructure of carbon fiber embedded concrete and to investigate the interface relationship that exists between the fibers and the cement matrix, scanning electron microscopy (SEM) examination was utilized. SEM pictures indicated that the fibers efficiently bridged fractures and cavities in the matrix, enhancing the distribution of stress and strain. This bridging effect is often associated with reactive fibers, which have a strong interfacial bond with the cement paste. This resulted in increased crack resistance and ductility of the composite, which is useful in situations where the material is subjected to cyclic stress or impact. Fig.5.1d shows the structure of the surface of a carbon fiber, which has grooves that strengthen the interface binding between the fibers and the matrix. To acquire a better understanding of how fiber degrades, SEM images were used. Because of the debonding mechanism described in Fig.5.1b, the carbon fibers employed in the experiments were unable to withstand the ultimate loads. The energy dispersive X-ray spectroscopy (EDX) technique was utilized in order to ascertain the elemental abundances present in the cast samples, as depicted in Figure 5.2. Ca-K and O-K were identified as the peak components. The generation of a strong interfacial bond with the cement paste and the enhancement of load transfer between the cement matrix and the fibers are two of the ways in which carbon fibers contribute to the improvement of the mechanical properties of concrete. These properties include toughness, flexural strength, and compressive strength. The mineral orientation and crystal structure of the cast concrete samples were studied by EDX and PXRD. As can be seen in Fig.5.3 Powdered

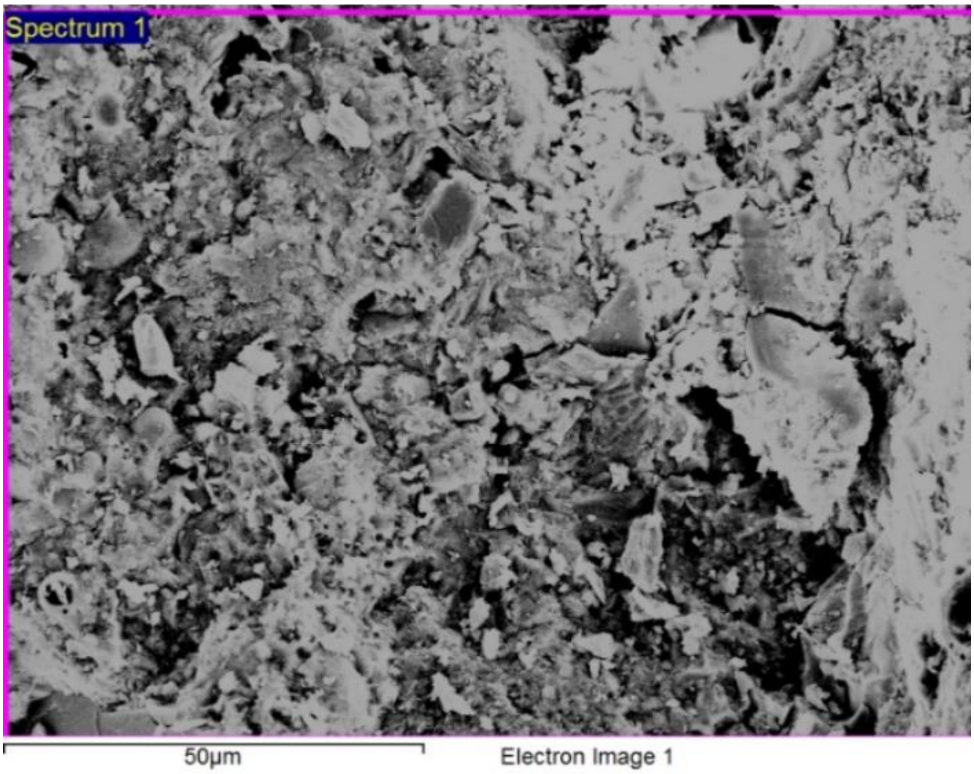
X-Ray diffraction (PXRD) analysis was done on concrete samples N1F1L0, N1F3L15, and N1F3L25 to better understand their mineralogical properties. Elements found in various cast samples were listed in Table 5.1. Table 5.2 contains all of the useful information about PXRD peaks, such as Miller indices, d-spacing, chemical formula, and crystal system which was obtained with the help of Xpert Highscore plus software. The fibers can induce changes in the phase composition of the cement matrix, such as the production of extra calcium silicate hydrate (C-S-H) phases, which can improve the strength and durability of the composite, according to PXRD analysis of carbon fibers reinforced concrete. These changes in the phase composition suggest that the carbon fibers interacted with the cement matrix, leading to the formation of new phases. Such interactions are characteristic of reactive fibers. Calcium silicate hydrate and calcium hydroxide were found to be the primary hydration products of the cement-based matrix, while chemical examination of the concrete matrix revealed that silicon and calcium crystalline made up the majority of the matrix composition. The presence of the carbon, oxygen, sodium, aluminium, calcium and silicon in the synthesized material was confirmed using X-ray photoelectron spectroscopy (XPS) analysis as shown in Fig.5.4 and the peaks of all the concrete elements present were shown in Table 5.3. The presence of carbon and oxygen in the concrete elements indicates that the carbon fibers played a role in modifying the chemical composition of the concrete. Reactive fibers are expected to contribute to these chemical changes. In summary, the results obtained from PXRD, EDX, XPS, and SEM analyses collectively suggest that the carbon fibers used in the study are of a reactive type. Their ability to induce changes in the phase composition of the cement matrix, enhance load transfer, and bridge fractures is indicative of their reactivity with the surrounding concrete. Reactive fibers are known for their capacity to chemically interact with the cementitious materials, leading to improvements in mechanical properties and durability. Fig.5.5 shows Fourier transform infrared spectroscopy (FTIR) techniques used to study concrete surfaces in order to develop a nondestructive method for analysing the distribution of hydrated and organic phases. The presence of metal oxygen link is shown at the 400 $cm^{-1}$ wavenumber and maximum intensity was observed in sample N1F3L25 which could be seen in the Fig.5.5. The presence of carbonate is observed at 1600 $cm^{-1}$ wavenumber with maximum bend and intensity for the sample N1F1L0.



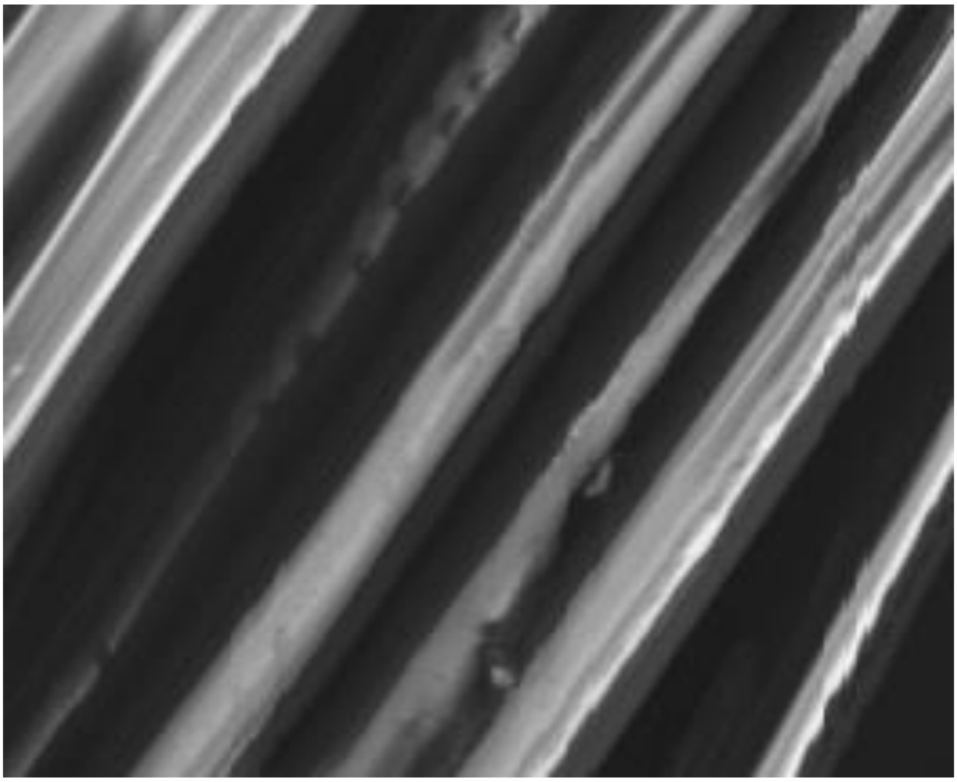
(a)


Spectrum 1
Fiber debonding locations
50µm
Electron Image 1

(b)

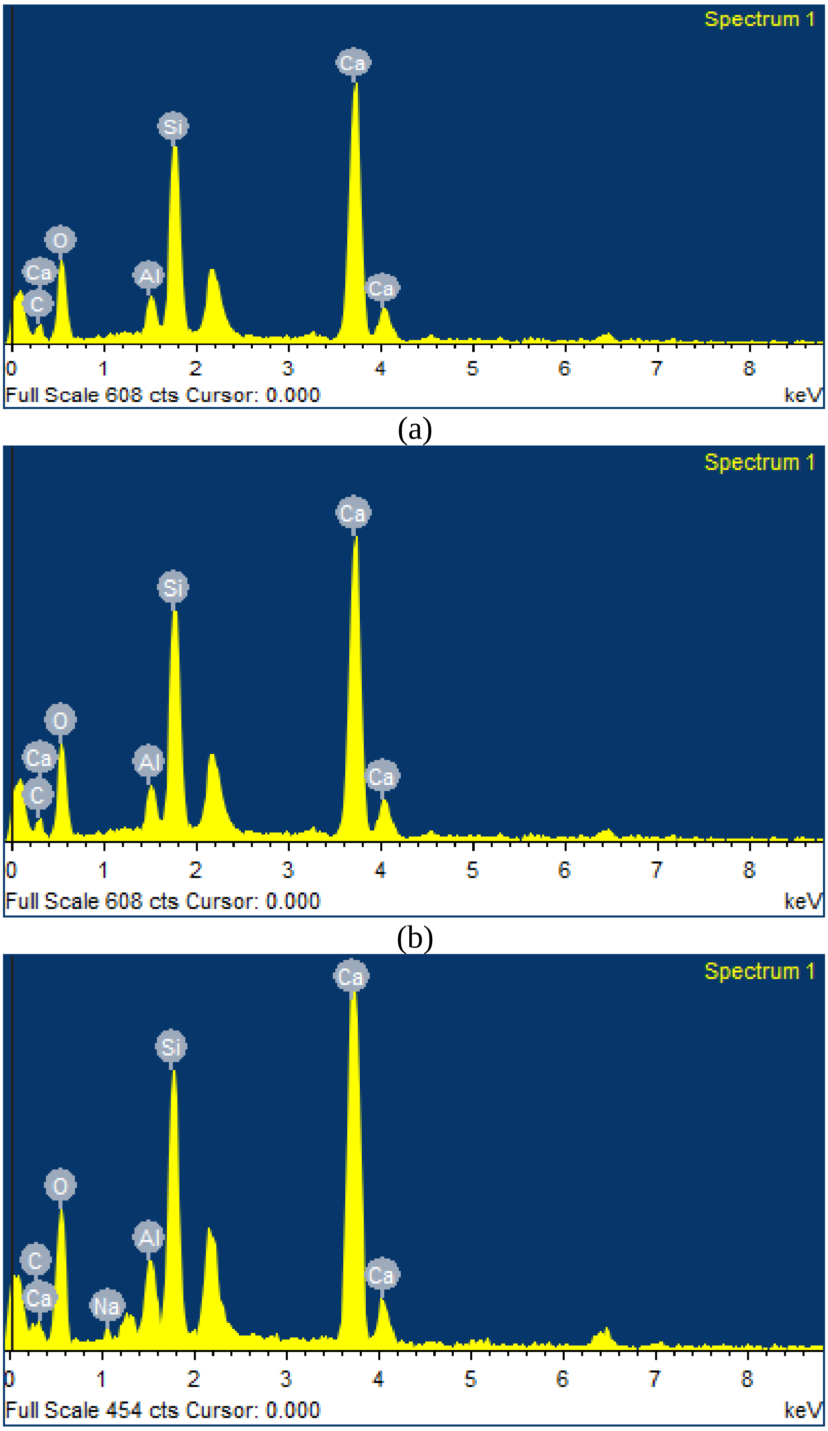

Spectrum 1
50µm
Electron Image 1

(c)



(d)

**Fig.5.1** Pictures taken with a scanning electron microscope: (a) N1F0L0; (b) NIF3L15; (c) N1F3L25; (d) carbon fibers enlarged view



(a)

(b)

(c)

**Fig.5.2** Energy dispersive x-ray spectroscopy results of (a) N1F1L0 (b) N1F3L25 (c) N1F3L15

**Table 5.1** Percentage weights of elements present found by EDX analysis

| | N1F1L0 | | N1F3L15 | | N1F3L25 | |
|---|---|---|---|---|---|---|
| Elements | Atomic (%) | Weights (%) | Atomic (%) | Weights (%) | Atomic (%) | Weights (%) |
| O-K | 58.71 | 49.38 | 9.49 | 1.07 | 60.93 | 50.24 |
| C-K | 19.77 | 12.48 | 9.43 | 5.06 | 10.82 | 6.76 |
| Na-K | 0.26 | 0.31 | | | 0.68 | 0.3 |
| Al-K | 2.5 | 3.55 | 1.42 | 1. 73 | 1.74 | 2.77 |
| Si-K | 8.31 | 12.27 | 11.23 | 15.07 | 11.09 | 11.49 |
| Ca-K | 10.45 | 22.01 | 16.33 | 30.85 | 14.73 | 28.1 |
| Total | | 100 | | 100 | | 100 |

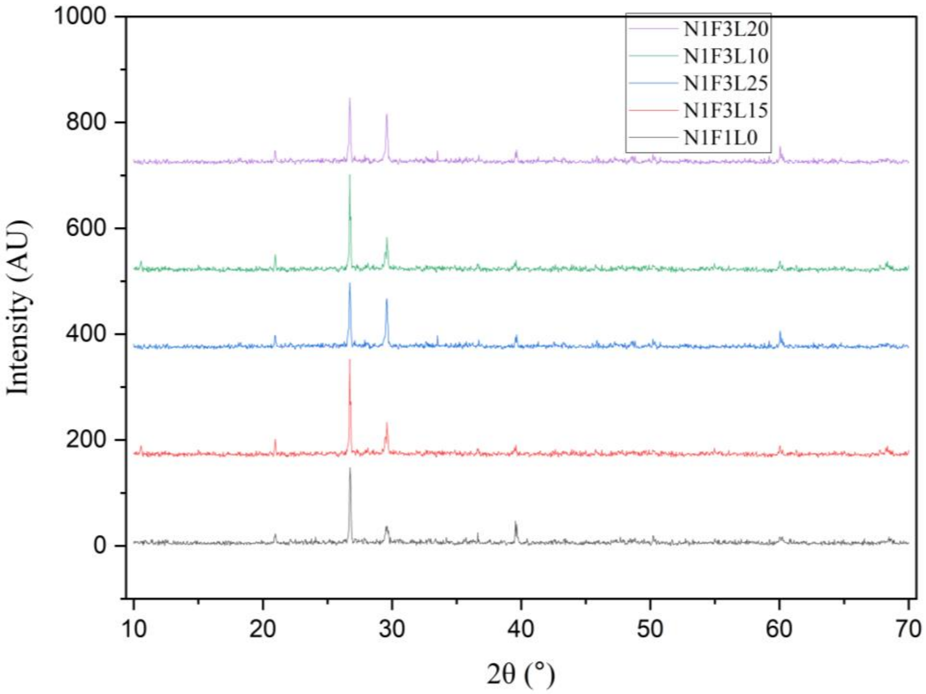


**Fig.5.3** X-ray diffraction results of N1F1L0, N1F3L15, and N1F3L25.

**Table 5.2** PXRD analysis.

| Peak No | h | k | l | d spacing ( Å) | Peak angle (deg) | Intensity (%) | Chemical Formula | Chemical name | Crystal system |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 0 | 0 | 4.257 | 20.85 | 22 | SiO2 | Silicon Oxide | Hexagonal |
| 2 | 1 | 0 | 1 | 3.342 | 26.65 | 100 | SiO2 | Silicon Oxide | Hexagonal |
| 3 | 1 | 1 | 0 | 2.457 | 36.54 | 8 | SiO2 | Silicon Oxide | Hexagonal |
| 4 | 1 | 0 | 2 | 2.282 | 39.45 | 8 | SiO2 | Silicon Oxide | Hexagonal |
| 6 | 2 | 0 | 0 | 2.127 | 42.46 | 6 | SiO2 | Silicon Oxide | Hexagonal |
| 8 | 1 | 1 | 2 | 1.8179 | 50.14 | 14 | SiO2 | Silicon Oxide | Hexagonal |
| 13 | 2 | 1 | 1 | 1.5418 | 59.94 | 9 | SiO2 | Silicon Oxide | Hexagonal |
| 16 | 2 | 1 | 2 | 1.382 | 67.75 | 6 | SiO2 | Silicon Oxide | Hexagonal |
| 17 | 2 | 0 | 3 | 1.3752 | 68.13 | 7 | SiO2 | Silicon Oxide | Hexagonal |
| 18 | 3 | 0 | 1 | 1.3718 | 68.32 | 8 | SiO2 | Silicon Oxide | Hexagonal |

**Table 5.3** Peak values of Binding energy of various concrete elements by XPS analysis

| **Elements** | **Binding energy (eV)** |
|---|---|
| C 1s | 280 |
| O 1s | 585 |
| Na 1s | 1071 and 1073 |
| Ca 2p | 350.7 and 347 |
| Al 2p | 285 |
| Si 2p | 100 and 104 |

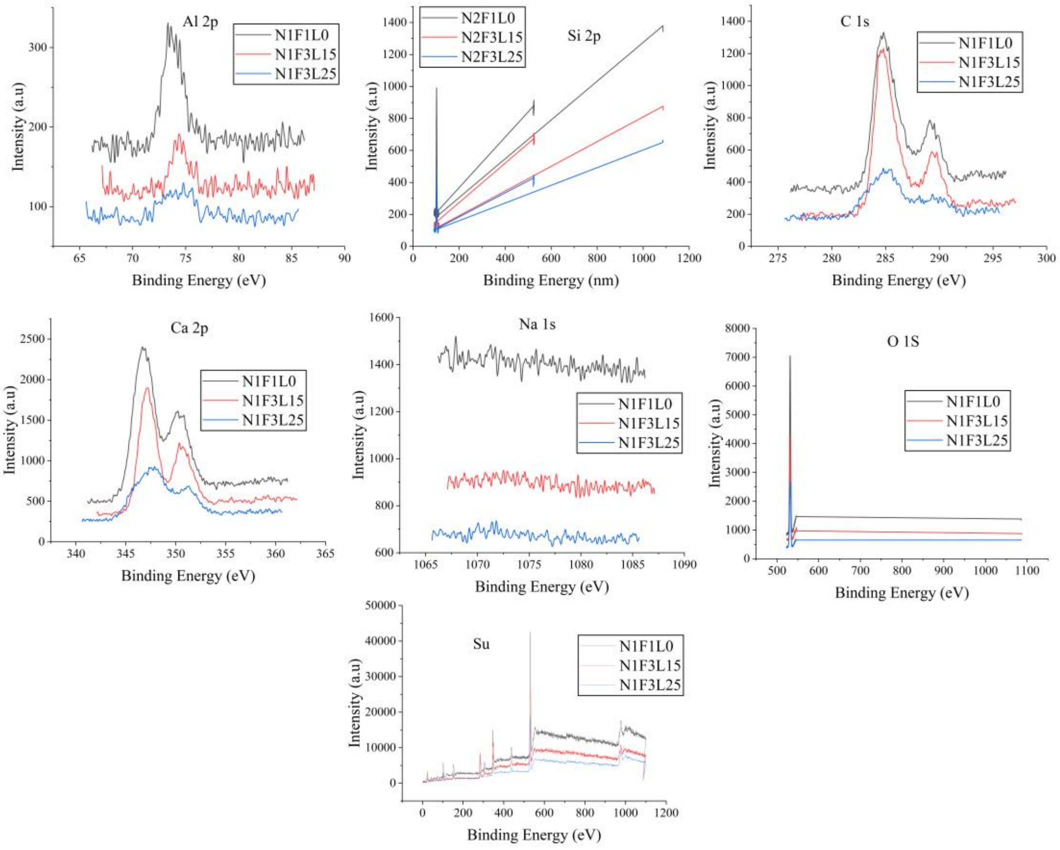


**Fig.5.4** X-ray Photoelectronic Spectroscopy of different elements present in concrete

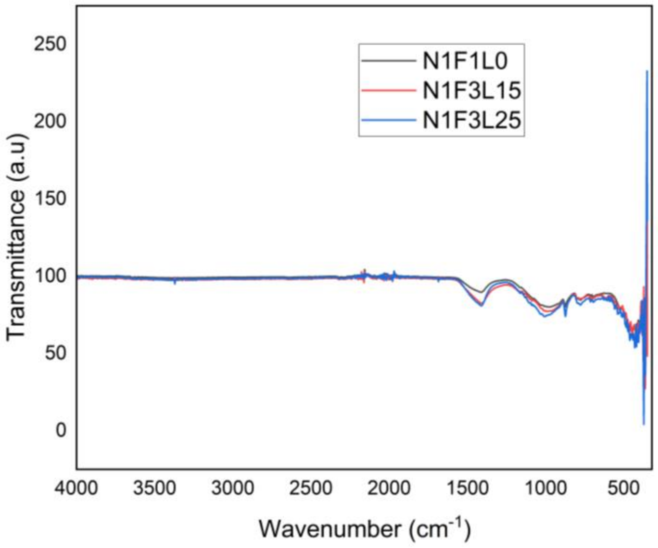
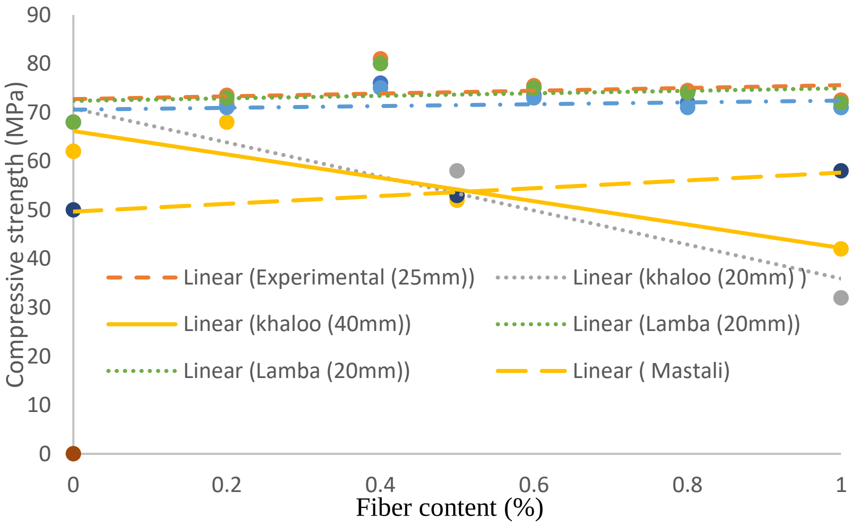


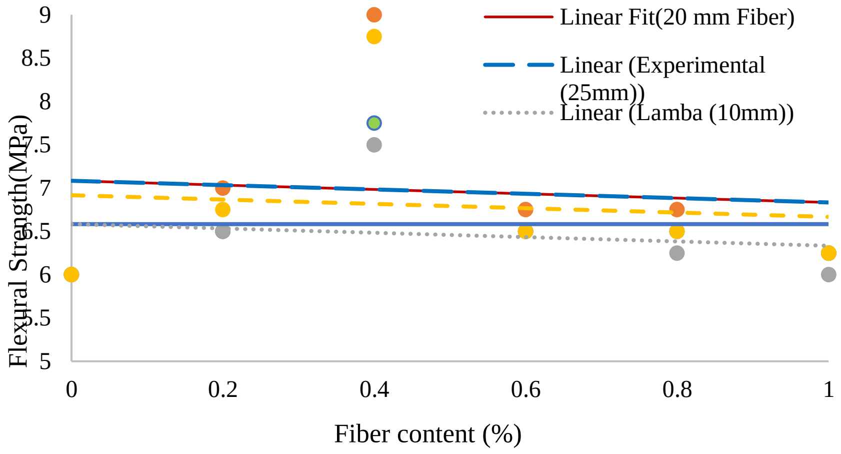
**Fig.5.5** FTIR analysis of concrete

## 5.2 Analytical study and comparisons with previous study

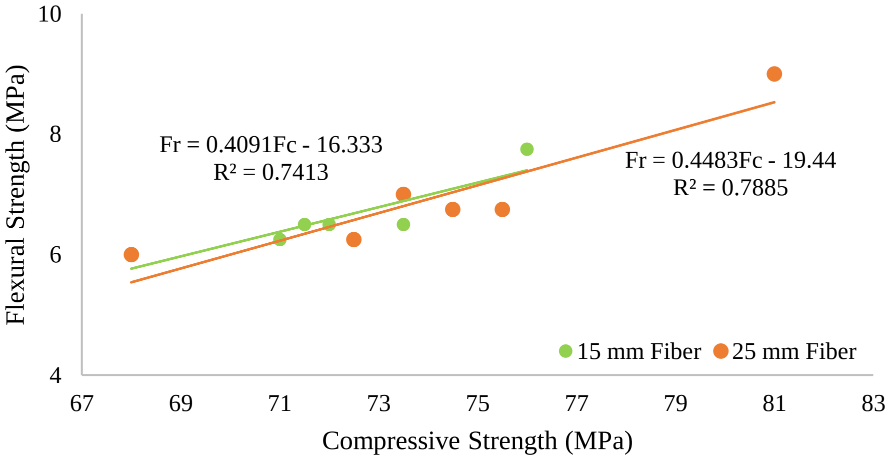
A vast database established a statistically significant relationship between the mechanical characteristics of reinforced high strength concrete and the aspect ratio and fiber dose employed in the concrete's manufacture. According to the results illustrated in Fig.5.6c, an empirical relationship was created after linear regression analysis between the mechanical attributes and varied dosages and lengths of fibers. Maximum increase in flexure and compressive strengths were calculated from the slopes of the resulting equations shown in Fig.5.6a and Fig.5.6b. Using a fiber with a specified aspect ratio and a length of 25mm in the experiment accelerated the development of flexural and compressive strength. More so, mechanical characteristics were significantly boosted once 25mm fiber length was inserted. The study's carbon fiber doses, percentages, or fiber content are denoted by Vf, the flexure strength value of the cast beam samples is denoted by Fr, and the compression strength of the cube samples cast for the study is denoted by Fc. As can be seen in Fig.5.6c, the reinforced specimens had a flexure strength that was directly proportional to their compression strength. Empirical connections between flexural and compressive strengths of reinforced specimens were shown in Table 5.4 as per correlation results data of mechanical characteristics by Ahmad and Shah (Shah & Ahmad, 1985) and ACI Committee’s prescribed standard codes (ACI 363R-92, 1997; ACI Committee 318, 2008). Fig.5.7 displays the results of a comparison between the equation developed using the experimental data from this study and the equation proposed by other researchers to describe graphs between compressive strengths and flexural strengths. Fig.5.8a and Fig.5.8b displays a linear relationship between fracture blows (both initial and final) and fiber contents. Fig.5.9a and Fig.5.9b illustrates the linear correlation that was found between compressive strengths and first crack blows as well as ultimate crack blows. Fig.5.10 shows a scatter plot of the current study's experimental data comparing the number of first crack blows to the total number of crack blows, together with data from prior studies. Table 5.5 shows the proven relationships between initial crack blows and final crack blows from previous studies.



**(a)**



**(b)**



**(c)**

**Fig.5.6** Fiber dose correlates with **(a)** Compressive Strength **(b)** Flexural Strength; and **(c)** Compressive Strength with Flexural Strength.

**Table 5.4** Compression strength and flexural strength: an empirical analysis of published studies

| Published studies | ACI 363R-92 1997 | ACI Committee 318 2008 | Shah and Ahmad 1985 |
|---|---|---|---|
| Attribute relationship | $Fr= 0.94\ Fc^{0.5}$ | $Fr= 0.62Fc^{0.5}$ | $Fr= 0.44\ Fc^{0.5}$ |

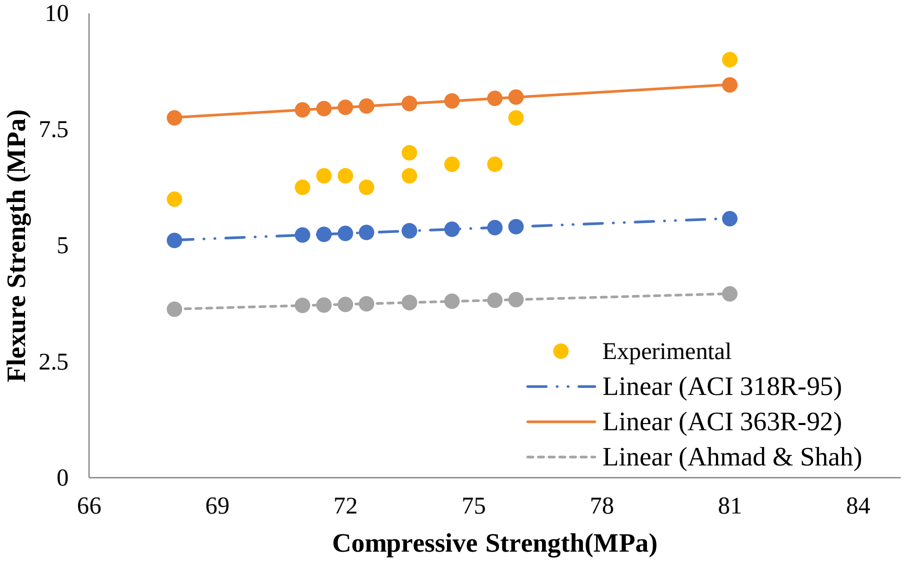
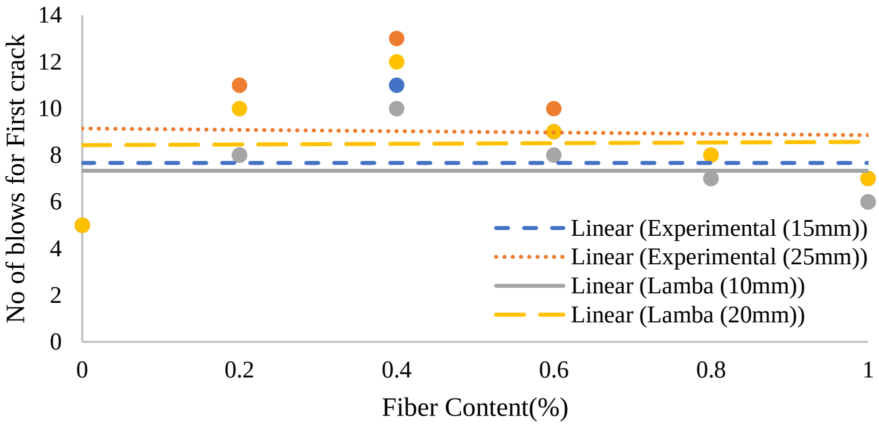
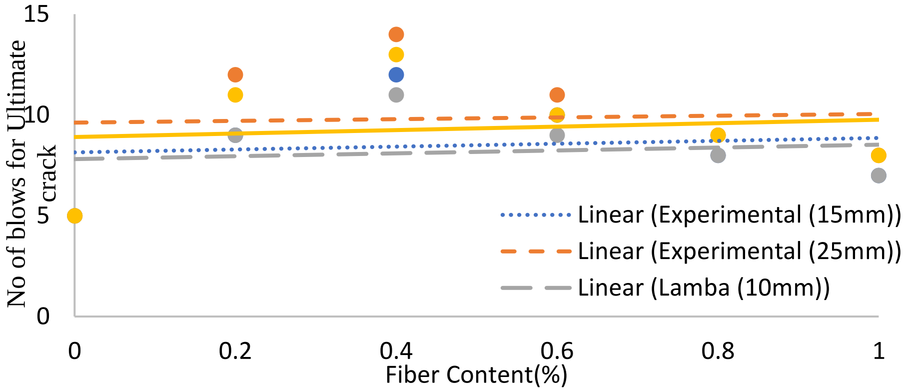


**Fig.5.7** Obtained Experimental results vs previous research work on flexural and compressive strengths

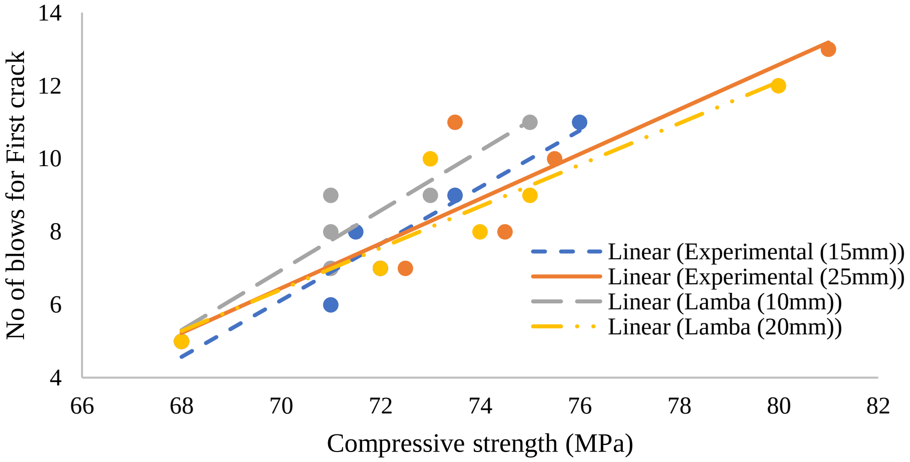


**(a)**

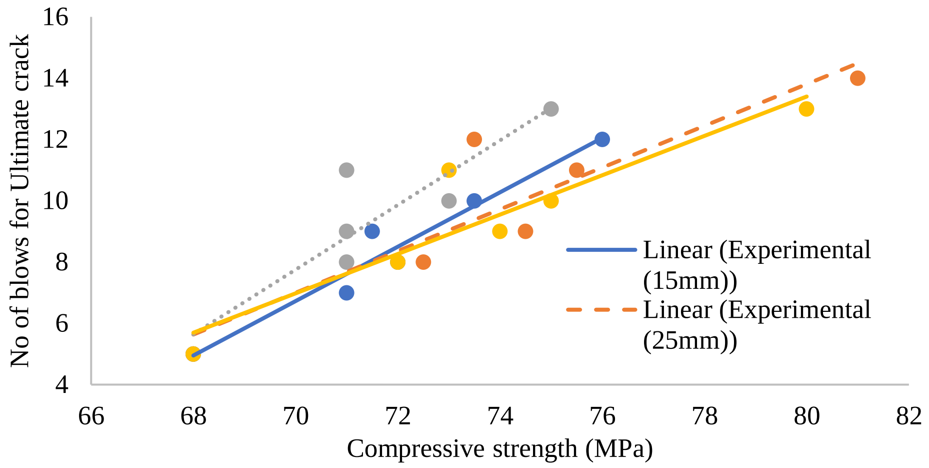


**(b)**

**Fig.5.8** Fiber dose's influence on **(a)** the first crack blows and **(b)** final crack blows



**(a)**



**(b)**

**Fig.5.9** Compressive strength as a function of **(a)**the number of blows required to cause the first crack and **(b)**the number of blows required to cause the ultimate crack

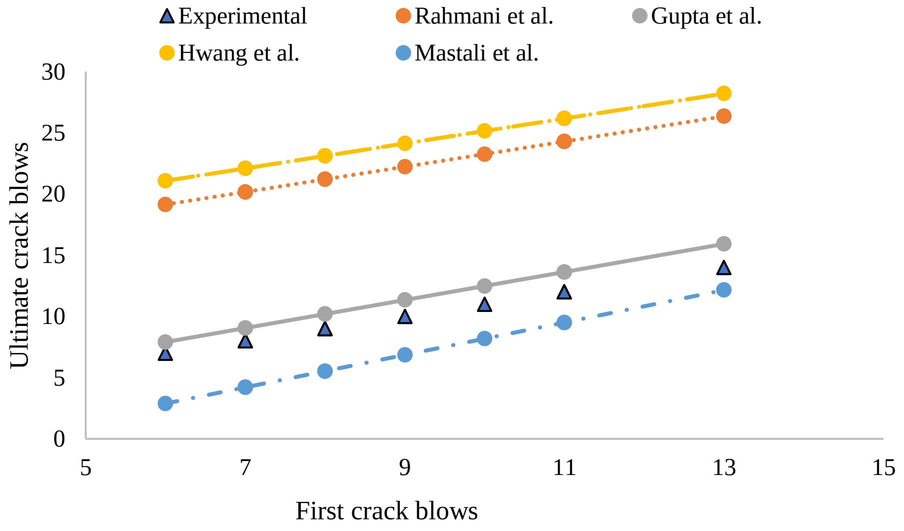


**Fig.5.10** Existing study analysis of initial crack-resistance to their ultimate crack-resistance

**Table 5.5** Comparison of initial and final crack resistance blows using an empirical literature review

| Published studies | Hwang, S., Song, P., & Sheu 2003 | Mastali and Dalvand 2016c | Gupta et al. 2015 | Rahmani et al. 2012 |
|---|---|---|---|---|
| Attribute relationship | Nu =1.018Nf+14.968 | Nu =1.3238Nf+5.056 | Nu =1.145Nf+1.037 | Nu =1.03Nf+12.96 |

# CHAPTER 6

# CONCLUSION, FUTURE SCOPE AND SOCIAL IMPACT

The following section encapsulates the essential findings of this study, exploring the mechanical properties, impact resistance, and durability of high-strength concrete reinforced with carbon fibers. The conclusions drawn from this research highlight the significant improvements in concrete performance due to the strategic inclusion of carbon fibers with various aspect ratios and dosages. Following the summary of key results, the section outlines potential directions for future research, emphasizing areas that require further investigation to optimize and expand the use of carbon fiber-reinforced concrete. Additionally, the social impact of this advanced construction material is discussed, considering its potential to enhance infrastructure resilience, sustainability, and overall societal benefits. This comprehensive overview not only reflects on the immediate contributions of the study but also envisions the broader implications and future advancements in the field of high-strength concrete.

## 6.1 Conclusion

This in-depth study investigated the reactivity of hardened concrete, with a specific emphasis on the incorporation of carbon fibers as the topic of primary interest. The primary purpose of this research was to investigate the influence that changing fiber doses and lengths have on the mechanical properties of high-strength concrete. Many useful insights were drawn into the behavior of the concrete by conducting a battery of experiments on it, such as testing its compressive strength, impact strength, flexural strength, measuring the ultrasonic pulse velocity, and testing its durability.

One interesting finding was that the ultrasonic pulse characteristics significantly decreased when both the aspect ratio and the fiber dosage percentage within the concrete matrix rose. This was a finding that merits attention. This decrease in pulse velocity suggested that there were modifications to the internal structure and porosity of the concrete. In contrast, a rise in fiber dosage percentage and aspect ratio led to noticeable increases in mechanical properties, notably in terms of flexural and compressive strength. The noteworthy property of limiting the propagation of cracks created initially under compressive loads led to a rise in compressive strength values as the dose was raised in the test samples, despite a large reduction in porosity; furthermore, it resulted in a decrease in compressive strength values after an optimum dosage point i.e., N1F3L10, N1F3L15, N1F3L20, and N1F3L25. The results of a chemical examination showed that crystalline silicon and calcium components predominated in the concrete matrix. This prompted researchers to hypothesize that the principal hydration products were calcium silicate hydrate and calcium hydroxide.

Based on an analysis of the SEM pictures, we determined that the most common cause of failure in carbon fibers is debonding at the fracture surfaces. Carbon fibers that had an aspect ratio (of 250) that was equivalent to 25 millimeters showed significant gains in flexural and compressive strength, as well as impact resistance.

The results of our investigation revealed some intriguing links. For example, there was a linear correlation between the mechanical properties, and the coefficients of determination ($R^2$) were higher than 84% for all fiber lengths. Furthermore, the link between the number of blows for first crack impact resistance and ultimate crack impact resistance strongly resembled published empirical equations, which further validated our findings. This relationship was found to closely follow established empirical equations.

According to the findings of our research, flexural strength and impact resistance improved in tandem with an increase in compressive strength, notably for fiber lengths of 15mm and 25mm. When compared to industry standards like the ACI 318R-95 code, the empirical equations that were developed through the correlation of mechanical features showed a high level of agreement.

RCPT results for carbon fiber reinforced concrete indicate an impressive performance with less than 100 coulombs charge for all types of mixes prepared for the study, suggesting very low chloride ions permeability in the concrete matrix.4

## 6.2 Limitations and Future Scope

The experimentation for the evaluation of mechanical properties of high-strength concrete was carried out on a small scale restricted to laboratory conditions. In contrast, the behavior of concrete is likely to vary marginally when replicated on a large scale at a site, which is very much acceptable considering the non-homogenous nature of concrete. The properties of high-strength concrete and carbon fibers can vary significantly based on the source and manufacturing process. This variability may affect the reproducibility of results. The concrete mix design is restricted to ordinary Portland cement, Badarpur sand, and carbon fibers if replication of work is required on a large or similar scale. Real-world applications are subject to diverse environmental conditions. The study may not capture all possible scenarios, such as extreme temperatures, aggressive chemical exposures, or long-term weathering effects. The performance of high-strength concrete may be influenced by construction practices, including mixing, curing, and placement methods. Variations in these practices could impact the durability of the concrete. The long-term performance of high-strength concrete with carbon fibers is a crucial aspect. Limitations may arise due to the difficulty in simulating extended periods of exposure and assessing the material's behavior over time. The intriguing nature of carbon fibers paved its way into the construction world, rapidly growing with numerous unexplored research areas. In the current research, unpredictable results were obtained using carbon fibers, necessitating more research in the current research area investigated. Explore the impact of various environmental factors, such as freeze-thaw cycles, aggressive chemical exposure, and UV radiation, on the long-term performance of high-strength concrete with carbon fibers. Conduct studies on the actual performance of structures made with high-strength concrete and carbon fibers in real-world conditions to validate laboratory findings. Research new mix designs incorporating different types of carbon fibers, additives, or admixtures to enhance both the mechanical and durability properties of high-strength concrete. Perform comprehensive life cycle assessments to evaluate the environmental impact of using high-strength concrete with carbon fibers compared to traditional concrete mixes. Explore successful applications of high-strength concrete with carbon fibers in real-world construction projects, highlighting any challenges faced and lessons learned. Advocate for and contribute to the development of standardized testing methods and guidelines for the use of high-strength concrete with carbon fibers in construction. Concrete could be evaluated for different aspect ratios of fibers, different mix designs, higher grades, fatigue, temperature resistances, durability aspects, etc., as part of future research considering fascinating properties of carbon fibers to withstand extreme loadings, stresses, mechanical resistances under harsh environmental conditions, etc.

## 6.3 Social Impact

The application of carbon fiber-reinforced high-strength concrete has significant social implications. The enhanced mechanical properties and durability of this material can lead to the construction of safer, longer-lasting, and more resilient infrastructure, which is crucial in areas prone to natural disasters such as earthquakes and hurricanes. The increased longevity of structures reduces maintenance costs and the need for frequent repairs, resulting in economic savings and less disruption to communities. Furthermore, the use of high-performance materials can contribute to sustainable construction practices by reducing the carbon footprint associated with the production and transport of construction materials. By extending the lifespan of buildings and infrastructure, carbon fiber-reinforced concrete supports the development of sustainable urban environments, ultimately improving the quality of life and safety for society at large.

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# List of Publications and their Proofs

1. Lamba, N., Raj, R. and Singh, P., (2024). Chopped carbon fibre reinforcement in high-strength concrete: Flexural characteristics. *Materials Science and Technology*. 2024;40(1):47-53. DOI: 10.1177/02670836231212615
2. Lamba, N., Raj, R. and Singh, P., (2024). Feasibility of Recycled Carbon Fiber-Reinforced Polymer Fibers in Cementitious Composites: An Experimental Investigation. *Arab J Sci Eng* DOI: https://doi.org/10.1007/s13369-024-08712-4
3. Lamba, N., Raj, R. and Singh, P., (2023). The Effects of Recycled Carbon Fibers on the Mechanical Properties of High-Strength Concrete and Its Resilience to Impact. *Iran J Sci Technol Trans Civ Eng,* DOI: https://doi.org/10.1007/s40996-023-01269-6
4. Lamba, N., Raj, R. and Singh, P., (2023) Mechanical response of recycled carbon fiber reinforced polymer fibers in high-strength concrete." *Materials Today: Proceedings* 78 603–607, DOI: https://doi.org/10.1016/j.matpr.2022.11.477
5. Lamba, N., Raj, R. and Singh, P., (2022) Mechanical characteristics of high strength concrete incorporating recycled CFRP fibers." *J. Appl. Polym. Sci.* vol 139, issue 47, DOI: https://doi.org/10.1002/app.53183

Research Article

Institute of Materials,
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*Materials Science and Technology*
2024, Vol. 40(1) 47–53

DOI: 10.1177/02670836231212615
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# Chopped carbon fibre reinforcement in high-strength concrete: Flexural characteristics

**Nitin Lamba[1], Ritu Raj[1] and Poonam Singh[2]**

**Abstract**

In this study, the flexural behaviour of high-strength concrete was tested with chopped carbon fibres that were 30 mm long and added in amounts of 0.2%, 0.4%, 0.6%, 0.8%, and 1%. Thirty-six prisms were evaluated experimentally for flexural strength at 28 days using an ultrasonic pulse velocity test and a flexural testing machine. X-ray diffraction and linear regression analysis were carried out to characterise crystalline material and linear correlation amongst different mixes. Increasing the number of carbon fibres in high-strength concrete led to unexpected and innovative findings, such as lower pulse velocities and improved flexural characteristics up to an optimum dosage point. In SEM images of chopped carbon fibres, debonding was the most prevalent cause of failure.

**Keywords**

Flexural strength, linear regression analysis, X-ray diffraction, carbon fibres, high-strength concrete, SEM, EDX

Received: 8 December 2022; accepted: 17 October 2023

## Introduction

Due to the fast-growing world's modernisation, there is high natural resource consumption with rapidly growing demands of urbanisation, industrialisation, etc., resulting in the dumping of scrap materials all over places, which is becoming a tedious task for humans to tackle this problematic situation. Hence it is highly essential to dispose of these scrap materials is utmost required. Hence the reuse of scrap materials could be a solution to save our mother earth and the environment from the harmful side effects of these scrap materials. In construction, several scrap materials are used worldwide, such as fly ash, silica fume, tire shreds, carbon fibres, etc. Innovative research is going on to develop high-strength concrete using scrap materials; this way, apart from attaining high strength, we are helping reuse processes. Research has been going on to understand the role of silica fume and fly ash in developing high-strength concrete.[1] Several studies have been carried out on the properties of carbon fibre reinforcement in cement-based materials, reinforcement effect, and flexural toughness in concrete.[2–4]

Moreover, some researchers have helped the construction field by enlightening the world with chopped fibres for attaining high-strength concrete.[5,6] Several researchers have benefited the construction industry by raising public awareness of incorporating chopped fibres to generate high-strength concrete.[5–11] In addition, research has been done to see if the performance of regular concrete may be enhanced by adding a variety of fibres to the mix.[12–16] According to the authors, there is relatively little research on using chopped carbon fibre fragments to achieve high-strength concrete.[6,13,17,18] High-strength concrete was developed by reinforcing chopped carbon fibres into the concrete matrix, and its unique and intriguing character made its usage in building relatively straightforward. So, the present research aimed to learn about the properties of chopped carbon fibre reinforcement to design high-strength concrete using waste products such as silica fume and fly ash. The flexural property of high-strength concrete with a novel aspect ratio and dosage values of chopped carbon fibres was chosen to offer originality to the study. So, a new investigation into enhanced high-strength concrete is required due to the exceptional and erratic outcomes of the ultrasonic pulse velocity test and the flexural strength test setup. Destructive and non-destructive testing, X-ray diffraction (XRD), and analytical analysis were used to

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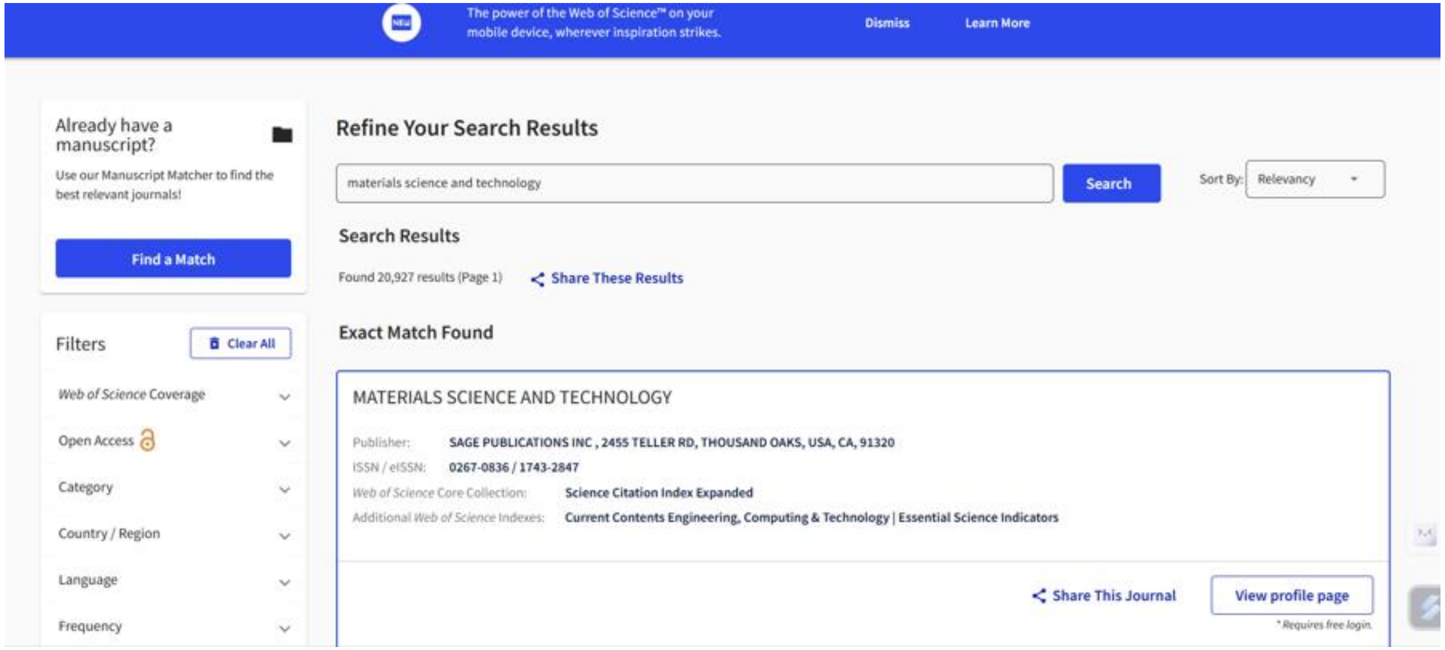

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RESEARCH ARTICLE-CIVIL ENGINEERING

# Feasibility of Recycled Carbon Fiber-Reinforced Polymer Fibers in Cementitious Composites: An Experimental Investigation

**Nitin Lamba**[1] · **Ritu Raj**[1] · **Poonam Singh**[2]

Received: 28 October 2023 / Accepted: 31 December 2023

**Abstract**

The purpose of the work presented here was to examine the viability of reinforcing high-strength concrete with recycled chopped carbon fiber-reinforced polymer fibers obtained from epoxy resin-coated fiber laminated sheets. The fibers were chopped to lengths of 3 mm and 30 mm, and dosages of 0.2, 0.4, 0.6, 0.8, and 1% fiber volume fraction were tested. Compression and flexure strength tests, as well as the nondestructive tests of ultrasonic pulse velocity (UPVT) and rebound hammer, were performed on concrete samples after 28 days of curing. Carbon fiber-reinforced concrete samples were subjected to elemental analysis, mineralogical analysis, and surface morphological examination using EDX, XRD, and SEM, respectively. Using an analytical analysis method, a correlation was drawn between the mechanical properties and the various fiber lengths and doses. The experimental study found that a higher dosage and fiber content of carbon fibers improved the mechanical properties of the carbon fiber-reinforced high-strength concrete. UPVT results demonstrated unpredictability even when maintaining a fiber aspect ratio of 1:10, highlighting the need for more study in this area.

**Keywords** XRD · SEM · EDX · Carbon fiber-reinforced polymers · Mechanical attributes · High-strength concrete · Epoxy coating

## 1 Introduction

The rapid pace at which the world is being modernized has led to a correspondingly rapid depletion of the planet's natural resources. Humans have a tough time keeping up with the proliferation of trash because of the expansion of cities, the rise of industry, and other necessities. Therefore, effective disposal of these waste products is essential to achieving a sustainable development. Therefore, safeguarding the mother earth and the ecology from the negative effects of these products, recycling and reusing may be a realistic choice. The construction sector utilizes waste products such as fly ash, silica fume, shredded tires, and reclaimed carbon fibers. The development of high-strength concrete from recycled materials is the subject of cutting-edge study; in doing so, not only high strength is achieved but also it aids in the recycling and reuse of materials. This also led to the motivation behind the choice, including the environmental and economic considerations that make recycled carbon fibers a pertinent and impactful subject of investigation in cementitious composites. Due to dwindling landfill space and rising disposal costs, waste recycling has been an increasingly pressing issue in recent decades. In order to use recycled materials in concrete works in environmentally friendly building technology, numerous studies and researches have been conducted. The study confirmed that recycling has both positive economic impacts and negative ecological effects [1]. According to the revised standards of ACI Committee 363 [2], high-strength concrete is defined as having a compressive strength of at least 8000 psi (55 MPa). High-strength concrete is a variety of concrete with a compressive strength higher than is generally achieved in a specific geographical region, despite the aforementioned statistics being universally acknowledged. Different applications have suggested strength as high as 140 MPa (20,000 psi). By bringing attention to the benefits of using recycled fibers in the production of high-strength concrete, a number of researchers have helped the construction sector [1, 3–8]. There has also been research into whether or not incorporating a variety of fiber

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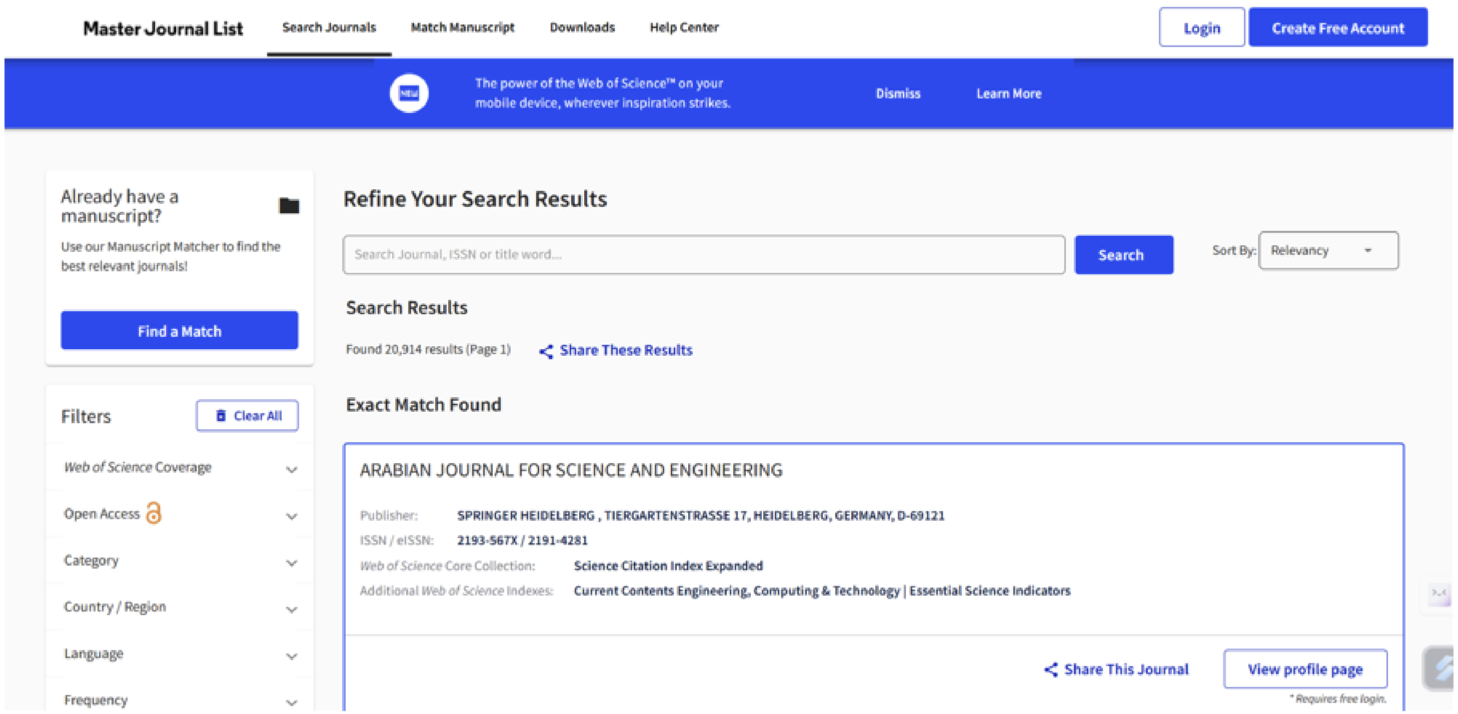

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https://doi.org/10.1007/s40996-023-01269-6

RESEARCH PAPER

# The Effects of Recycled Carbon Fibers on the Mechanical Properties of High-Strength Concrete and Its Resilience to Impact

**Nitin Lamba**[1] · **Ritu Raj**[1] · **Poonam Singh**[2]

Received: 21 June 2023 / Accepted: 13 October 2023

## Abstract

The presented work investigated the mechanical properties and impact resistance (with a modified ACI test setup) of high-strength concrete by reinforcing it with two different aspect ratios, i.e., 150 for 15 mm fiber length and 250 for 25 mm fiber length of carbon fibers with varying dosages of 0.2, 0.4, 0.6, 0.8, and 1% volume fraction of fibers. Various tests, including flexure tests, compression tests, impact resistance tests, and ultrasonic pulse velocity tests, were conducted on test samples after 28 days of curing in water. Energy-dispersive X-ray spectroscopy along with powdered X-ray diffraction analysis was conducted on samples to find out various chemical compositions of elements present and mineralogical properties, respectively. The surface morphology of concrete samples was determined with the help of scanning electron microscope (SEM) equipment. The mechanical characteristics and impact resistance were connected with an analytical analysis technique. The carbon fiber with the largest aspect ratio of length equivalent to 25 mm showed good growth in the rate of flexural, compressive strength, and impact resistance. SEM images revealed that the primary cause of failure in recycled carbon fibers was the debonding of fibers at fracture surfaces. The increase in carbon fibers' volume fractions or dosages enhances the compressive strength and increases the porosity of concrete samples up to the optimum dosage of recycled carbon fibers. Chemical examination showed that silicon and calcium crystalline were the primary components of the concrete matrix, which suggested that calcium silicate hydrate and calcium hydroxide were the primary hydration products of the cement-based matrix.

**Keywords** PXRD · SEM · Carbon fibers · Mechanical properties · Impact resistance · High-strength concrete

**Abbreviations**

| | |
|---|---|
| C | $CaCO_3$ |
| O | $SiO_2$ |
| Si | $SiO_2$ |
| Ca | Wollastonite |
| Al | $Al_2O_3$ |
| Na | Albite |

## 1 Introduction

Natural resources are being consumed at a high rate as a result of the fast-paced modernization of the planet. With the increasing growth of urbanization, industrialization, and other needs, scrap materials are being dumped all over the place, making it a difficult task for humans to deal with this problem. As a result, a sustainable development is critical, and proper disposal of these discarded materials is critical. As a result, recycling and reusing discarded materials may be a viable option for protecting our mother earth and the ecosystem from the detrimental impacts of these materials. Fly ash, silica fume, tire shreds, recycled carbon fibers, and other scrap materials are employed in the building industry all over the world. Innovative research is being conducted to make high-strength concrete utilizing scrap materials; this way, in addition to achieving high strength, we are also assisting in the recycling and reuse of materials. There have been a lot of studies and investigations done to find ways to use recycled materials in concrete works in environmentally friendly construction methods. Some research introduced an innovative electric field-induced manipulation method for recycling short-chopped carbon fibers (SCCFs), offering a pollution-free, cost-effective, and efficient approach with broad applications in sustainable manufacturing (Ma et al. 2022). Some explored the feasibility and environmental benefits of using recycled carbon fiber-reinforced polymer (CFRP) in rubberized concrete, demonstrating

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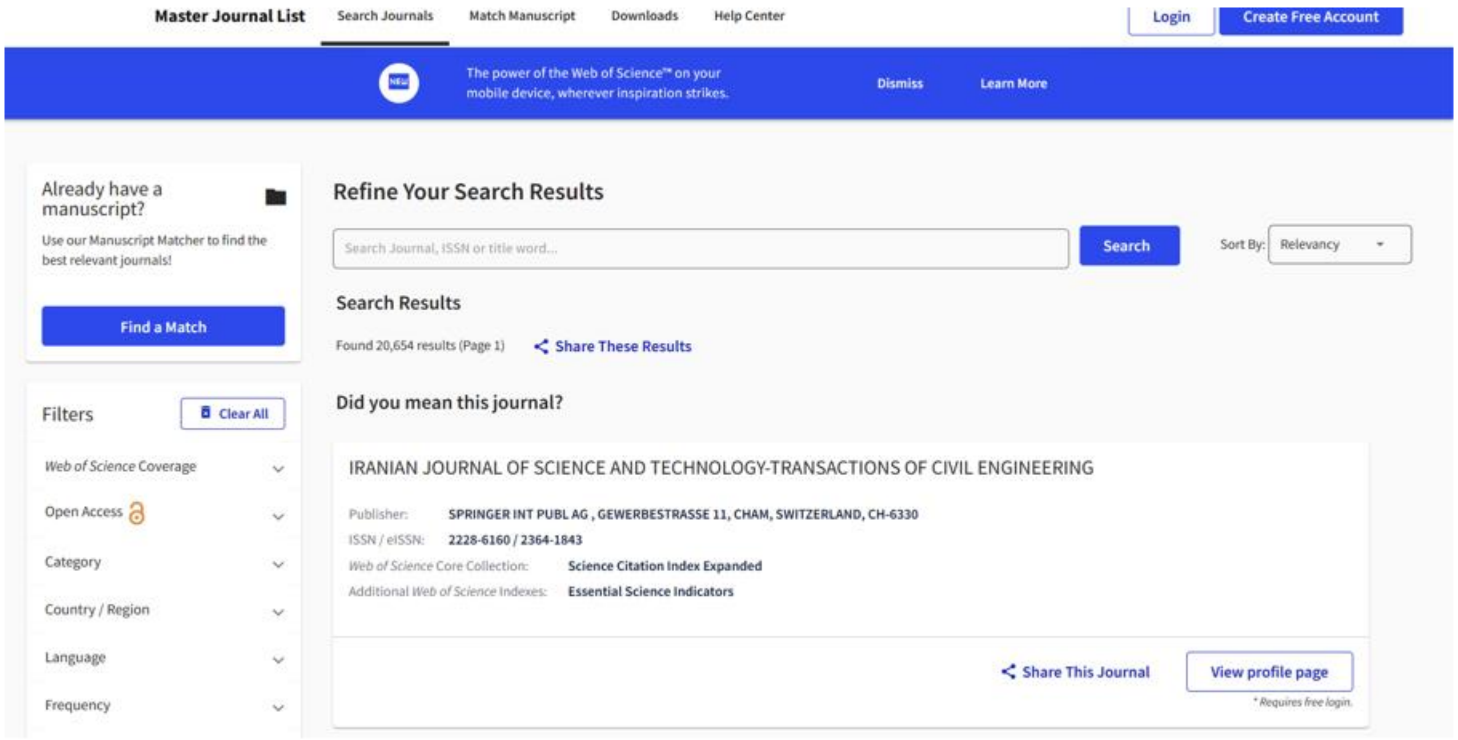

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Received: 9 May 2022 | Revised: 11 August 2022 | Accepted: 23 August 2022
DOI: 10.1002/app.53183

RESEARCH ARTICLE

Applied Polymer SCIENCE WILEY

# Mechanical characteristics of high strength concrete incorporating recycled CFRP fibers

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**Funding information**
Delhi Technological University (DTU)

**Abstract**

The current research article assesses the feasibility of recycled CFRP (Carbon-Fiber- Reinforced-Polymer) fibers in high-strength concrete. Different dosages of recycled CFRP fibers (0.2%, 0.4%, 0.6%, 0.8%, and 1%) as well as different aspect ratios of CFRP fibers with 10 and 20 mm fiber lengths is assessed for hardened state characteristics of reinforced high-strength concrete. Furthermore, ultrasonic pulse velocity test, compression test, flexure test, and impact resistance test are performed to understand the hardened properties of specimens. The chemical composition of various elements present in the various kinds of concrete samples is qualitatively and quantitatively found with the help of energy-dispersive X-ray spectroscopy (EDX) equipment. To understand the surface morphology of carbon fibers incorporated in concrete samples, Scanning electron microscope (SEM) photographs are obtained to examine the prepared samples thoroughly. Linear regression analysis, an analytical analysis technique, is incorporated to linearly correlate the different hardened mechanical characteristics of specimens taking into account varying lengths and different dosages of recycled CFRP fiber. The findings reveal that increasing the CFRP fiber dosage and the aspect ratio of recycled CFRP fiber improves the reinforced mix composition's mechanical characteristics.

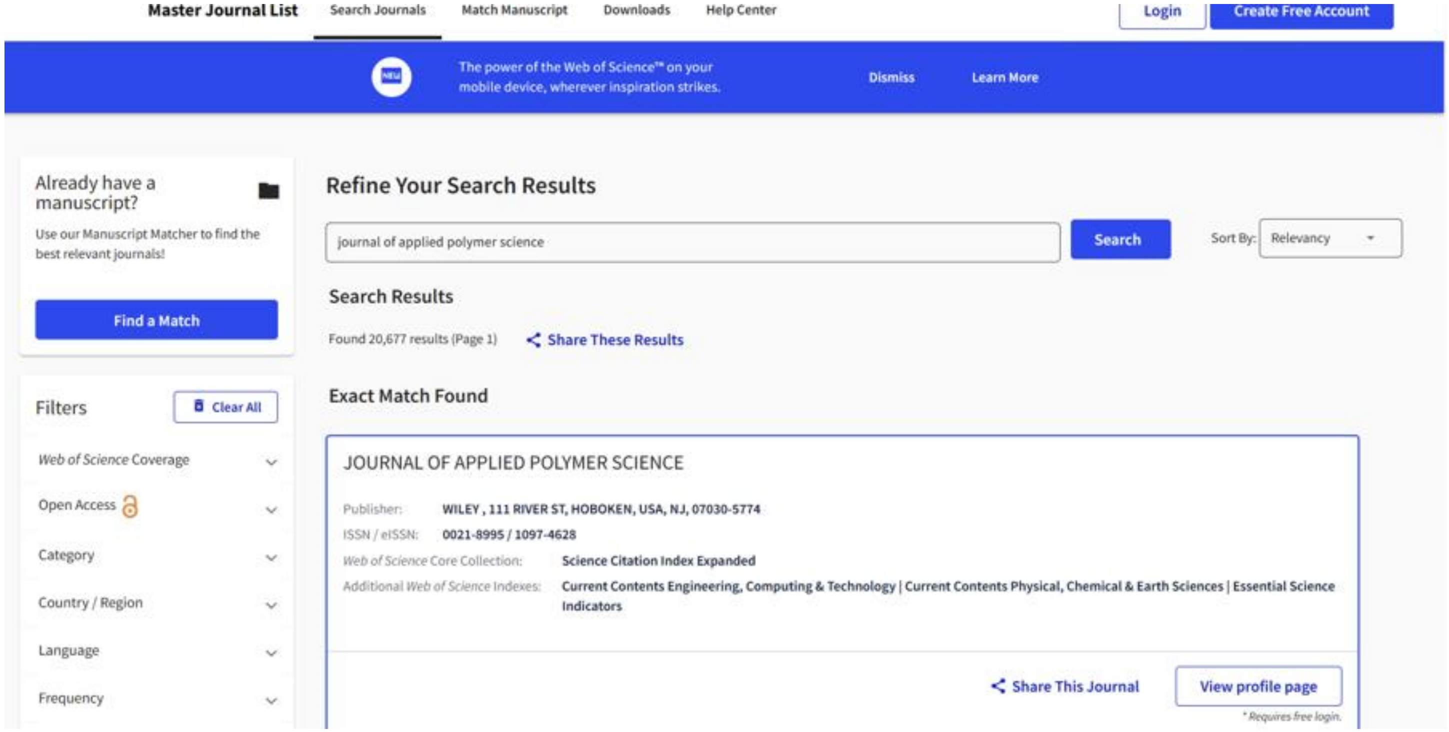
**KEYWORDS**

composites, fibers, mechanical properties, recycling, X-ray

## 1 | INTRODUCTION

Due to severe space constraints and rising costs, trash materials recycling has become increasingly alarming over the last few decades. Various studies and research have been done on employing recycled materials in concrete works in sustainable construction technology. The findings revealed that utilizing waste materials simultaneously has cost-cutting and unfavorable environmental implications.[1] Concrete, when tested for compressive strength giving the strength of over 41 MPa, is commonly referred to as high-strength concrete as per revised reports of ACI Committee 363.[2] Although the previous values are widely established, high-strength concrete is a type with compressive strength more significant than typically attained in a given geographical region. Different applications have called for Strengths of up to 140 MPa. Various types of research have recently been conducted to understand the ability of recycled fibers to attain high-strength concrete.[1,3–8]

Furthermore, some research has been done to see if incorporating a combination of different kinds of fibers in plain regular concrete is beneficial in the performance of concrete.[9–13] The findings demonstrated that combining recycled fibers in standard and high-strength concrete improves mechanical characteristics and impact



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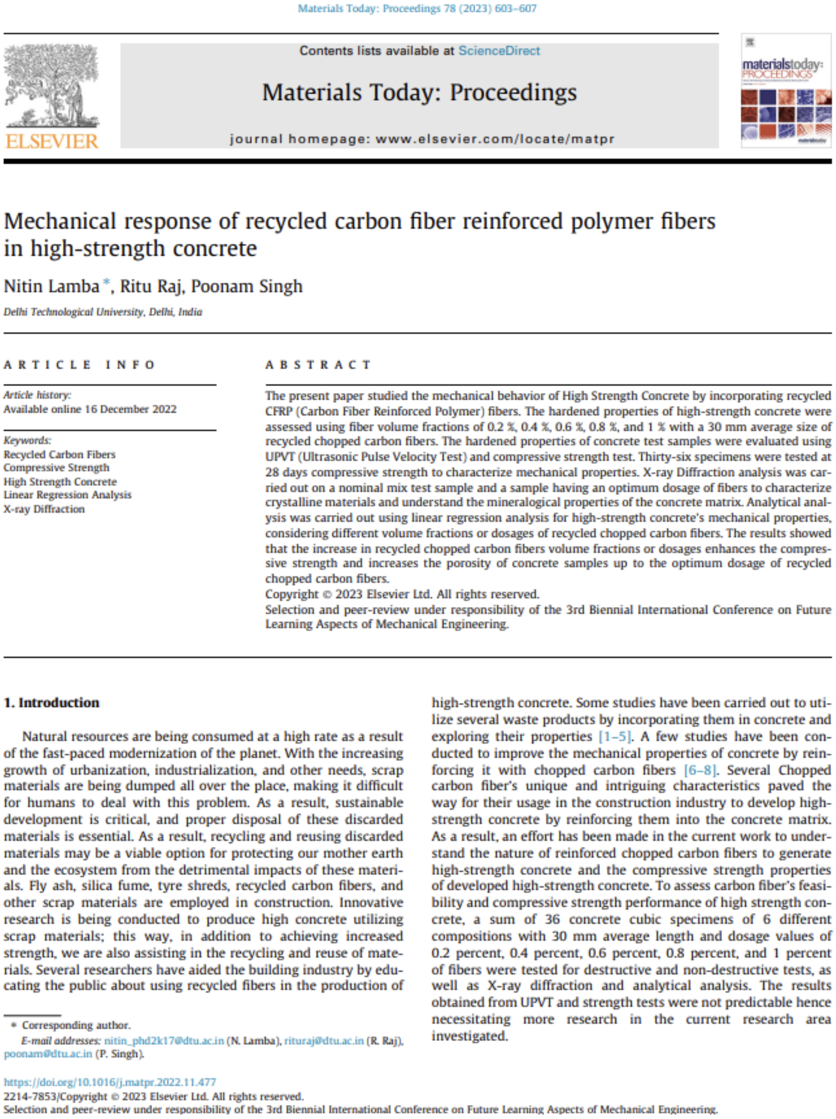

Materials Today: Proceedings 78 (2023) 603–607

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# Mechanical response of recycled carbon fiber reinforced polymer fibers in high-strength concrete

Nitin Lamba *, Ritu Raj, Poonam Singh

*Delhi Technological University, Delhi, India*

A R T I C L E  I N F O

*Article history:*
Available online 16 December 2022

*Keywords:*
Recycled Carbon Fibers
Compressive Strength
High Strength Concrete
Linear Regression Analysis
X-ray Diffraction

A B S T R A C T

The present paper studied the mechanical behavior of High Strength Concrete by incorporating recycled CFRP (Carbon Fiber Reinforced Polymer) fibers. The hardened properties of high-strength concrete were assessed using fiber volume fractions of 0.2 %, 0.4 %, 0.6 %, 0.8 %, and 1 % with a 30 mm average size of recycled chopped carbon fibers. The hardened properties of concrete test samples were evaluated using UPVT (Ultrasonic Pulse Velocity Test) and compressive strength test. Thirty-six specimens were tested at 28 days compressive strength to characterize mechanical properties. X-ray Diffraction analysis was carried out on a nominal mix test sample and a sample having an optimum dosage of fibers to characterize crystalline materials and understand the mineralogical properties of the concrete matrix. Analytical analysis was carried out using linear regression analysis for high-strength concrete's mechanical properties, considering different volume fractions or dosages of recycled chopped carbon fibers. The results showed that the increase in recycled chopped carbon fibers volume fractions or dosages enhances the compressive strength and increases the porosity of concrete samples up to the optimum dosage of recycled chopped carbon fibers.

Selection and peer-review under responsibility of the 3rd Biennial International Conference on Future Learning Aspects of Mechanical Engineering.

## 1. Introduction

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https://doi.org/10.1016/j.matpr.2022.11.477

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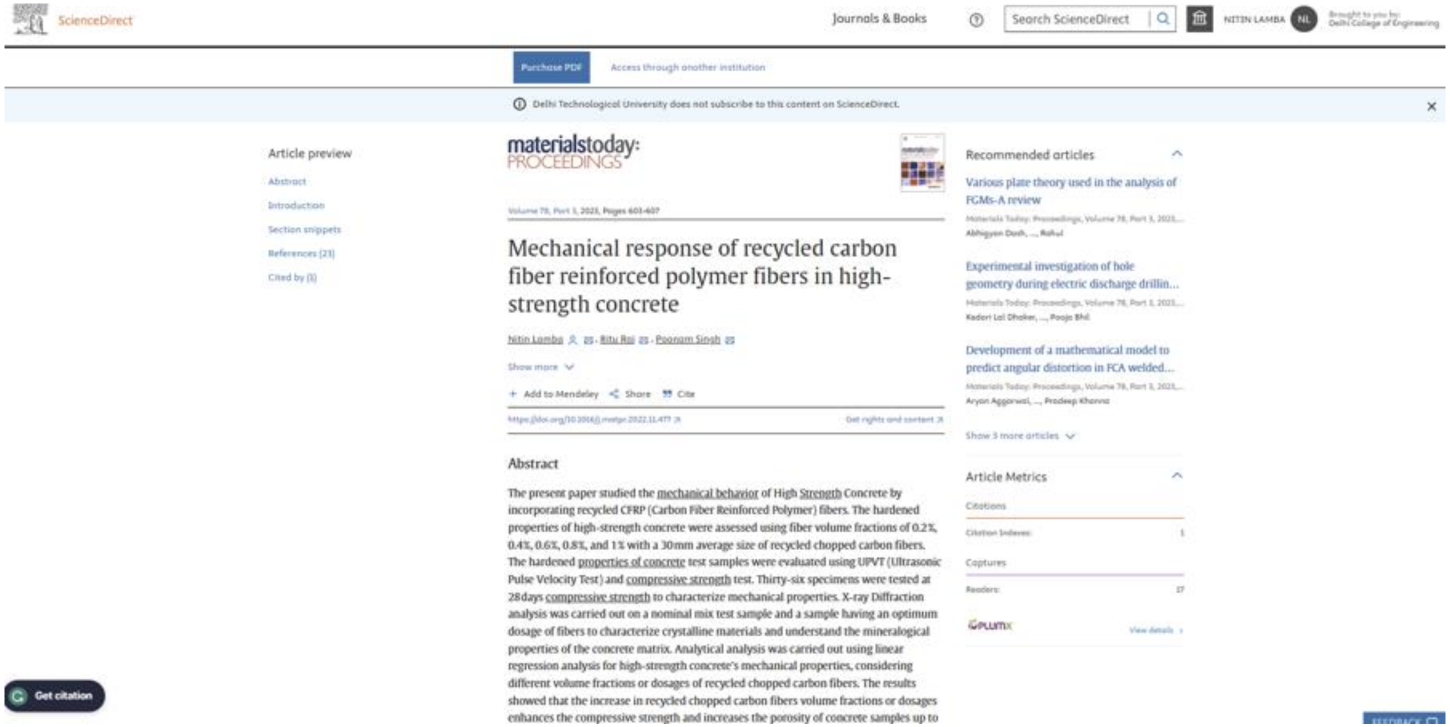

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Nitin Lamba, Ritu Raj, Poonam Singh

https://doi.org/10.1016/j.matpr.2022.11.477

## Abstract

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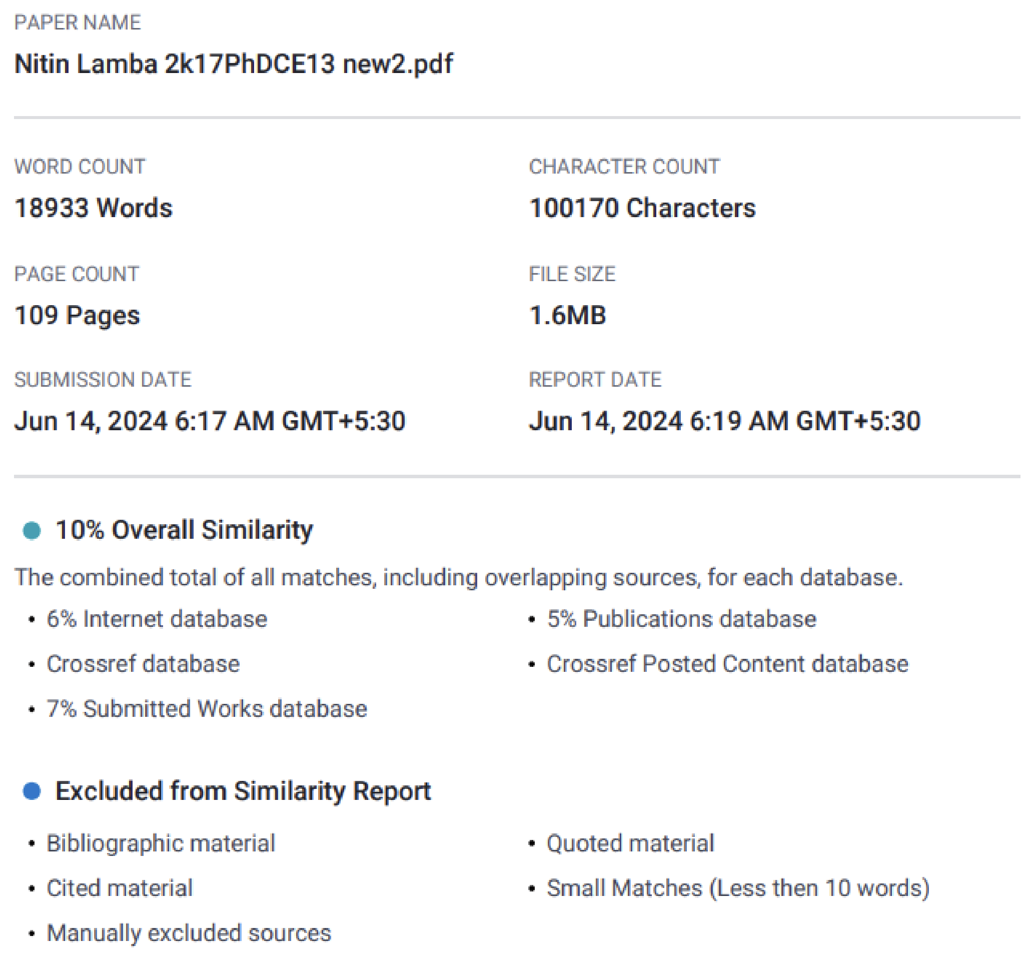

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# Curriculum Vitae

Mr. Nitin Lamba is an Assistant Professor at Noida International University, Greater Noida, India. He is a research scholar at Delhi Technological University, New Delhi, India. He received his M.Tech degree in Structural and Construction Engineering from Dr. B. R. Ambedkar NIT, Jalandhar, in 2016 with an MHRD scholarship through the GATE (2014) exam, and a B.E degree in Civil Engineering from Bangalore Institute of Technology, Bangalore, in 2013. He previously worked as an Assistant Professor at Netaji Subhas University of Technology (West Campus-Formerly CBPGEC), Jaffarpur, New Delhi. From his Ph.D. tenure at DTU Delhi, he has published 5 SCIE Indexed journal research papers from reputed publishers such as Elsevier, Springer, Wiley, and Sage, 03 International conference papers, 01 Scopus indexed journal research paper, and an Indian patent published to his name. He is an active reviewer of several peer-reviewed journals of international repute such as Alexandria Engineering Journal, Materials Research Express, Engineering Research Express, Surface Topography: Metrology and Properties, etc. He holds several memberships of Civil Engineering Professional Bodies such as the American Society of Civil Engineering (ASCE), the Institution of Civil Engineers (ICE), the Institution of Structural Engineers (IStructE), the International Association for Promoting Geoethics (IAPG), and many other reputed societies.