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Impact of Freeze-Thaw on Mechanical Properties of Concrete Having Hybrid Fibers for Structural Application

by

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I extend my heartfelt appreciation and dedicate this thesis to:

My Father

"whose endless sacrifices and encouragement have been the driving force behind my academic journey. This thesis is a realization of his hopes and dreams for me."

My Mother

"whose unwavering prayers and belief in my abilities have been my rock throughout this process."

My Wife

"whose encouragement, patience, and understanding have been the cornerstone of my success. Her support has provided the motivation needed to complete this academic endeavor"

My Supervisor

"for their unwavering guidance and enduring support, making this achievement possible despite the challenges."

CERTIFICATE OF APPROVAL

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Published Articles

1. **Arsalan. A**, Majid. A, "Impact of Artificial and Natural Fibre Hybridization on Properties of Fresh Concrete," *ICACEE-2023*.

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Abstract

Concretes capabilities and properties are the reasons, it is frequently utilised as a prime construction material in numerous infrastructures. One of the biggest risks for pavements is freeze-thaw, which they must endure because of changes in seasonal temperatures. During construction, certain precautions should be taken to protect the concrete pavements from freeze-thaw damage. If the early crack propagation is controlled, the behaviour of concrete during freeze-thaw can also be enhanced. Fibers have long been used in concrete to enhance its qualities. Fibers are utilised to improve the mechanical properties, absorbing properties, and crack-control properties of concrete, among other attributes. A mix of jute and nylon fibre have been used due to several benefits since they are inexpensive, widely available, and pose less health risks. Three different freeze-thaw cycles (10, 20 and 30) are tested in the experiments. Considerations include a single combination of mix design, water cement ratio, fibre length, and content.

This study's overall aim is to investigate how plain concrete (PC) and hybrid fibre reinforced concrete (HFRC) behave dynamically and mechanically after being subjected to freeze-thaw cycles. For the preparation of PC, the mix design ratio is 1:1.5:2.5:0.6. (cement: sand: aggregate: w/c). For the preparation of HFRC, jute and nylon fibres are added in equal amounts in a similar mix design ratio with a ratio of 5 percent by mass of cement. PC and HFRC specimens' mechanical and dynamic properties are measured using ASTM standards. According to ASTM standard C666/C666M-15, procedure B is employed, which involves quick freezing in the air and quick thawing in the water for the freeze-thaw process. The temperature must be dropped from 4 to -18oC and then returned to 4oC in a period of neither less than 2 hours nor more than 5 hours to complete one cycle of freeze-thaw. Measurements are made of the specimens' mass and dynamic properties after a 28-day curing period before the start of the freeze-thaw process. After the freeze-thaw cycles are completed, each specimen's mass and dynamic properties are tested to see how the process affected PC and HFRC specimens. Utilizing the experimental findings of HFRC and PC, a practical example is calculated and results are analyzed.

With the same mix design and w/c ratio, HFRC has a lower workability than PC, which results in a lower slump value of around 13.5% in HFRC in comparison to PC. In comparison to PC specimens, HFRC specimens are lighter by approximately 2.1%. HFRC specimens have lower densities than PC specimens as a result of their lower weight. When compared to PC specimens, the percentage of mass loss resulting from various freeze-thaw cycles is greater in HFRC specimens upto 10% in Cylinders and upto 11% in beams. In comparison to PC specimens, the relative dynamic modulus of elasticity (Pc) of HFRC specimens is dropping much more slowly, indicating that HFRC specimens can withstand more freeze-thaw cycles. When compared to PC specimens, the flexural strength of HFRC specimens are raised by 9.3%. However, the compressive strength and split tensile strength of HFRC specimens is found to be lower by 20% and 19%, respectively . As the frequency of freeze-thaw cycles increases, strength of PC and HFRC specimens decreases. The number of freeze-thaw cycles, mass loss, compressive strength, and flexural strength are used to develop relationship, which are then compared to the results of PC at zero cycles. With the use of the experimentally discovered compressive strength, modulus of rupture (MoR), and modulus of elasticity, design thickness of rigid pavement is measured. Hybrid fibres in concrete, as opposed to ordinary concrete, reduce the thickness of stiff pavement.It has been analyzed that in order to withstand the effects of 30 cycles of freeze-thaw, a 23 percent increase in pavement thickness is required. However, only a 17 percent increase in thickness is needed when employing hybrid fibres.

Keywords: Jute Fiber, Nylon Fiber, Freeze-Thaw, Rigid Pavement, Mechanical Properties

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Abbreviations and Symbols

A	Aggregate
C	Cement
CS	Compressive Strength
Cr. E	Cracked Energy Absorption After Maximum Load
C. Em	Compressive Energy Absorption upto Maximum Load
CTI	Compressive Toughness Index
m^3	Cubic Meter
ξ	Damping Ratio
Em	Energy Absorption upto Maximum Load
FS	Flexural Strength
FRC	Fiber Reinforced Concrete
FT	Freeze-Thaw Cycles
GFRC	Glass fiber Rreinforced Concrete
Hz	Hertz
HFRC	Hybrid Fiber Reinforced Concrete
j	Joule
JF	Jute Fiber
JFC	Jute Fiber Concrete
JFRC	Jute Fiber Reinforced Concrete
kg	kilogram
KN	kilo-Newton
fl	Longitudinal Frequency
P_{max}	Maximum Load
MJ	Mega Joule

MPa	Mega Pascal
mm	Millimetre
NFRC	Natural Fiber Reinforced Concrete
PC	Plain Concrete
PRC	Plain Reinforced Concrete
E_d	Relative Dynamic Modulus of Elasticity
S	Sand
s	Second
SHTM	Servo-Hydraulic Testing Machine
STS	Splitting Tensile Strength
δ	Stress
CE	Total Compressive Energy Absorbed
TE	Total Energy Absorbed
TTI	Total Toughness Index
fr	Torsional Frequency
ft	Transverse Frequency
w/c	Water-Cement

Chapter 1

Introduction

1.1 Background

Structures made of concrete deteriorate under freeze-thaw conditions. Day and night temperature variations in cold regions can harm solid materials like concrete. Water expands when freezing, increasing volume by up to 9 percent of the total volume. Although roads are used as a means of transportation, they can suffer damage in cold climates owing to temperature changes. The average life span, functionality, and strength of pavement are compromised as a result of damages and cracks induced by temperature variations. Water seeps into the pavements through leak joints and pavement fractures as the pavements thaw. Water that had penetrated the rigid pavement at the freezing stage froze, which led to expansion. This causes cracks to emerge in rigid pavement and degrades the pavement strength. Mass loss and changes in mechanical and dynamic properties are brought on by cycles of freeze-thaw. Due to temperature variations, these cycles are the main factors that results in reducing the durability of rigid pavement [1]. When concrete pavements are subjected to the cycles of freeze and thaw, relative dynamic modulus of elasticity decreases and the mass of loss increases [2]. Li et al. [3] explored the effects of water during freeze-thaw conditions on concrete pavements. It was determined after carrying out the experimental procedures that water was the main cause of cracks and other problems in concrete under freeze-thaw conditions.

The lifespan, serviceability, durability, and strength of pavements under freeze-thaw conditions were also found to be significantly reduced by water. Flexural strength is a crucial factor in rigid pavement's ability to withstand faulting caused by cyclical freezing and thawing. Fibers can be added to concrete to increase its flexural strength while also avoiding the need for a thick pavement. Fiber addition causes the concrete's flexural, impact, and tensile strength properties to rise. According to studies, adding fibers to concrete increases its hardness and crack resistance properties.

Concrete's mechanical and durability properties are improved by the addition of fibres. Increased durability is a result of the bonding process between the fibre matrix and the multi-directional fibre reinforcement, which reduces volumetric changes. By reducing or eliminating the rate of concrete deterioration, fibres also increase the durability of concrete. Natural fibres are being used in civil engineering applications, according to studies. There are very few studies on fibres for use in rigid pavement applications. Natural fibres can be utilised in construction, as evidenced by the literature. However, more research needs to be done before it can be used practically for large-scale uses. This will pave the way for the economically advantageous construction of firm pavements, which is important for developing nations. As a result, adding fibres can improve the performance of a structure and the properties of concrete.

1.2 Research Motivation and Problem Statement

To get from one station to another, one uses roads as a mode of transit. The nation's economy and expansion are aided by roads. Due to their great load carrying capacity and low maintenance requirements, rigid pavements are recommended. The need for rigid pavement safety is growing every day. There are numerous techniques to enhance the mechanical properties of concrete and the bonding of concrete materials but implementing them raises the cost of pavement as a whole. The ideal approach is to use fibers in rigid pavements, where fibers also lower the cost [4]. Hence the problem statement is:

A major expense of the state is utilized in repairing and replacing rigid pavements damaged through different distresses. Mechanical properties of concrete pavement are affected by variations in temperature. Due to which rigid pavement become weak and failure occurs. Economically improving these mechanical properties is a major concern. Hence hybrid fibers can be used to improve rigid pavement performance against temperature variations.

1.2.1 Research Questions

Followings are research questions which are explored in this study:

- What is the effect of Hybrid fiber reinforced concrete(HFRC) on mechanical properties of concrete?
- What is the effect of freeze and thaw cycles on Plain Concrete(PC) and Hybrid fiber reinforced concrete(HFRC)?
- How much rigid pavement thickness can be reduced by the use of Hybrid fiber reinforced concrete(HFRC)?

1.3 Overall Goal of the Research Program and Specific Aim of this MS Thesis

The overall goal of the research program is to have an improved behavior of new concrete pavements that are more sustainable and can perform better than ordinary rigid pavements after exposing to different distresses.

The specific aim of this MS thesis is to carry out an investigation to study the improved mechanical properties of hybrid fiber reinforced concrete for the use of rigid pavement, that are more sustainable, after exposure to different number of freeze-thaw cycles. Plain concrete will be taken as a reference for testing and comparing results.

1.4 Scope of Work and Study Limitations

Two Samples are used for an average as reported by Affan [46]. Experiment will be conducted for different cycles, i.e.,10, 20, and 30 cycles of freeze-thaw. Single combination of mix design, water cement ratio, fiber length and content will be considered.

This study is purely limited to dynamic, mechanical and micro-structural properties of concrete having jute and nylon hybrid fibers. The variation in the content of fiber and its length is not included in the scope of this research. The research is only limited to lab work with ASTM Standards whereas testing on actual pavement or any AASHTO testing is not included in this research thesis.

1.4.1 Rationale Behind Variable Selection

Jute and nylon fibers are selected based on the easy availability and for the sustainable approach. The selected jute and nylon fibers are 50mm in length and 50% by mass of cement equally because these length and content properties are reported to have optimum outcome [9, 14, 30, 46, 71]. These fibers are selected on the basis of their property to resist the formation and propagation of cracks with the enhancement of tensile strength. These fibers may help for bridging micro as well as macro-cracks and they may provide good physical properties as investigated by previous researchers. The use of both of these fibers can improve the concrete's overall mechanical properties, allowing for a reduction in rigid pavement thickness while improving the pavement's sustainability.

1.5 Novelty of Work, Research Significance and Practical Implementation

Concrete is a brittle material with low strain capacity and low toughness. Owing to the fact of having low tensile strength, it becomes vulnerable towards amalgamation in micro-cracking. In an experimental study it was revealed that the resistance against impact loading significantly improved by the addition of agricultural waste natural fibers in concrete. The mechanical properties of concrete were observed to be improved by introducing short discrete fibers in concrete [13]. Previous studies indicated that properties of concrete can be enhanced by addition of natural fibers. In this way, performance of structures can also be enhanced [14]. This work may contribute for understanding the hybridization of agricultural wastes. The use of these agricultural wastes as sustainable construction materials to minimize the ecological effects of concrete and the harmful impacts of these agricultural wastes if not disposed properly. This study may also contribute to counter the flaws of concrete by using these agricultural wastes after hybridization process.

As of the best to the knowledge of the author, there is no research yet conducted on the combined use of nylon and jute fiber in concrete for rigid pavement application. Thus, the current study is aimed to analyze the mechanical properties of concrete having nylon and jute fiber. This material will help in production of crack-resistant and ecofriendly concrete for use in pavement application. This study will help to achieve sustainable concrete pavements in terms of finance and minimize emissions, which are caused by repairing and construction of damaged pavement frequently.

When used for pavement applications, this material can reduce the amount of material needed for construction while producing concrete with improved properties compared to ordinary concrete. It also produces concrete that performs better overall. It is a very useful material to employ in the construction industry since jute and nylon, both are widely available, easy to extract, and have the potential to improve the mechanical properties of concrete.

1.6 Brief Methodology

The properties of concrete having nylon and jute as hybrid fiber (HFRC) and plain concrete (PC) are determined after exposure to the cycles of freeze-thaw. The mix design ratio for PC and HFRC is 1:1.5:2.5:0.6 (cement: sand: aggregate: w/c) with 50 mm long jute & nylon with a fiber content of 5% by mass of cement will be used for preparing of HFRC. Locally and commercially available Cement, Sand and Aggregate will be used. According to ASTM C666, procedure B have been used in which rapid freezing in air and thawing in water is achieved with a time of not more than 5 hours and neither less than 2 hours. Mechanical and dynamic Properties including Compressive strength, splitting tensile strength, flexural strength, density, modulus of rupture, loss in mass and dynamic behavior were measured. For compression and splitting tensile strength cylinders having size D-100 mm and H-200 mm have been utilized. Whereas for flexural strength beams having size of 450x100x100mm have been utilized. Relevant material properties i.e., Elasticity and Modulus of Rupture have been used to check pavement under practical conditions being used by previous researchers.

1.7 Layout of Thesis

There are six chapters in this thesis:

Chapter 1: Chapter 1 contains the introductory information. This chapter explains the effects of freeze-thaw cycles on rigid pavements. Additionally, it includes research motivation, a problem statement, an objective, scope of work, methodology, and a thesis outline.

Chapter 2: Chapter 2 consists of the literature review section. Moreover, Background information, freeze-thaw behavior of rigid pavement, fiber-improved concrete, Fiber Reinforced Concrete in rigid pavement, and summary make up this section.

Chapter 3: Chapter 3 contains the experimental program of this MS thesis. Background information, all ingredients of concrete, concrete preparation procedures for PC and HFRC, specimen information including their sizes, mechanical and dynamic testing protocols, and a summary are included.

Chapter 4: Chapter 4 covers the experimental evaluation. Whereas, background, freeze-thaw cycle effects, mechanical properties, dynamic properties, fibre failure mechanism, and summary are also included.

Chapter 5: Chapter 5 includes a brief background, a discussion on energy absorption and toughness index, the investigation of mechanical properties, implementation in practical applications with real-world examples, and a summary.

Chapter 6: Chapter 6 comprises of conclusion based on the analysis on results from chapter 4 and chapter 5 and some recommendations are provided based on the analysis for future work.

Chapter 2

Literature Review

2.1 Background

Rigid pavements are preferred above flexible pavements due to the high load carrying capability. However, these pavements are only structured for the heavy vehicular traffic because of the distresses that emerge on the rigid pavement such as shrinkage cracking and bottom-up cracking. The likelihood of cracking can be decreased by improving the overall mechanical properties of this rigid pavement. Using various organic components in it is one approach to do this, which can also result in reduced thickness and a reduction in the overall cost of the pavement. When natural and synthetic fibres are used to improve the mechanical characteristics of concrete, costs are reduced. On the other hand, the fibres employed can improve the mechanical properties as well as have the potential to prevent the initiation of cracks. Since ancient times, fibres have been employed to improve the mechanical properties and performance of concrete. The performance of fibre reinforced concrete (FRC) in terms of energy absorption, toughness index, and resistance to freeze-thaw effects has been demonstrated. Additionally, fibre reinforced concrete (FRC) performed better under dynamic loads. Exploring the usefulness of natural and synthetic fibres for improving resistance to temperature fluctuation is urgently needed because they are affordable and environmentally beneficial. One natural fibre that is frequently produced in South Asian nations is jute fibre whereas nylon fiber that is a synthetic fiber also produced in these countries.

2.2 Deficiencies in Rigid Pavements

Due to its use, rigid pavements have been more popular during the past few years in developing nations. Additionally, rigid pavements provide structural performance with durability. The high expense of construction for rigid pavement still prevents its widespread adoption. Plain concrete, which is brittle by nature, has a limited strain capacity and tensile strength. Due to their exposed surface to the environment and the combined impacts of drying shrinkage, temperature curl, volumetric changes, and temperature gradient, rigid pavements frequently fail from fatigue [28]. Although rigid pavements have many benefits, they also have some serious disadvantages. The amount of water will not be sufficient to completely hydrate the concrete particles if the water cement ratio of the concrete is less than 0.40 [29]. Concrete particles become more susceptible to shrinkage, which speeds up the cracking process [30]. The observed cracks in the concrete pavement are depicted in Figure 2.1.

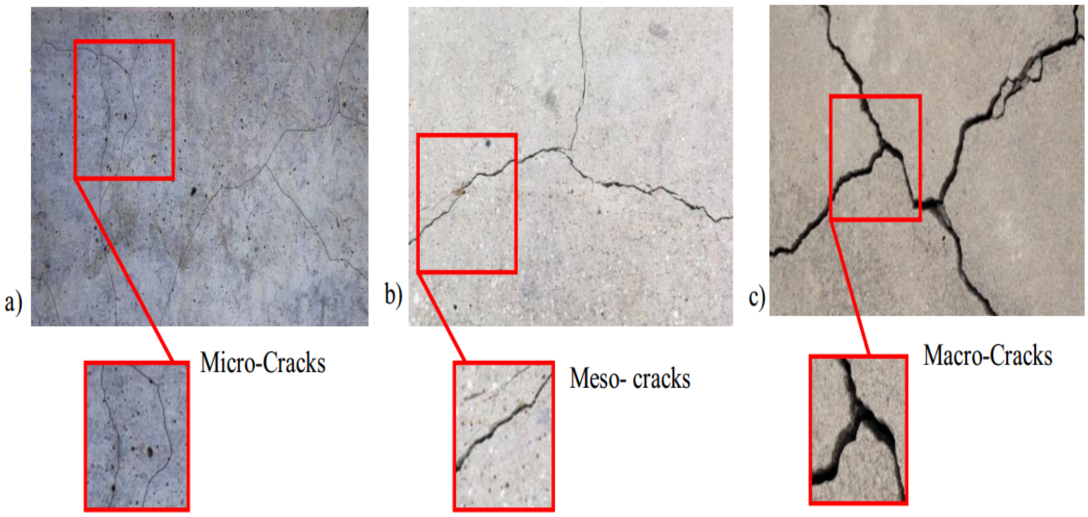

Figure 2.1: Cracking in Concrete Pavement; a) Microcracks, b) Mesocracks, c) Macrocracks [55]

Over the course of their lengthy useful lives, concrete structures, particularly rigid pavements, sustain a number of defects that require urgent maintenance and repair. Even before adding force to the structure, volumetric changes that occur during drying shrinkage produce micro cracks [32]. The process of evaporation from the surface of concrete causes a change in volume [33]. Structures exposed to the environment are more likely to experience this problem, which causes more structural collapse [34]. When the weather is changing, this is a serious issue of concern [35]. As a result, tensile stresses are enhanced in comparison to concrete's tensile strength [36]. Such damage repairs are expensive and time-consuming [37]. Due to differing shrinkage rates between the repaired material and the concrete substrate, the structure experiences occasional failures following repairs. The phenomena of differential shrinkage can subject repaired material to high loads and cause the repaired material to become unbonded from structural concrete [57]. Keeping these fissures from developing appears to prevent structural failure [58].

Rigid pavement's purpose is to provide resistance to fractures that form due to environmental and loading factors [59]. By resisting strong traffic loading, concrete's flexural strength feature plays a critical role in the performance of concrete. Since a few years ago, employing natural fibres in rigid pavements has become more popular [60]. Their lower density, ability to regenerate, local availability, and lower price when compared to other synthetic fibres are the causes of their rising demand [61]. Fibers can be added to fabrics to minimise stress generation during drying shrinkage [62]. For many structural applications, fibre reinforced concrete is currently employed to improve the performance of plain concrete. The flexural, compressive, fatigue, tensile, impact, and shrinkage properties of concrete can all be improved by fibre reinforced concrete, which is made of fibre and concrete.

2.2.1 Freeze-Thaw Behavior in Rigid Pavement

Freeze-thaw exposure on the concrete pavements in extreme weather areas is main contributor which decrease its life, affects its serviceability, compromises its functionality and damages the pavement physically. Using freeze-thaw conditions, Adkins and Christiansen [12] investigated the behaviour of concrete pavement. Data from the lab and the field were utilised to assess the pavement's performance. Increased freeze-thaw cycles led to the development of strains that led to pavement cracking and decreased pavement resilience. In Figure 2.2, cracking mechanism in concrete pavements can be observed.

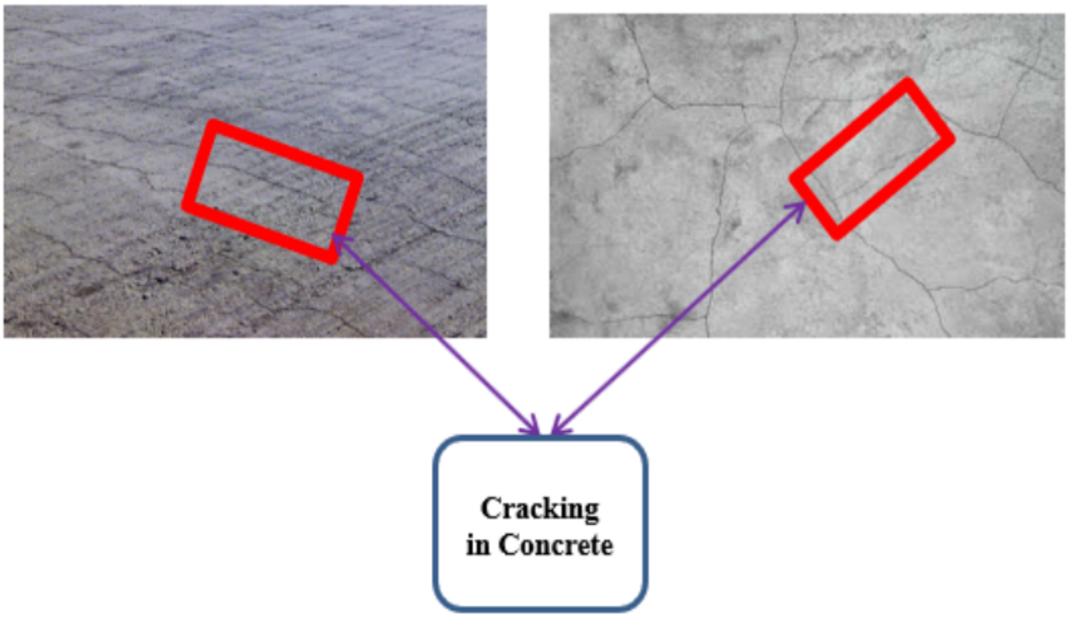

FIGURE 2.2: Observed Cracks in Rigid Pavement[32]

According to Ozgan and Serin [13], concrete pavement abnormalities were noticed as a result of the cycles of freeze-thaw. The comparison was conducted between the two periods of of these cyclesof freeze and thaw, one before these cycles and one conducted after these freeze thaw cycles. It was determined that freeze-thaw cycles reduced pavement stability while increasing ultrasonic velocity and void ratio. According to Amini and Tehrani [14], the passage of water during freeze-thaw cycles increased pavement degradation because of temperature changes. The impact of freeze-thaw cycles on the thermal characteristics and mechanical properties of concrete pavements was studied by Pan et al. [15]. Using a thermal constant analyzer, the thermal characteristics of concrete pavement were investigated. According to a report, freeze-thaw results in volume expansion, which lowers the material's thermal conductivity and mechanical properties. Freeze-thaw cycles were reported by Tang et al. [16] as a major factor in concrete pavement degradation. The impact of the cycles of freeze and thaw on rigid pavement were studied by Jaskula and Judycki [17]. Pavement specimens made of concrete was prepared in a lab. On the ready specimens, one, fifty, and one hundred and fifty freeze-thaw cycles were used. The experiment for the specimens of PC and HFRC is conducted for 10, 20 and 30 cycles of freeze-thaw [71]. Whereas, the number of cycles suggested by standard is either 300 cycles at maximum or the process of freeze-thaw must be stopped when the value of relative dynamic modulus of elasticity reached 60 percent of the original value. The use of freeze-thaw cycles has reduced the lifespan of pavement.

2.3 Improvement in Concrete Due to Fibers

As of previous studies, it was assesed that using fibers in the prepration of concrete generally enhances most of its mechanical and dynamic properties. While in some cases a little decrease in compressive strength has been observed due to low density of fibers. In figure 2.3, cross section of some natural fibers including Bamboo and Coconut fiber can be observed.According to Richardson [18], adding fibres to concrete can increase the durability of plain concrete. Utilizing fibres in concrete to increase bonding and tensile strength following freeze-thaw cycles has improved the characteristics of concrete. Pliya et al. [19] evaluated the concrete spalling due to freeze-thaw. Freeze-thaw was discovered to be one of the main factors reducing concrete's strength. Concrete with fibres were used to decrease spalling in the pavements. Concrete's mechanical properties and durability were enhanced by the inclusion of fibres. According to Mu et al. [20], fibre reinforced concrete (FRC) has superior mechanical properties versus plain concrete. For the structues, which had to endure weather exposure like pavements, durability is an extremely crucial factor. The addition of fibres to concrete decreased spalling's impact, increased residual strength, and improved concrete's resistance to the impact of freeze-thaw process.

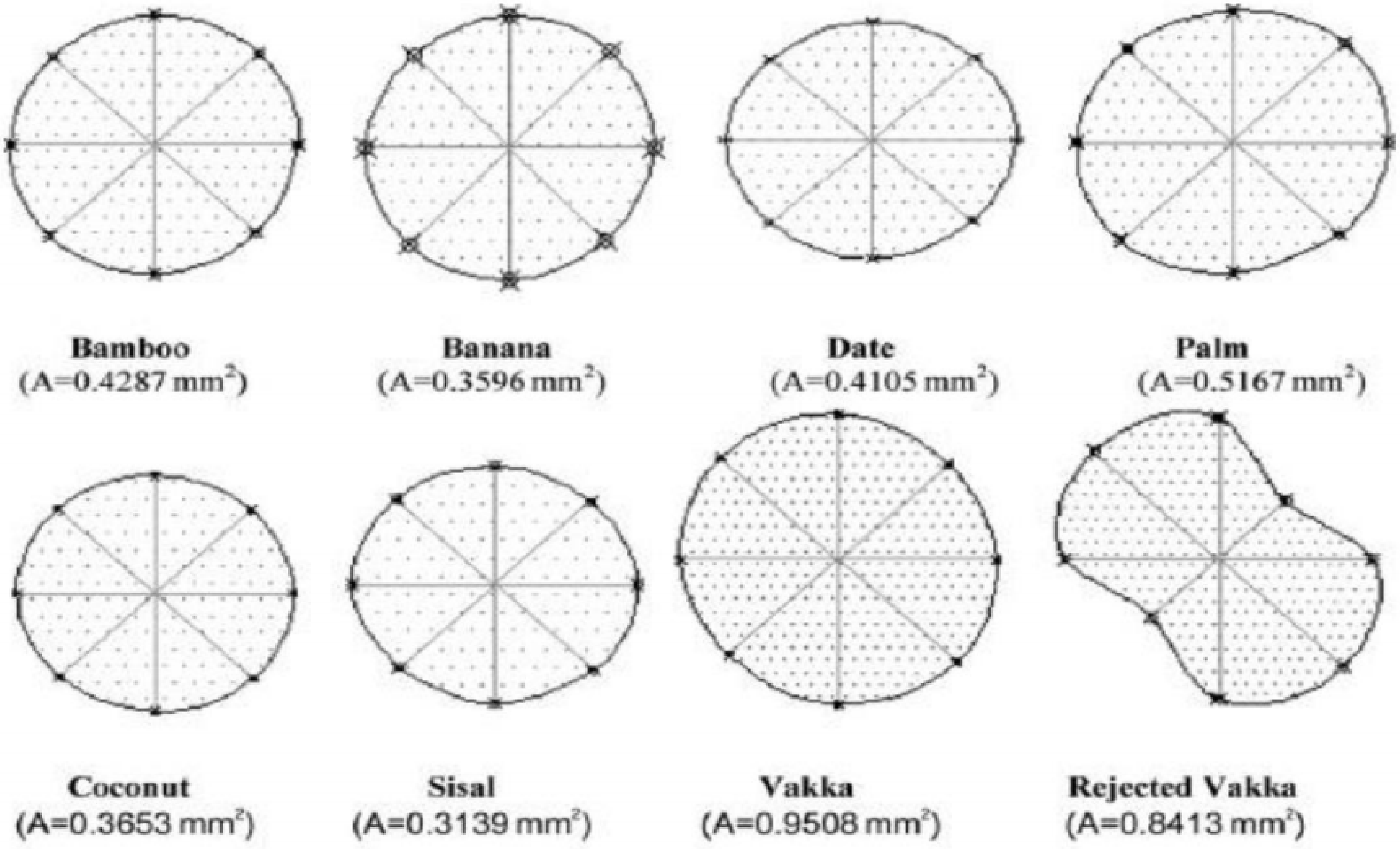

FIGURE 2.3: Cross Section of Fibers [28]

Using jute fibres, Chakraborty et al. [21] examined the characteristics of cement mortar. By including jute fibres into cement motor, properties (such as compressive strength and flexural strength) of cement mortar were improved. Jute fibres were used by Kundu et al. [22] to modify the non-pressurized concrete pipe's mechanical properties. According to Lee and Barr [23], adding fibres to ordinary concrete improved the concrete's fatigue behaviour. The durability has been studied by many researchers with the help of limited freeze-thaw cycles i.e., 150, 400 and 300 cycles, and concluded that 300 cycles are equivalent to almost 10 years of exposure to freeze-thaw conditions in a typical cold climate [76–78]. According to Yap et al. [24], the use of fibres improved the mechanical properties of oil plam shell fibre reinforced concrete (OPSFRC). Results had indicated an improvement in density, tensile strength, and compressive strength. Jute fibre reinforced concrete was prepared by Kristina and Yadav [25] using jute fibres at a ratio of 0.5 percent, 1 percent, and 2 percent in ordinary concrete. Mechanical properties were determined by conducting several tests.

Tests were conducted 7, 14, 28 and 56 days later. Results showed that JFRC's mechanical properties have improved (like compressive strength, split tensile strength, and flexural strength). Under freeze-thaw circumstances, Salemi and Behfarnia et al. [29] investigation of the mechanical characteristics of polypropylene fiber reinforced concrete(FRC) was compared to that of plain concrete (PC).According to the research findings, it was observed and concluded that concrete with fibres can withstand the effects of the freeze-thaw process. Using jute, nylon, and polypropylene fibres in the ratios of 1:3:1.5:0.7, together with 50 mm long fibres with five Percent by cement mass, Zia and Ali [9] reduced the seepage of canal-lining. In order to measure mechanical properties, plain concrete PC was used as a reference. Results showed that samples of jute fibre reinforced concrete had superior mechanical properties to PC. In order to control early age microcracks, Khan and Ali [30] utilized with 50 mm long fibres in concrete having five Percent by cement mass, and better results were obtained. Jute fibres' effectiveness in concrete as a reinforcing material was investigated by Zakaria et al. [26]. Standard-sized specimens underwent tests for flexural strength, split tensile strength and compressive strength.

Table 2.1: Fibres in Concrete and Their Effects

Sr. No	Reference	Fibers	Matrix	Conclusions
1	Zia & Ali [9]	Jute Fiber	Concrete	Jute Fiber Reinforced Concrete can be economical and effective Material.
2	Zakrai et al. [26]	Jute Fiber	Concrete	Conventional Mix Design (1:2:4) was utilized and observed significant improvement in tensile and flexural strengths
3	Aziz & Mansur [27]	Jute Fiber	Concrete	Sand content was doubled in mix design i.e. (1:3:1.5). Significant improvement was observed in toughness and energy absorption of JFRC
4	Kundu et al. [22]	Nylon Fiber	Concrete	Enhanced the mechanical properties of non-pressurized concrete pipes
5	Chakraborty et al. [21]	Nylon Fiber	Mortar	Enhanced the mechanical properties of mortar prepared with cement

Jute fibres were added to concrete, and the mechanical properties showed a noticeable improvement. Table 2.1, shows the fibers utilized in concrete and its effects. As a result, it was concluded that concrete's mechanical properties can be enhanced by the introduction of natural as well as artificial fibres. Due to the organic nature of jute fibres, durability is a key factor. NFRC durability could be incresed with a variety of methods, including partial replacement of ordinary Portland cement (OPC) with undensified silica fume, carbonation of the matrix in a CO_2 rich atmosphere, or blast furnace slag. Regarding hybrid utilization of jute and nylon fibres, there is a need of study to estimate the concrete design life. The sole drawback of employing alone natural fibres in concrete composite is that, due to the organic nature of the fibres, additional care must be taken to preserve their endurance, hence, nylon is utilized as hybrid fiber. By evaluating the strength gain or reduction over time under various ageing conditions, it is possible to assess the resilience of fibre reinforced concrete.

2.3.1 Use of Hybrid Fibers in Concrete

It has been observed that there are certain drawbacks of using natural fibers as due to organic nature they need a lot care hence, a different type of fiber from a different category is required to be assesed with its utilization in concrete with natural fiber. FRC is divided into four groups by ACI 544 [49] based on the type of material utilised. The action and capability of reinforced concrete are improved by using fibres [8]. Reinforced concrete can perform and behave better when made with natural fibres [8]. Fiber reinforced concrete (FRC) was researched by James et al. (2002) to see if it would enhance mechanical qualities [19]. The majority of investigations focuses on steel, carbon, glass, and propylene fibres. However, these fibres are very expensive. Furthermore, it is difficult to buy these fibres. Additionally, these fibres are much stiffer, which adversely affects how easily concrete flows. According to several studies, natural fibres should be used instead of metallic ones. Researchers are interested in using natural fibres in polymeric materials because of their beneficial characteristics and low maintenance requirements. By chemically treating natural fibre, the adhesive property between the polymer matrix and the fibre surface can be improved. Khan and Ali [19] investigated how silica fume, coconut fibres, and fly ash affected the characteristics of concrete. By adding natural fibres to concrete, the concrete matrix's resistance to sulphate and alkaline assault was increased [2]. Wheat straw was found to boost concrete's flexural strength by up to 7.5 percent [27]. Hari and Mini investigated the effects of hybrid sisal and nylon fibres on the mechanical and durability properties of self-compacting concrete [23]. Coir fibre reinforced concrete's compressive toughness was raised by 910 percent. Bamboo fibre was used to enhance asphalt road performance and fracture resistance. The dynamic modulus and stress endurance were improved by bamboo fibre [55]. Among the numerous possibilities, hybrid fibre ratios of 0/100, 25/75, 50/50, 75/25, and 100/0 are among the options. It was determined that water absorption caused a decrease in fibre breakdown and had an effect on durability. Concrete's strength and durability are increased when nylon fibre is mixed with sisal. The splitting-tensile strength of concrete containing percent bamboo fibre by weight of cement and a bamboo fibre length of 2 cm was studied by Wahyuni et al. [28]. After 28 and 90 days, the cylinder's splitting tensile strength was also tested. It was discovered that the BFRC's tensile strength was 26 percent greater than the PC's. Ahamed et al. [35] examined coir, which consists of sisal, jute, hemp, banana, and pineapple fibres, in order to evaluate the properties of concrete. They observed that each organic fibre has unique qualities that can change particular concrete properties.

Ahamed et al. [35] examined coir, which consists of sisal, jute, hemp, banana, and pineapple fibres, in order to evaluate the properties of concrete. They observed that each organic fibre has unique qualities that can change particular concrete properties. Coir, sisal, and other natural fibres (such as pine and wheat fibres) are abundant in the Yunnan Province of China, according to a study by Wang et al. These materials are frequently utilised to build walls and homes because to their ecological benefits, and complete fulfillment. The durability of jute fibres was examined by Park et al. [13] using a micro mechanical test and non-destructive acoustic emission. The tensile strength of jute fibres was shown to drastically diminish as the bars expanded and weakened during a boiling water test. Jute fibers generally exhibit a rougher texture compared to nylon fibers due to their natural

Table 2.2: Properties of Jute Fibers[46]

Properties	**Values**
Length	50mm
Diameter	0.40mm
Aspect Ratio	125
Density	1460 Kg/m3
Specific Gravity	1.5
Water Absorption	13%
Tensile Strength	393-773 MPa
Elongation	1.5-1.8 %
Stiffness	10-30 kN/ mm2

composition [74]. Ravikumar et. al [75] have investigated the roughness of jute fibers through surface analysis using techniques like response surface methodology. This inherent roughness impacts interfacial bonding within concrete matrix and influences their mechanical properties. Sen et al. [14] investigated into the mechanical and toughness characteristics of composites made of jute fibres under various conditions. Consuming salt water media has more detrimental impacts on longevity and mechanical attributes when compared to pure water and salt water. Mechanical properties of Jute fiberare shown in table 2.2.

Concrete specimens reinforced with coconut fibres were evaluated in three different pH solutions: tap water, calcium hydroxide, and sodium hydroxide by Toledo and Filho et al. [22]. After 420 days in sodium hydroxide, coconut fibre reinforced concrete retained 60.9 percent of its initial strength. The effects of various test conditions have been studied. The importance of plant fibres, such as wheat straw, was investigated in order to evaluate flexure and shear reinforcement. 25 mm long wheat straw was utilised as the main filler for the mass of concrete with a mix design ratio of (1:2:4) for PC. Energy absorption, flexure strength, and toughness index were three parameters that saw improvements of 7.5 percent, 30.4 percent, and 11.1 percent, respectively. Crack growth was somewhat slowed down by the usage of wheat straw. Wheat straw fibres demonstrated enhanced behaviour on rough pavements and are capable of producing comparable patterns [5].

Agopyan et al. [45] replaced the asbestos fibres with sisal and coir fibres and applied the three-point bending test. The test results showed that both sisal and coir could withstand the maximum load, but when coir tile was put up against sisal tile, the coir demonstrated the greatest strength. Experimental research was done to see if date palm agricultural wastes might be utilised to create sound-absorbing buildings. Samples in the following dimensions: 25, 35, 45, and 55 mm were made. The samples with the maximum sound absorption had a thickness of 55 mm, it was found [50]. It is widely accepted by researchers who have examined sisal and coir fibre reinforced concrete extensively that the ideal fibre content changes as the source of the fibres changes. The durability of fibres from hibiscus and cannabinus, coconut, sisal, jute, and other plants was investigated by Ramakarishan and Sundarararajan [10]. For 60 days, they immersed the samples in water that was acidified with lime and sodium hydroxide while alternating wetting and drying cycles. They discovered that the fiber's chemical makeup had changed. Coconut fibre was discovered to have the strongest tensile characteristics of the group. This method is used to evaluate the durability of natural fibres over time.

A bamboo sheet twinning tube was created and used as a column together with recycled aggregates. The outcomes demonstrated a considerable improvement in ductility, compressive strength, and residual bearing capacity [51]. Hemp concrete was developed to compare its hydrothermal performance to that of conventional concrete. It has been demonstrated that hemp concrete can lower a building's environmental impact while improving its energy efficiency [52]. Agricultural wastes can be used as insulation by combining them with other composite materials [53]. To conclude with, it can be summed up that due to certain limitaions and drawbacks of natural fiber this research is being conducted using a mixture of natural and artificial fiber in equal amounts will be utilized.

2.4 Fiber Reinforced Concrete in Rigid Pavements

Concrete having fiber, used in rigid pavement may be utilized under different conditions to asses its behaviour upon different deficiences in rigid pavement. The usage of polyester fibre reinforced concrete in stiff pavement was examined by Gupta et al. [32]. It was claimed that polyester fibres improved the mechanical properties of concrete, such as its split tensile strength, compression strength, and flexural strength. For six months, Nobili et al. [4] observed PFRC roads. Direct stresses were measured while constructing an Italian concrete pavement. Results showed that the addition of fibres to concrete increased the pavement's longevity while also making it safer and more affordable. By employing recycled steel fibres in concrete, Graeff et al. [33] investigated the fatigue and the crack mechanism of the concrete pavement. The findings showed that recycled steel fibres enhanced micro-crack mechanisms, improved fatigue behaviour, and decreased pavement thickness by up to 26 Percent.The functionality of fibres of various lengths on multi layer cracks is depicted in Figure 2.4. The fibres chosen for this study have the best qualities compared to other locally accessible fibres.

Table 2.3: Different Mix Design Proportions and Their Results from Earlier Studies[84]

Fiber Content	**Mix Design Proportions**	**Fibre Length (mm)**	**CS**	**STS**	**FS**
P.C	-	-	100.0	100.0	100.0
J.F.R.C	-	-	-	-	-
0.60Kg/m3	1:1.75:3.25	30	120	-	155
0.25%	1:1.51:3	15	106	106	120
0.50%	1:1.51:3	15	99	79	91
0.25%	1:2:4	15	103	102	112
0.50%	1:2:4	15	89	114	102

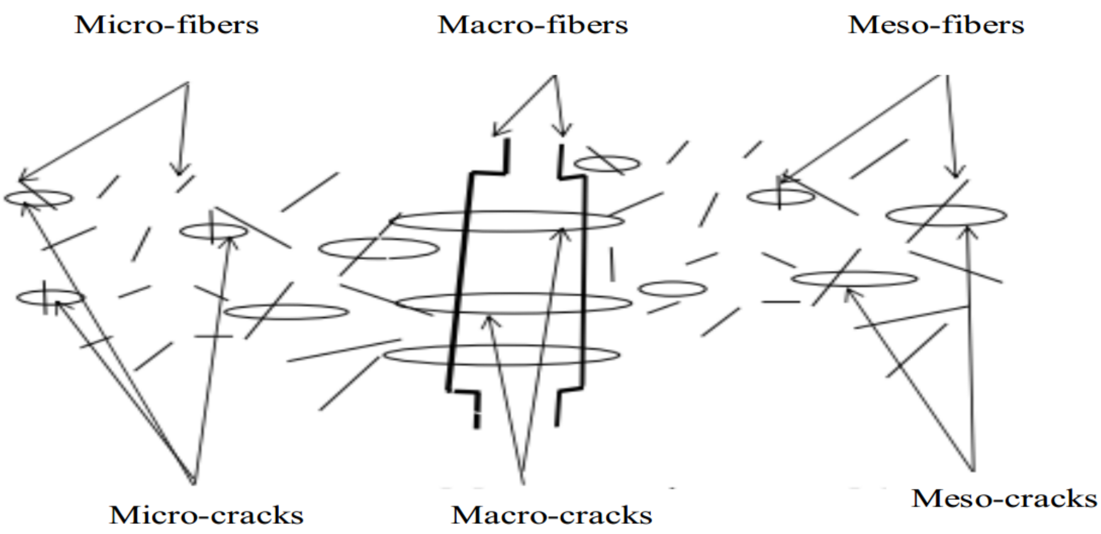

FIGURE 2.4: Conceptual Diagram of Hybrid Fiber Resistance to Cracks in Concrete; a) Microcracks, b)Macrocracks, c) Mesocracks[54]

Properties of Jute fiber with different concrete mixes and with different lengths along with their results are shown in table 2.3. Jute and Nylon fibres both have strong tensile properties that help prevent cracking in hybrid fibre reinforced concrete. Crack Propagation is also resisted by the less water absorption property of nylon fibers. Studies in the literature demonstrate that adding hybrid fibres to concrete improves its characteristics. Jute fibres were utilized in concrete pavement by Patel and Patel [34]. The inclusion of jute fibres boosted the concrete's performance, according to measurements of its mechanical properties. By integrating locally accessible natural fibres that is wheat straw in concrete, Farooqi and Ali [35] investigated the impact of fibres in rigid pavements. Results showed that fibres decreased the microcracks. Investigation of split tensile strength of wheat straw-reinforced concrete (SWRC) was also conducted. Additionally, it became evident that the split toughness index (STI) of the wheat straw-reinforced concrete (SWRC) was higher than that of the referenced plain concrete. The mechanical properties of FRC and how they affect concrete pavements were researched by Khan and Ali [36]. Concrete was made using wave polypropylene and human hair fibres, with PC serving as the reference material. The experimental process was carried out in accordance with ASTM standards, and the mechanical properties of wave polypropylene fibre reinforced concrete (WPFRC) and human hair fibre reinforced concrete (HFRC) were compared with reference PC. When compared to PC, the mechanical parameters of HFRC and WPFRC, such as compressive, split tensile, and flexural strength, were improved. Using the results of the HFRC and WPFRC experiments in comparison to PC, the thickness of the concrete pavement was lowered. Consequently, adding fibres to concrete can enhance a number of the properties of rigid pavements.

2.5 Summary

The literature review makes it obvious that fibres can be added to concrete to improve its mechanical properties and resistance to freeze-thaw conditions. Synthetic fibres are the subject of the majority of study. Typically, synthetic fibres are more expensive than natural fibres but for this research nylon fiber is selected as it is an inexpensive synthetic fiber available. Secondly, natural fibres are kind to the environment. Investigations into the combined behaviour of natural fiber (i.e. jute fiber) and synthetic fiber (i.e. nylon fiber) in concrete during freeze-thaw conditions still needs to be explored and investigated.

Chapter 3

Experimental Program

3.1 Background

The use of fibre to improve mechanical properties and endurance to freeze-thaw is growing every day. Due to their superior mechanical properties, accessibility, environmental friendliness, and low price, natural fibres have drawn considerable attention in the concrete research field, along with synthetic fibres. Due to their low density and capacity to increase high pulling tensile strength, the fibre that has been chosen in this research is a blend of jute and nylon fibre. The major aspects of hybrid fibre reinforced concrete are an improvement in mechanical properties, toughness, and energy absorption. Through experimental studies, the potential of jute and nylon as hybrid fibre to improve resistance to freeze-thaw cycles is investigated. Ingredients, concrete preparation methodology, specimen details, and testing methodology are all thoroughly covered in this chapter.

3.2 Ingredients

Normal cement (OPC), sand, and aggregate (3/4"down) has been utilized to prepare plain cement concrete (PCC). The ordinary Portland cement (OPC) specifications' are presented in Table 3.1.

TABLE 3.1: Ordinary Portland Cement Properties[46]

Composition	**Percentage**
CaO	62.80
SiO2	22
Al2O3	5.03
SO3	1.52
FE2O3	3.25
MgO	2.57
Loss in ignition	1.82
No. of Days	**Com. Strength (MPa)**
3 Days	27.37
7 Days	33.65
28 Days	47.27
Setting Time	**Minutes**
Initial Setting time	175
Final Setting Time	375

Jute fiber is relatively rougher compared to Nylon fiber due to its natural texture and composition [73]. In concrete, Jute fibers may exhibit a higher tendency to pull out of the matrix due to their rougher surface texture, which might result in lesser bonding with the concrete compared to Nylon fibers. Whereas, subject of discussion is the length of fibre. Fibers shouldn't be so short that one side of the broken surface completely pulls away from them. Additionally, fibre length should be kept to a minimum to prevent balling effect during mixing. A lot of researchers have also used concrete with 50 mm-long fibres [9, 35, 36]. Nylon fibers typically exhibit a percentage elongation at break ranging from 6% to 16% [64], showcasing their inherent elasticity, while Jute fibers demonstrate a lower percentage elongation of about 1.5% to 1.8% [63], emphasizing their natural flexibility.

These distinct values influence how each fiber type contributes to the mechanical properties of Hybrid Fiber-Reinforced Concrete (HFRC). Table 3.2 displays the physical characteristics of used jute and nylon fibres.

Table 3.2: Physical Properties of Selected Fiber

Properties	**Jute Fiber**	**Nylon Fiber**
Length (mm)	50	50
Diameter(μm)	10-50	10-50
Percent Elongation (%)[63, 64]	1.5 - 1.8	6 - 16
Tensile Strength (MPa)[82, 83]	393	10.45

Whereas Table 3.3, shows sand and aggregates' sieve analysis. The same materials are mixed with 50 mm long jute and nylon fibers to produce hybrid fibre reinforced concrete (HFRC).

Table 3.3: Sieve Analysis of Aggregate

Size (mm)	**Passing (%)**		**Specifications**	
	FA	CA	FA	CA
25		100		100
19		89.1		90-100
10	100	20.81	100	20-55
4.75	99.7	1.11	95-100	0-10
2.38	97		80-100	
1.20	76		50-85	
0.60	56		25-60	
0.30	26		10-30	
0.15	11.5		0-15	

3.3 Selection of Mix Design, Concrete Prepration, Fresh Properties and Specimens

The high energy absorption, high breaking strength, low cost, and local material make jute fibre suitable for usage [22, 36]. Along with jute fiber, nylon fiber is also locally available and it is inexpensive. In rigid pavement, jute fibre reinforced concrete was used, and mechanical properties improved [34]. Use of fibres with a 10 mm to 50 mm length and fibres of 1 percent to 10 percent by mass of cement is common. However, the most effective results were achieved by utilising cement that had 5 percent fibres by mass and fibres that were 50 mm long [9, 30]. Therefore, the selected PC and HFRC mix design ratio is 1:1.5:2.5:0.60 with the application of 5 percent of hybrid fibres (2.5 percent of each fibre) by cement mass, having a 50 mm length. The same mix design was used for both mixes so that the results of HFRC and PC could be compared in order to assess the effectiveness of hybrid fibres when used in the same proportion as in PC. In order to increase the mechanical properties of concrete, Zakrai et al. [26] mixed 1:2:4 with jute fibres. The aggregate content is decreased from 4 to 2.5 in the current study so that more mortar will be present to grip fibres for high toughness and less compression strength would be compromised.Moreover, aggregate and sand ratios are reduced a little in order to attain high strength of concrete.

Considering the PC manufacturing 0.6 w/c ratio is utilized along with cement, fine aggregate, and coarse aggregate in the ratios of 1:1.5:2.5. For hybrid fibre reinforced concrete, the same mix design ratio is utilized with the addition of 50 mm long jute and nylon fibres, which are added with five percent by total cement mass. All the materials are taken by measuring in mass. Using a non-tilting pivoting type drum concrete mixer, PC and HFRC were prepared. Cement, sand, and aggregate are all put into the mixer drum with water for three minutes in order to manufacture plain concrete (PC). Using ASTM standard C143/C143M-15, the workability of HFRC and PC specimens is evaluated before to the filling of moulds at the fresh stage [38]. A separate method is utilized to manufacture HFRC [21]. To absorb the required amount of water, jute and nylon fibres are submerged into water for 24 hours. Fibers are then exposed to fresh air for 30 minutes. Layer by layer materials are then added to the mixer for avoiding balling effect. The blender drum is filled with one-third each of aggregate, sand, cement, nylon and jute fibres. Until all of the components are loaded into the blender drum, the same procedure is repeated. Then 1/3rd water is poured on the materials once these have been fully inserted into the blender drum. The remaining water is progressively poured into the mixer after it has been turned on. To get homogenous concrete, the mixer is turned for six minutes. Before pouring HFRC into moulds, a slump test is conducted. As seen in Figure 3.1, the value of slump is lower for HFRC than for PC. This is a result of the ability of jute and nylon fibres to absorb water. The number is lower because fibres have already been soaked into water for 24 hours, so the difference could be greater if the fibres are utilized in a dry environment. Molds are poured in 03 progressive layers, along with a rod being used for temping down each layer 25 times. The same process is used to fill PC and HFRC specimens.

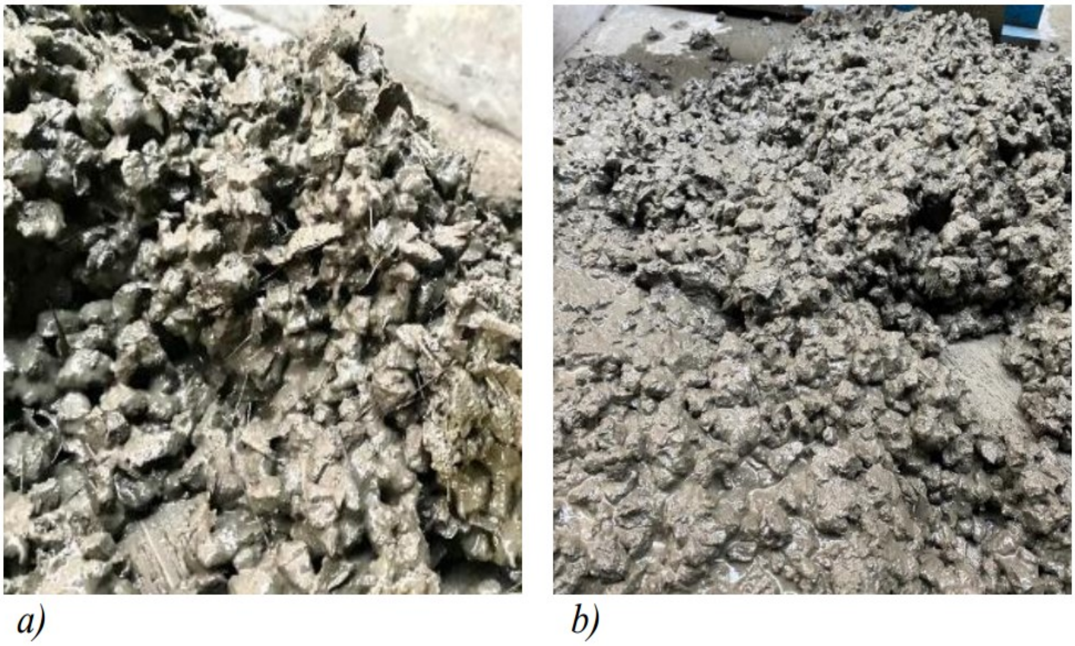

Figure 3.1: Fresh Concrete: a) HFRC b) PC

The specimens were demolded after 24 hours and put in a water tank to cure for 28 days. The density of PC and HFRC is calculated by dividing the mass of each specimen by its volume after 28 days prior to the mechanical testing. The density of PC and HFRC are both measured in accordance with ASTM standard C642-13 [39]. Due to the lack of fibre reinforced concrete standards (FRC), the workability and density of HFRC are assessed using the same methods as PC. Due to the usage of hybrid fibres and the lighter weight of HFRC specimens in comparison to Plain Concrete, the density of HFRC specimens were lower than that of PC.

Table 3.4: Fresh Properties of PC and HFRC

Concrete Sample	**Slump**	**Compaction Factor** **Value**	 **Workability**	**Density**(Kg/m^3)
PC	88 mm	0.89	Plastic	2310
HFRC	76 mm	0.80	Stiff Plastic	2262

In Table 3.4, the slump and density values for PC and HFRC are displayed. By adding a mix of jute and nylon fibers, it was noticed that the fresh density of the concrete was reduced to notable percentage as weight of concrete was reduced significantly whereas the volume was fixed. Observed densities of Plain concrete and hybrid fiber reinforced concrete were 2310 Kg/m^3 and 2262 Kg/m^3, respectively. Hence, a reduction of upto 2.1 percent was observed as compared to the reference concrete i.e., plain concrete. As a conclusion it was noted that addition of fibers significantly reduced the density of fresh concrete.

Cylinders and beamlet specimens are casted to study the characteristics of plain concrete (PC) and hybrid fiber reinforced concrete (HFRC) under freeze-thaw conditions. In comparison to each cycle and test, an average of two specimens are used. 8 of the 16 cylinder specimens are made up of PC and 16 are made up of HFRC. Eight PC and eight HFRC cylinders each are utilised to calculate the compressive strength at zero, ten, twenty, and thirty freeze-thaw cycles from a total of 16 PC and 16 HFRC cylinders. The split tensile strength is calculated using the remaining 8 cylinder specimens of PC and HFRC at zero, ten, twenty, and thirty freeze-thaw cycles, with one batch having no free-thaw cycles applied. Eight specimens among the 16 cast beam-let specimens are cast for PC and eight for HFRC. Mass loss,damping, fundamental frequencies properties, and cracks or voids are determined on every sample once cycles of freeze and thaw are completed. Before inserting the specimens into the servo-hydraulic testing equipment for mechanical testing, mass loss, damping, fundamental frequencies, and cracks or voids in the samples are determined for each specimen after the completion of each cycle of freeze-thaw to examine the changes happened in beam and cylinder specimes owing to the phenomenon of freeze and thaw.

3.4 The Process of Freeze-Thaw

The freeze and thaw technique is carried out on Plain Concrete (PC) and Hybrid Fiber Reinforced Concrete (HFRC) specimen cylinders and beamlets in accordance with ASTM standard C666/C666M-15 [11]. As per ASTM standards, one cycle of the freeze-thaw process takes 5 hours to complete. Once the freeze-thaw procedure is completed, the temperature is changed from 4^oC to -18^oC and back again to 4^oC. After completion of all freeze thaw cycles, each PC and HFRC specimen's relative dynamic modulus of elasticity is computed. Significant strength i.e., 99% is usually is gained in 28 days and remaining strength i.e., 1% is gained over a relatively longer period of time [75]. Therefore, testing of specimens after completion of freeze-thaw cycles with some delay can be considered reasonable. The experiment for the specimens of Plain Concrete (PC) and Hybrid Fiber Reinforced Concrete (HFRC) will be conducted for 10, 20 and 30 cycles of freeze-thaw [71]. For the phenomenon of freeze thaw, the relative dynamic modulus of elasticity (E_d) is crucial because the process must be terminated when it achieves a value that is 60 percent of its original value or when the cycles of freeze-thaw exceeds three hundred [11].

3.5 Testing Procedure

Measurements are made for both Plain Concrete (PC) and Hybrid Fiber Reinforced Concrete (HFRC) with different cycles including 0, 10, 20, and 30 cycles of freeze-thaw to determine the relative dynamic modulus of elasticity, mass loss, compressive strength, load time curve, strength-strain relationship, tension strength, load-deflection relationship, and flexural strength.

3.5.1 Dynamic Properties

According to C215-14 [40], the dynamic characteristics of the cylinders and beamlets for both Plain Concrete (PC) and Hybrid Fiber Reinforced Concrete (HFRC) are determined. As of C666/C666M-15 [11], relative dynamic modulus of elasticity (E_d) is computed to determine damping ratio. Frequencies, mass loss, and relative modulus of elasticity are measured twice: once before each specimen begins the freeze-thaw process and once the required cycles of freeze and thaw are completed. Figure 3.2 shows a figurative procedure for dynamic testing of concrete specimens.

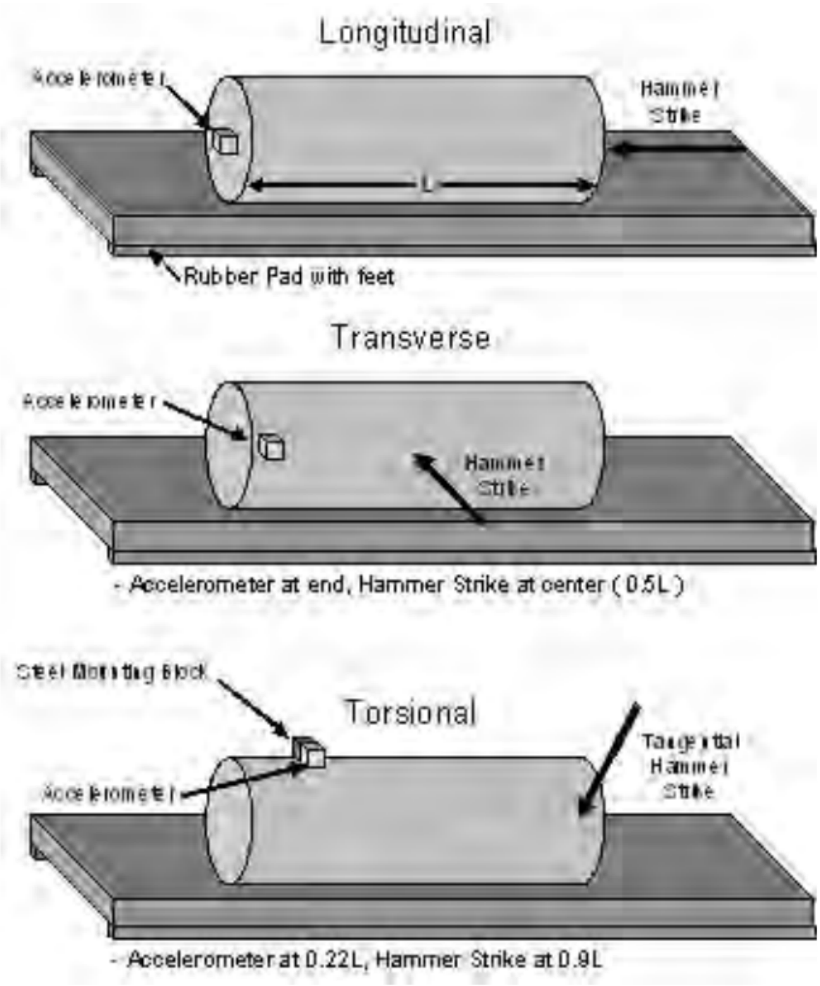

FIGURE 3.2: Dynamic Testing Procedure

3.5.2 Mechanical Properties

3.5.2.1 Compression Strength

As of ASTM standard C39/C39M-18 [10], cylinders are utilized to assess the compressive strength (f'c) of PC and HFRC specimens using a servo hydraulic testing machine (STM). Compressive strength, strain, and stress-strain curve are determined from the test data. The stress-strain curve is also used to determine compressive energy properties and toughness.

3.5.2.2 Splitting Tensile Strength

As per C496/C496M-17 [41], standard size PC and HFRC cylinders are used in servo-hydraulic testing machines (STM) to measure tension strength. Spliting-tension strength and a load deformation curve are obtained from test data. The load deformation curve is used to determine the split tension energy properties and toughness.

3.5.2.3 Flexural Strength

As per C78/C78M-16 [42], standard size PC and HFRC beamlets are utilized in servo-hydraulic testing machines (STM) to measure flexural strength. Flexural strength and a load-deflection curve are determined from test data. The load-deflection curve is used to determine the flexural energy properties and toughness.

3.5.3 Hybrid Fiber Bond in Broken Specimens

Images from SEM analysis are used for further evaluation of fractured surfaces of the tested materials at the microscopic level. Images of broken surfaces are captured for assessing how the cycles of freeze and thaw cycles have affected HFRC specimens. Identification of the failure mechanism and fibre bonding with concrete materials are the objectives.

3.6 Summary

Plain Concrete (PC) Specimens are prepared using a 1:1.5:2.5 mix design and with a 0.6 water to cement ratio, whereas Hybrid Fiber Reinforced Concrete (HFRC) specimens were prepared using the same mix design ratio but with 5 percent jute and nylon fibres added by mass of cement. 48 specimens altogether, of which 16 beamlets are used to determine flexural strength, and 32 cylinders are used to determine compressive strength and split tensile strength at zero, ten, twenty and thirty freeze-thaw cycles. To determine the relative dynamic modulus of elasticity, mass loss, and damping ratio, all specimens are evaluated.

Chapter 4

Results & Discussions

4.1 Background

The cement, sand, aggregate, and water/cement mix design ratio are 1:1.5:2.5:0.6. For HFRC, the same mix design ratio is employed, but 50 mm long jute and nylon fibres are added with five percent by cement mass overall. This chapter discusses the experimental findings using PC and HFRC specimens during various cycles of freeze and thaw .

4.2 Impact of Freeze and Thaw cycles

The effects of the FT cycles on the HFRC and PC surfaces are shown in figures 4.1. On the surfaces, cracks caused by FT cycles are also visible in every sample's testing image. Figure 4.1, makes it evident that crack propagation increases along with an increase in cycles. On physical observance, approximately 4-8%, 10-15% and 20-35% surface was damaged after 10, 20 and 30 cycles of freeze-thaw, respectively. Due to compaction, there are a least number of voids in PC and HFRC surfaces at zero cycle. In comparison to 10 cycles of freeze and thaw, there are more and larger surface voids at the completion of 20 cycles of freeze and thaw. In comparison to 20 cycles of freeze and thaw, there are more and larger surface voids after 30 cycles. Both PC and HFRC specimens show this type of trend. Therefore, as the amount of cycles of freeze and thaw rose, so did the size and quantity of voids on the surface. Water enters the void during the thawing process and turns into ice during the freezing stage, increasing the size and number of surface voids. When water is freezing, its volume is increased by almost 09 percent of its initial volume. As a result, there are more and larger surface voids during the freezing stage.

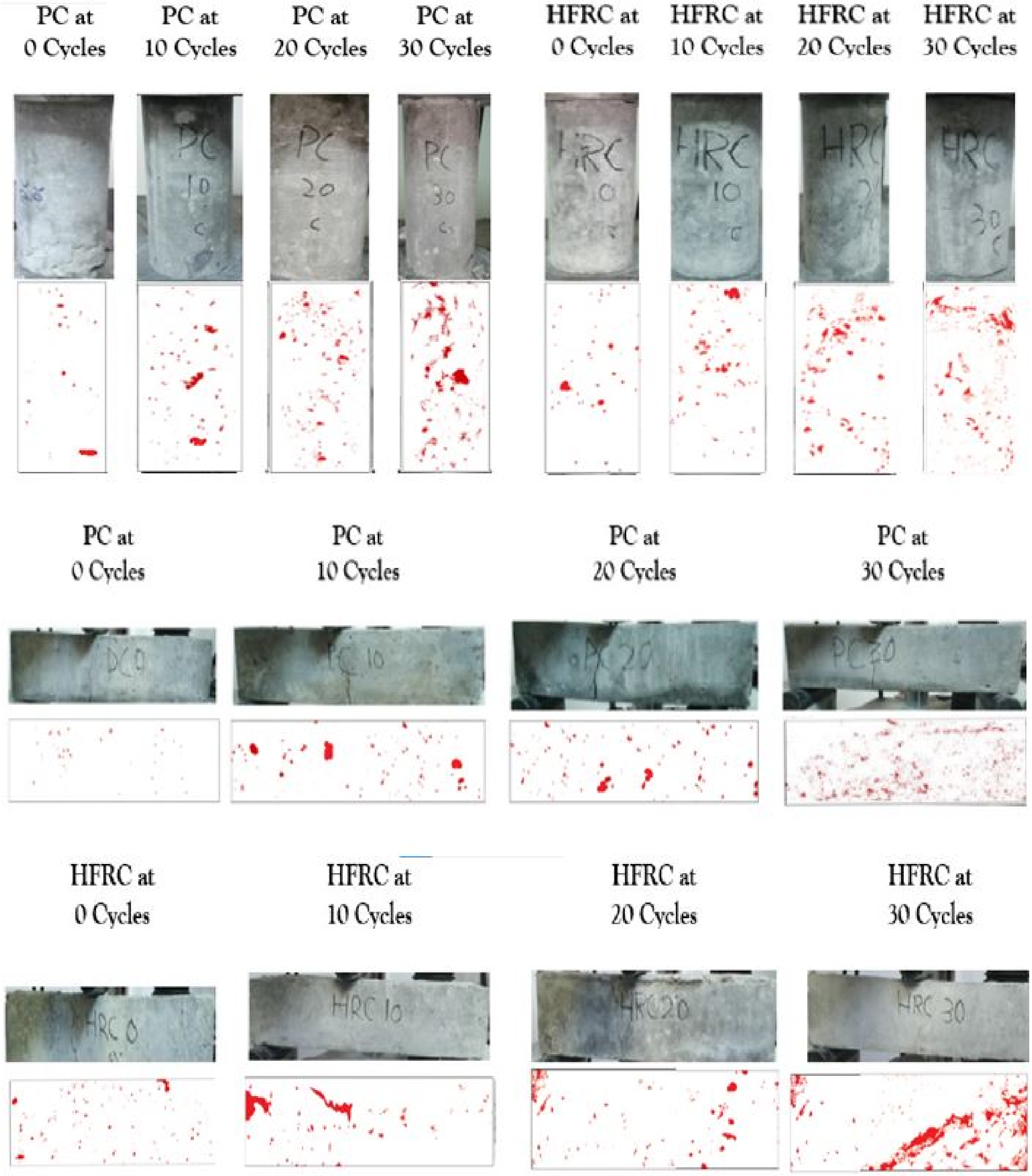

FIGURE 4.1: Schematic Diagram Showing Crack Formation Due to FT at 0,10,20 and 30 Cycles

HFRC specimens have slightly higher damage than PC specimens. This is caused by the way jute fibres absorb water. Whereas nylon fibres being artificial and synthetic in nature were not much affected by water and also resisted the effect of FT in HFRC samples. Throughout the casting, curing, and thawing processes, jute fibre absorbed water. As a result of expansion that takes place when absorbed water in HFRC specimens freezes, cracks start to develop in the samples. Only the top layer of the surface layer is harmed in HFRC cylinders and beam samples, and crack propagation is increased as the number of cycles of freeze and thaw increases. HFRC specimens have a few tiny cavities formed on their surface. This is a result of the HFRC specimens' strong jute fibre concrete composite bonds. On the other hand, the PC samples's surface is generated with deep spaces. With more frequent cycles of freeze and thaw cycles, there are more deep voids as a result of HFRC and PC specimens cracking during cycles of freeze and thaw cycles. As the FT cycles were applied to the samples, there surface started to deteriorate. The deteriorated mass fell off the sample hence this mass loss was occurred.

Table 4.1 displays the percentage of mass loss caused by the cycles of freeze and thaw effect in PC and HFRC specimens. When compared to the mass of PC beam and cylinders at zero cycles of freeze and thaw, PC cylinders and beam-lets experienced mass losses of 0.50 percent, 0.75 percent, 1.75 percent and 0.58 percent, 0.92 percent, 1.66 percent, respectively, at ten, twenty, and thirty cycles of freeze and thaw.In comparison with the mass of HFRC cylinders and beamlets at zero cycles of freeze and thaw, there was a mass loss of 0.55 percent, 1.10 percent, 1.93 percent, and 0.62 percent, 1.06 percent, 1.85 percent, respectively. It can be seen from Table 4.1 that the mass loss in HFRC specimens during the cycles of freeze and thaw condition was more than in PC specimens. The relationship between mass loss and durability in concrete due to freeze-thaw cycles is complex [65]. While mass loss is often considered an indicator of surface deterioration [66], relying solely on mass loss to durability is inconclusive, especially with limited FT cycles. A higher mass loss percentage could suggest increased surface vulnerability, potentially impacting the concrete's external layer. However, establishing a direct correlation between mass loss and overall durability requires a more comprehensive assessment involving multiple factors such as strength, permeability, and micro-structural changes [67]. The limited range of FT cycles hinder a conclusive association between mass loss and concrete durability, emphasizing the need for a broader analysis to evaluate long-term performance. However, due to the organic nature of natural fibres, durability is a significant concern. A mass loss variation between 0-2% was observed. The damage to concrete after 300 freeze-thaw cycles is equivalent to approximately 10 years of exposure to freeze-thaw conditions in a typical cold climate [76–78]. The minimal effect observed on the mass loss curve, could indeed stem from the lower number of cycles conducted [79]. This limited range might not sufficiently portray the concrete's full response to freeze-thaw cycles; thus, this can be linked with short term durability. As such, linking this particular observation on mass loss directly to long term durability is premature or inconclusive given the range of cycles tested. This is indeed an indicative of a limited effect and can be associated with improved durability in concrete.

Table 4.1: Mass Loss in PC and HFRC Samples

Specimen	**Symbol**	**Mass Before FT Cycles (Kg)**	**Mass After FT Cycles (Kg)**	**Mass Loss (%)**
Cylinders	PC0	4.01	-	
	PC10	4.28	4.26	0.50
	PC20	4.19	4.16	0.75
	PC30	4.05	3.98	1.75
	HFRC0	3.63	-	-
	HFRC10	3.71	3.69	0.55
	HFRC20	3.75	3.71	1.10
	HFRC30	3.55	3.48	1.93
Beam	PC0	12.02	-	-
	PC10	12.41	12.34	0.58
	PC20	12.22	12.11	0.92
	PC30	12.30	12.10	1.66
	HFRC0	11.34	-	-
	HFRC10	11.06	10.99	0.62
	HFRC20	11.23	11.11	1.06
	HFRC30	11.51	11.30	1.85

4.3 Dynamic Properties

Measurements are made on the dynamic characteristics of Plain Concrete (PC) and HFRC beam and cylinder samples. Frequencies, Pc, and damping ratio of Plain Concrete (PC) and HFRC specimens are determined in accordance with American Society for Testing and Materials (ASTM) C215-14 [40] and ASTM standard C666/C666M-15 [11], respectively. Dynamic properties are measured in 02 different phases, once before phenomenon of cycles of freeze and thaw process and second, after the number of cycles of freeze and thaw are achieved. Due to lack of standards, HFRC adheres to the same criteria. Once before the start of cycles of freeze and thaw cycles and second when the cycles are finished, the frequencies of each Plain Concrete and HFRC samples are measured. In comparison to Plain Concrete specimens, HFRC specimens have greater transverse frequencies. With the rise in quantity of cycles of freeze and thaw, the measured transverse frequencies of both Plain Concrete and HFRC samples are decreasing. Relative Dynamic Modulus of Elasticity (Pc) in every sample is determined using transverse frequencies in accordance with American Society for Testing and Materials (ASTM) standard C666/C666M-15 [11]. At various cycles of freeze and thaw cycles, HFRC beam and cylinder samples had more relative dynamic modulus of elasticity (Pc) than Plain concrete beams and cylinders . At zero freeze and thaw cycles , PC and HFRC cylinders and beamlets relative dynamic modulus of elasticity (Pc) is 100 percent. After ten Freeze and thaw cycles, cylinders of PC10 and HFRC10 have Pc values of 99.43 percent and 99.68 percent, respectively. Whereas, at ten cycles of freeze and thaw , beamlets have relative dynamic modulus of elasticity (Pc) of 99.57 percent and 99.74 percent, respectively, in comparison to plain concrete and HFRC beams and cylinders at Zero freeze and thaw cycles. Relative dynamic modulus of elasticity (Pc) of plain concrete PC and HFRC cylinders at 20 cycles of freeze and thaw is 98.63 percent and 98.99 percent following the completion of 20 freeze and thaw cycles, whereas relative dynamic modulus of elasticity (Pc) of plain concrete (PC) and HFRC beamlets is 99.07 percent and 99.45 percent following the completion of 20 cycles of freeze and thaw, respectively. Relative dynamic modulus of elasticity (Pc) for plain concrete PC and HFRC cylinders at

30 cycles of freeze and thaw is 97.55 percent and 98.55 percent, whereas relative dynamic modulus of elasticity for plain concrete PC and HFRC beamlets is 98.52 percent and 99.21 percent when compared to the Pc value for PC and HFRC beams and cylinders at zero freeze and thaw cycles.HFRC specimens can even withstand more cycles of freeze and thaw then PC samples because of modest loss in relative dynamic modulus of elasticity in HFRC specimens. Depending on the values of Pc, the freeze and thaw cycles can be stopped. Any specimen's freeze and thaw procedure needs to be stopped when Pc value is less than 60 percent of what it was at zero freeze and thaw cycles or when it reaches 300 cycles [11]. Tables 4.2 compares the damping ratios of PC and HFRC specimens during the corresponding freeze and thaw cycles.

TABLE 4.2: Dynamic Properties of PC and HFRC Samples

Specimen	**Cycles**	**Transverse Frequencies before FT (Hz)**	Transverse **Frequencies after FT (Hz)**	**Relative Dynamic Modulus of Elasticity (-)**	**Damping Ratio (%)**
Cylinder	PC0	4365	4365	100	2.12
	PC10	4365	4340	99.43	2.35
	PC20	4365	4305	98.63	2.78
	PC30	4365	4258	97.55	3.69
	HFRC0	5642	5642	100	3.42
	HFRC10	5642	5624	99.68	4.04
	HFRC20	5642	5585	98.99	5.45
	HFRC30	5642	5560	98.55	6.19
Beam	PC0	6761	6761	100	0.70
	PC10	6761	6732	99.57	1.40
	PC20	6761	6698	99.07	1.75
	PC30	6761	6661	98.52	2.05
	HFRC0	8053	8053	100	1.27
	HFRC10	8053	8032	99.74	1.67
	HFRC20	8053	8009	99.45	1.82
	HFRC30	8053	7989	99.21	2.17

From 0 to 30 cycles of freeze-thaw, the HFRC cylinders' damping ratios are 3.42, 4.04, 5.45, and 6.19 %, respectively. This is greater when compared to PC samples against their corresponding FT cycle samples. At zero, ten, twenty, and thirty freeze and thaw cycles, the PC cylinders' damping ratios are 2.12, 2.35, 2.78, and 3.69, respectively. From 0 to 30 FT cycles, the HFRC beamlets' damping ratios are 1.27, 1.67, 1.82, and 2.17 percent, respectively. This is higher than that of PC specimens compared to the corresponding cycles of freeze and thaw cycle specimens in each case. At zero, ten, twenty, and thirty FT cycles, the PC beamlets' damping ratios are 0.70, 1.40, 1.75, and 2.15 percent, respectively. It is evident from the test findings that HFRC cylinder & beam-let specimens have a higher damping ratio than PC specimens. The decreasing trend is observed for Ft and Ed whereas, increasing trend is observed for damping ratio. It is well known that there is an increase in damping ratio when there is decrease in Ft [81]. It should be noted that the increase in damping ratio is due to increased potential damage. While on comparing PC with HFRC, HFRC show enhanced values of Ed due to resistance of inner core of concrete which shows its improved energy dissipation. As a result, HFRC can perform better in rigid pavement than PC.

4.4 Mechanical Properties

4.4.1 Compression Behavior and its Properties

Figure 4.2 displays the strength-strain relationship of all HFRC and PC samples following compression testing and cycles of freeze and thaw. The compressive absorbed energy up to peak stress is defined as the region beneath the stress-strain curve up to peak stress (CEp). The compressive absorbed energy from peak stress to final stress is defined as the area below the the strength-strain relationship between the peak and final strength (CEf). The total energy under compression is defined as the total area below the strength-strain relationship between zero and final strength (CTE). Compressive toughness index (CTE/CEp) is the ratio of the compressive total cracked absorbed energy to the compressive absorbed energy up to peak stress (CTI).

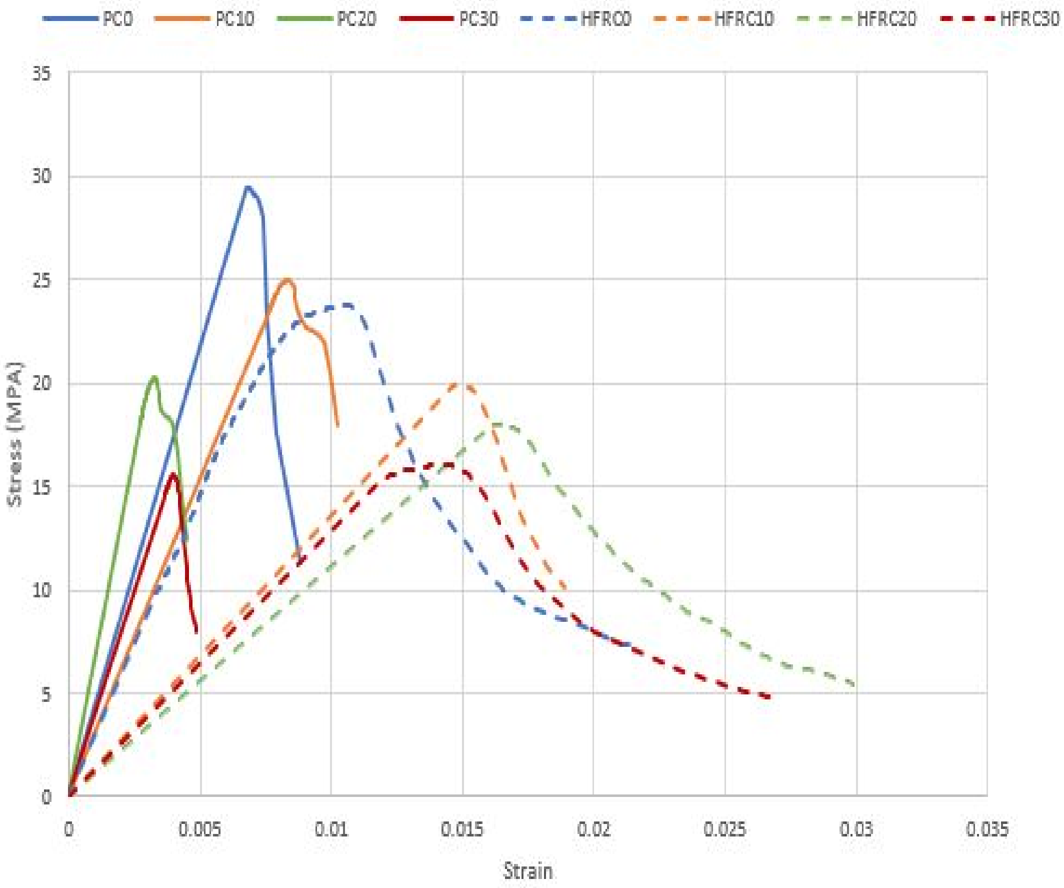

Figure 4.2: Compression Behaviour of PC & HFRC at Zero, Ten, Twenty & Thirty Freeze-Thaw Cycles

Figure 4.3 illustrates the crack growth during mechanical testing. The behavior of initial cracks and final breaking in both Plain Concrete (PC) and Hybrid Fibre Reinforced concrete (HFRC) samples can be observed in this figure. When compared to the initial crack that developed in all PC specimens (PC0, PC10, PC20, and PC30), the first cracks in all HFRC specimens (HFRC0, HFRC10, HFRC20, and HFRC30) are incredibly small in both length and width (PC0, PC10, PC20, and PC30). When cracks are most numerous, their width and length are greater in every PC sample than they are in all HFRC specimens. All PC specimens experience some concrete pieces falling to the ground with ultimate loading, however only more cracks and larger cracks appear in HFRC specimens. Due to the strong attachment of jute and nylon fibres with the components of the concrete, HFRC specimens have demonstrated improved performance.

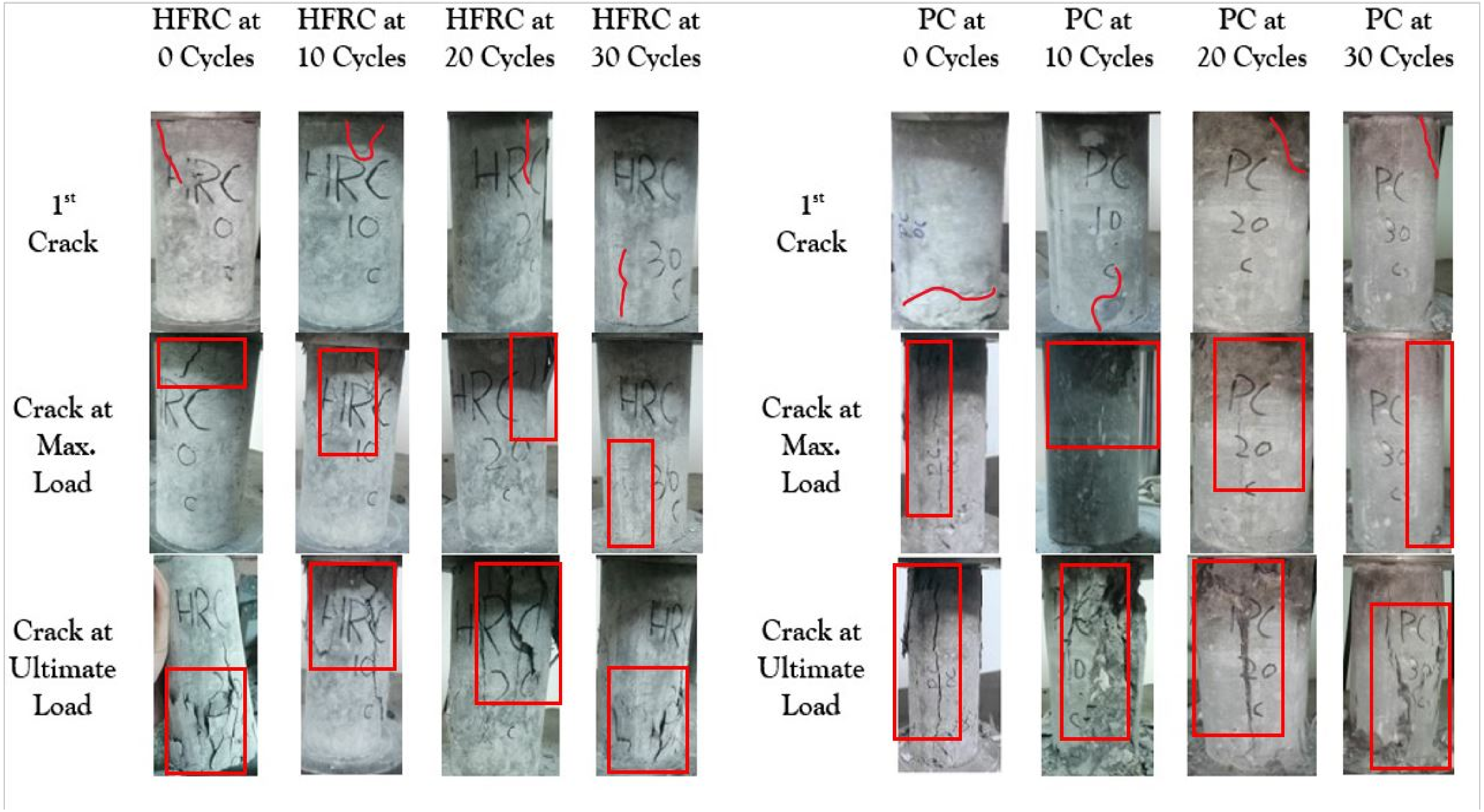

FIGURE 4.3: Crack Propagation during Mechanical Testing (Compression)

All HFRC specimens are purposefully broken in order to examine the fibres' failure process. In all HFRC specimens, almost half of the fibres are taken out, whereas remaining half of the fibres are broken. For PC and HFRC samples, crack propagation enhanced as the cycles of freeze and thaw increased which is evident from the pictures of each HFRC and PC specimen in Figure 4.3.

Table 4.3: Compression Strength Properties of PC and HFRC

Specimen	**f ′c**	**E**	**Strain**	**Compressive Energy Absorption**			**CTI**
				CEp (upto Peak)	**CEf (Peak to Final)**	**CTE**	
	(MPa)	**(GPa)**	**-**	(MJ/m^3)	(MJ/m^3)	(MJ/m^3)	**-**
PC0	29.38	25.48	0.007	0.089	0.042	0.13	1.47
PC10	25.01	23.50	0.0084	0.069	0.042	0.111	1.60
PC20	20.25	21.15	0.0033	0.035	0.021	0.057	1.61
PC30	15.53	18.52	0.004	0.032	0.021	0.053	1.67
HFRC0	23.78	22.92	0.011	0.173	0.139	0.313	1.81
HFRC10	19.92	20.98	0.015	0.158	0.132	0.29	1.84
HFRC20	18.03	19.96	0.017	0.154	0.137	0.291	1.89
HFRC30	16.02	18.81	0.014	0.149	0.148	0.298	2.00

Note : For compression testing loading rate was 0.25MPa/s as per ASTM standard C39/C39M-15a an average of min and max.

It is evident from Table 4.3 that compressive strength decreases with the increase in FT cycles, energy absorption decrease in comparison to the prior number of FT cycles of the same specimens of HFRC and PC. The reduction in compressive strength of FRC over PC is often a compromise for attaining other desirable properties such as improved toughness. This reduction is also due to lower density of samples due to inclusion of fibers [69]. The effects of fibers can weaken the material in compression, but these materials offer advantages in other aspects, like crack resistance and improved energy absorption. This allow HFRC to absorb more energy and deform further before reaching failure, resulting in a higher strain at the peak load compared to the less-reinforced and more brittle behavior of PC. This may help to prevent concrete pavement degradation. On the other hand, design will also experience a slight drop in compressive strength. Comparing the compressive strength of PC specimens and HFRC specimens, it was shown that PC specimens were stronger under the same cycles of freeze and thaw cycles as HFRC specimens. Comparing HFRC0, HFRC10, HFRC20, and HFRC30 to PC0, PC10, HFRC20, and PC30, the compressive strength of each material decreases by 5.60 MPa, 5.09 MPa, 2.22 MPa, and 0.49 MPa, respectively. In comparison to the Plain concrete PC specimens, HFRC specimens have absorbed greater energy. In comparison to PC0, PC10, PC20, and PC30, the CTE in HFRC0, HFRC10, and HFRC30 increased by 0.183 MJ/m^3, 0.179 MJ/m^3, 0.234 MJ/m^3, and 0.245MJ/m^3, receptively. As the quantity of cycles of freeze-thaw is increased, energy absorption decreases.

4.4.2 Splitting Tension Behavior and its Properties

Figure 4.4 displays the load-deformation curves for all PC and HFRC specimens following split tension testing and cycles of freeze and thaw cycles. The PC curves at 0, 10, 20, 30 cycles show a peak load of 140.7kN, 120.5kN, 109.8kN and 77.8kN, respectively. Whereas, the HFRC curves shown by dotted lines show peak load value of 113.3kN, 96.5kN, 84.8kN and 62.7kN at 0, 10, 20 and 30 FT cycles. In PC curves, there is a sudden drop after attaining peak value which shows no energy absorption after peak load, whereas, in HFRC specimens, after attaining peak value the specimen tend to bear load due to fibers which shows energy absorption after peak loading. In HFRC specimens, the curves tend to move towards right side as the FT cycles propagates while the peak load value decreases. This shows the strength and energy absorption behaviour upon application of FT cycles.

Figure 4.5 illustrates the creation, formation, and propagation of cracks during mechanical testing. When compared to the first cracks in every PC samples (PC0, PC10, PC20, and PC30), the first cracks in every HFRC samples (HFRC0, HFRC10, HFRC20, and HFRC30) are incredibly small in both length and width. Every PC spample is disassembled into 02 parts at their peak load. While the crack size and their number are enhanced in the case of HFRC specimens under maximum loading. Nevertheless, as shown in Figure 4.5, all HFRC specimens take load at the ultimate loading even though their sizes alter as a result of the loading.

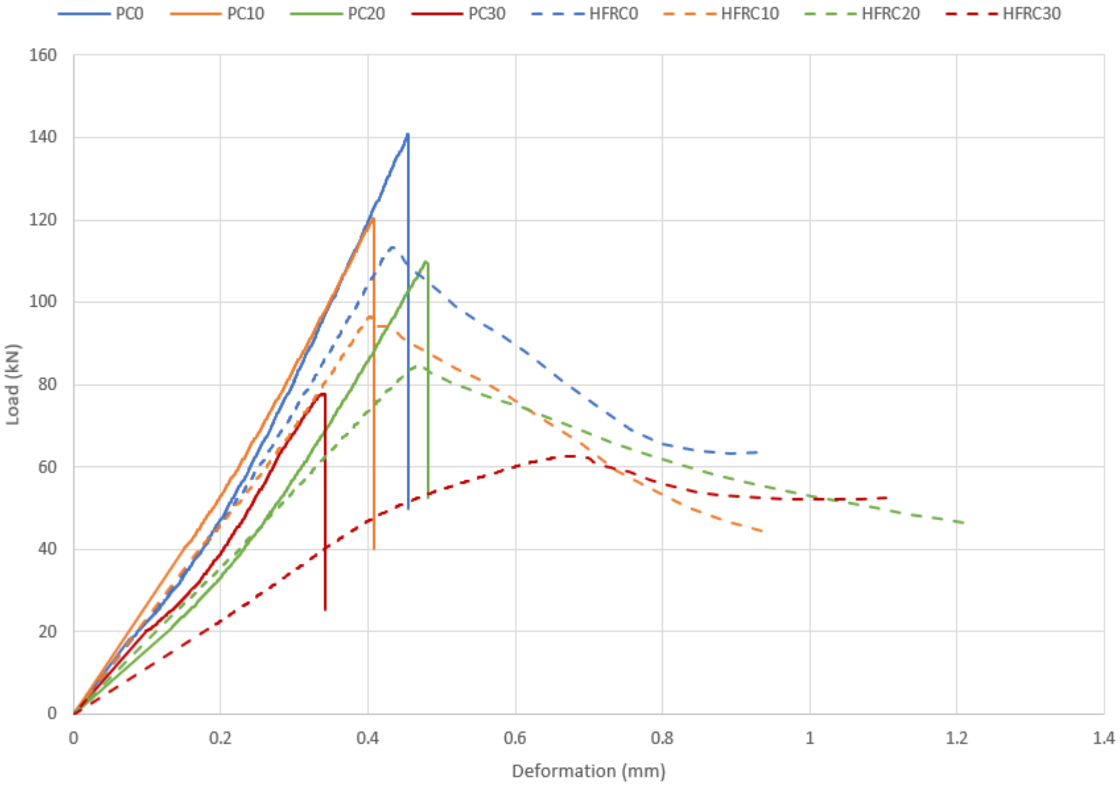

Figure 4.4: Splitting Tensile Behaviour of PC & HFRC at Zero, Ten, Twenty & Thirty Freeze-Thaw Cycles

For improved crack observation, real pictures are shown, as seen in Figure 4.5. Due to the strong grip of jute & nylon fibres with concrete, HFRC specimens have shown improved performance. All HFRC specimens are broken to examine the fibre-failure process. While approximately 50 percent of the fibres in concrete are removed, 50 percent of the fibres are broken down.

With more FT cycles applied to HFRC & PC specimens, crack propagation during mechanical testing increases which is seen from HFRC and PC samples' shown in Figure 4.5. From Table 4.4, it is evident that split tension strength decreases with increasing the number of FT cycles compared to the prior number of FT cycles of the same specimens. Under tensile loading, such kind of trend is seen in every PC and Hybrid Fiber Reinforced Concrete (HFRC) sample when comparing PC.

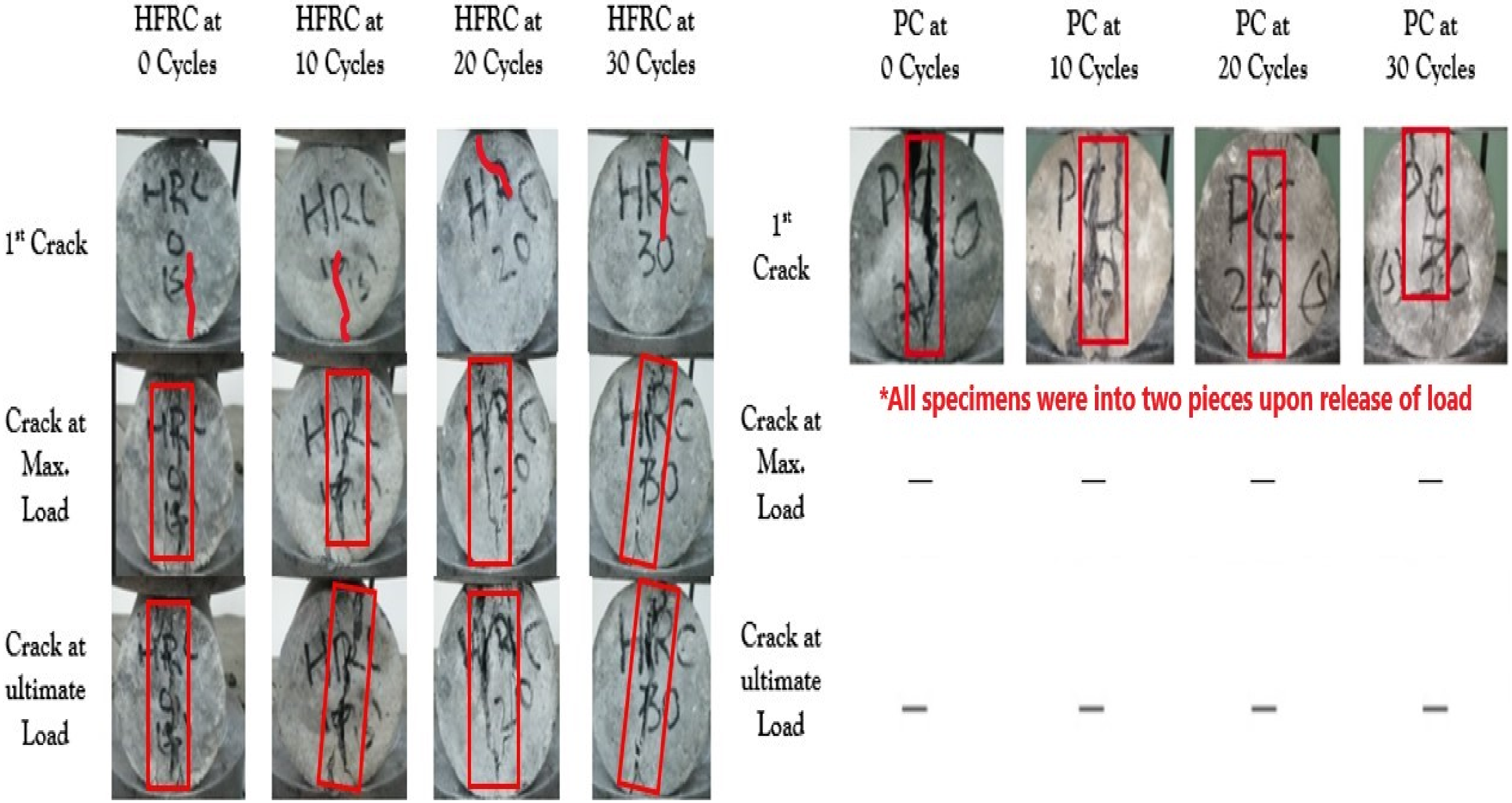

FIGURE 4.5: Crack Propagation during Mechanical Testing (Split Tensile)

specimens and HFRC specimens for split tensile strength.In comparison to plain concrete PC specimens under identical cycles of freeze and thaw cycles, HFRC specimens have greater split tensile strength.

Table 4.4: Splitting Tensile Strength Properties of PC and HFRC

Specimen	**Fst**	**Splitting Tension Energy Absorption**			**STI**
		SEp (up to Peak Load)	**SEp(Peak to Final Load)**	**STE**	
	(MPa)	**(J)**	**(J)**	**(J)**	
PC0	4.34	28.08	0	28.08	1
PC10	3.72	23.16	0	23.16	1
PC20	3.39	22.53	0	22.53	1
PC30	2.40	12.34	0	12.34	1
HFRC0	3.5	23.15	40.72	63.86	2.76
HFRC10	2.98	18.86	43.46	62.32	3.30
HFRC20	2.62	20.18	46.10	66.28	3.28
HFRC30	1.93	19.89	42.55	62.44	3.14

Note : For Splitting Tension Strength loading rate was 1.05MPa/Min as per ASTM standard C496/C496M-11 an average of min and max.

Because HFRC has absorbed more energy than plain concrete, it is substantially more resistant to early-stage micro-cracks in rigid pavement. Furthermore, when compared to PC specimens, HFRC specimens have absorbed much more higher energy. When HFRC0, HFRC10, HFRC20, and HFRC30 are compared to PC0, PC10, PC20, and PC30, there is an increase of 35.78J, 39.16J , 43.75J , and 50.10J, receptively, in Split Tensile Energy. It can be observed that PC specimens outperform in split tensile strength but the rate of increase of energy in HFRC as compared to PC is much higher. Whereas, for every HFRC and PC specimens, energy absorption diminishes as the cycles of freeze and thaw increases. Every HFRC Sample shows an increase in STI as compared to PC specimens.

4.4.3 Flexural Behavior and its Properties

Figure 4.6 displays the load-deflection curves for each PC and HFRC specimen after being put through flexural testing and cycles of freeze and thaw cycles. The PC curves at 0, 10, 20, 30 cycles show a peak load of 11kN, 10.6kN, 9.1kN and 7.6kN, respectively. Whereas, the HFRC curves shown by dotted lines show peak load value of 12.05kN, 11.2kN, 10.1kN and 8.48kN at 0, 10, 20 and 30 FT cycles. In PC curves, there is a sudden drop after attaining peak value which shows no energy absorption after peak load, whereas, in HFRC specimens, after attaining peak value the specimen tends to bear load due to fibers which shows energy absorption after peak loading. In HFRC specimens, the curves tend to move towards left side as the FT cycles propagates while the peak load value decreases. This shows the strength and energy absorption behaviour upon application of FT cycles.

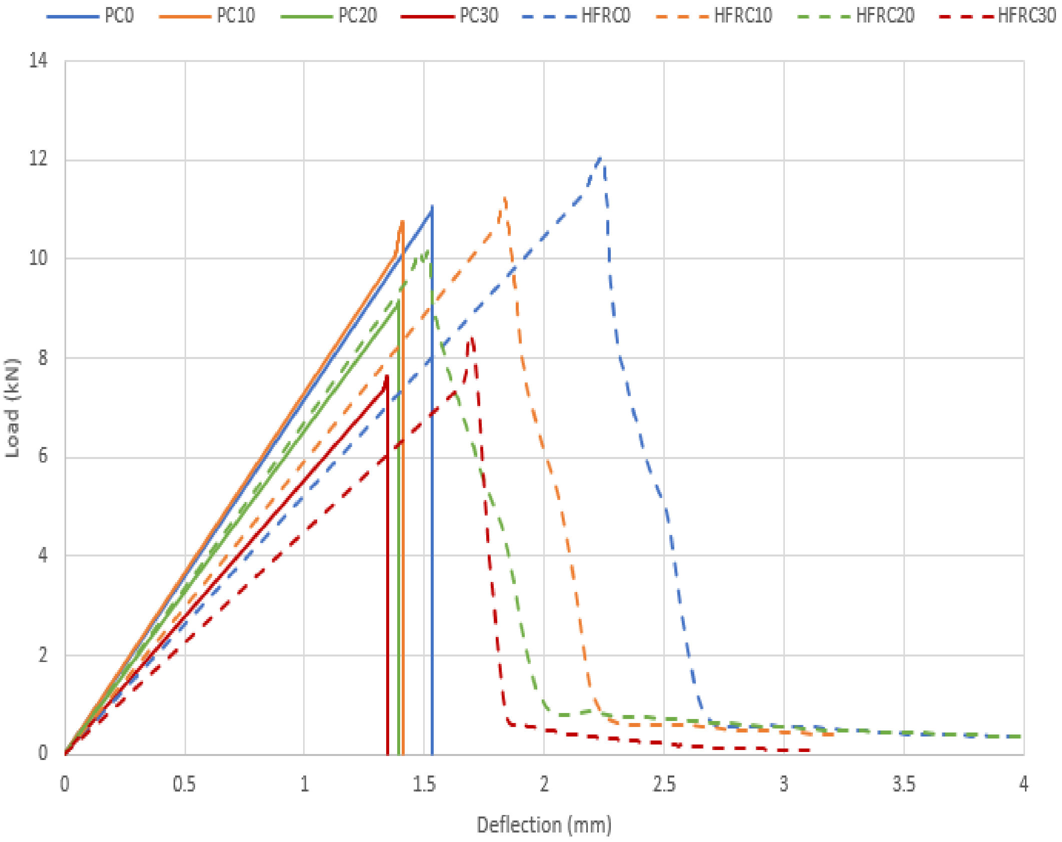

Figure 4.6: Flexural Behaviour of PC and HFRC at Zero, Ten, Twenty and Thirty Freeze-Thaw cycles

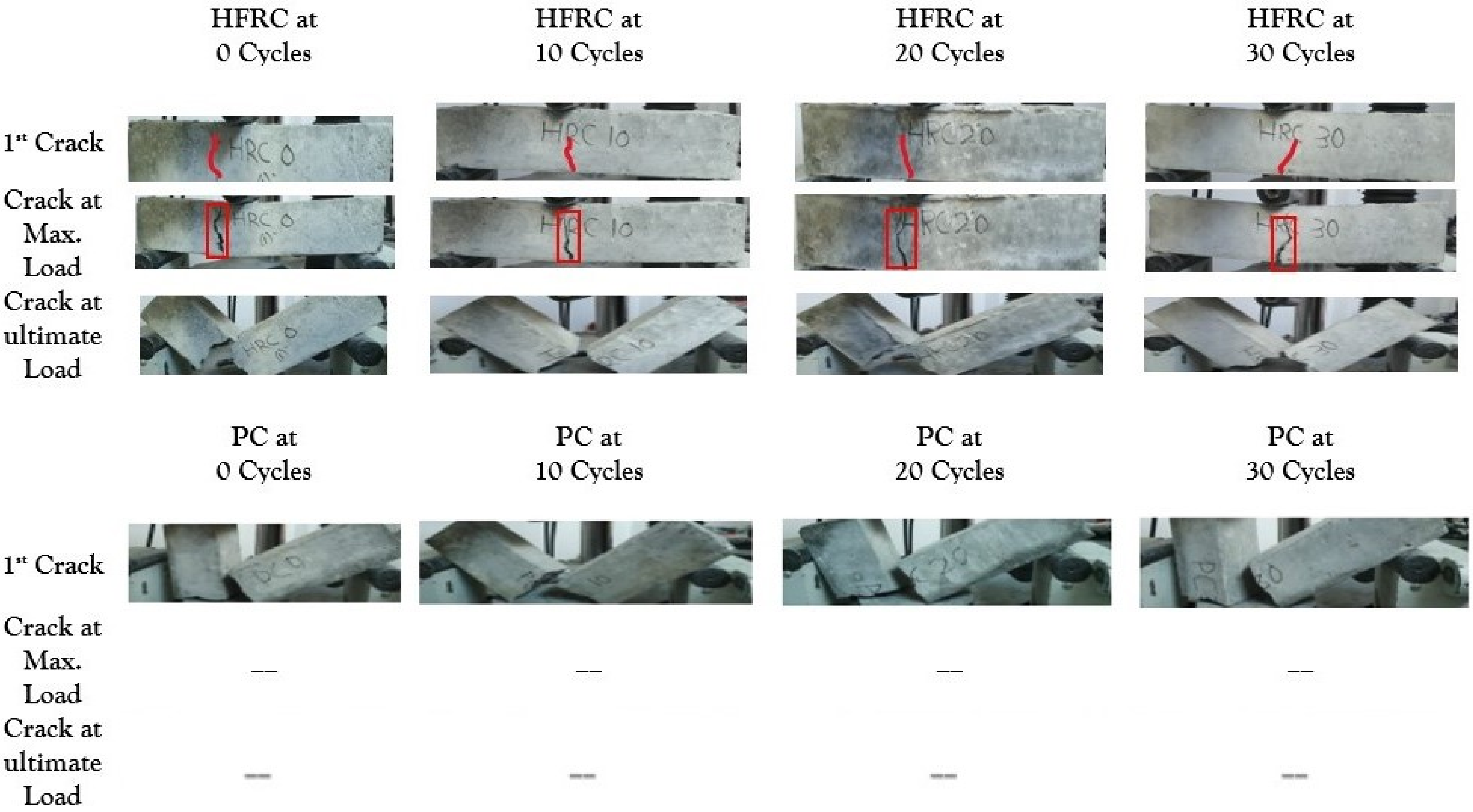

Figure 4.7: Crack Propagation during Mechanical Testing (Flexural)

Figure 4.7 depicts the cracks propagating under flexural pressure. First cracks are quite small in length and width in all HFRC specimens (HFRC0, HFRC10, HFRC20, and HFRC30) compared to all PC specimens' first cracks (PC0, PC10, PC20, and PC30). All PC specimens are split in half during peak loading. The size and length of cracks grow in HFRC specimens at peak loading as opposed to splitting into two pieces. However, all HFRC specimens are sound at maximum loading and crack widths widen. All HFRC specimens have connections between their top and bottom surfaces, as presented in Figure 4.7.

Table 4.5: Flexural Strength Properties of PC and HFRC

Specimen	**Sc**	**Max Deflection**	**Flexural Energy Absorption**			**FTI**
			FEp(up to Peak Load)	**FEp(Peak to Final Load)**	**FTE**	
	(MPa)	**(mm)**	**(J)**	**(J)**	**(J)**	
PC0	6.40	1.54	8.46	0	8.46	1
PC10	6.18	1.41	7.25	0	7.26	1
PC20	5.29	1.39	6.34	0	6.34	1
PC30	4.44	1.34	5.00	0	5.01	1
HFRC0	7.00	2.24	13.08	3.06	16.13	1.23
HFRC10	6.51	1.84	9.97	2.70	12.66	1.27
HFRC20	5.90	1.52	7.68	2.99	10.67	1.39
HFRC30	4.93	1.69	4.32	2.00	6.32	1.46

Note: For Flexural Strength test loading rate was 1.03MPa/min as per ASTM standard C78/C78M-15b an average of min and max.

For a better understanding of fracture propagation, real images of broken samples are shown. Because jute along with nylon fibres and concrete materials have a strong connection, HFRC specimens have performed better. All HFRC specimens are purposefully broken in order to examine the fibres' failure process. Concrete fibres break and are pulled out in a 50 : 50 ratio. With more cycles of freeze and thaw cycles applied to HFRC and PC specimens, crack propagation during mechanical testing also increases. That is evident from the figure 4.7 for HFRC and PC samples.

According to Table 4.5, flexural strength decreased as the number of cycles of FT cycles rose when compared to the prior number of FT cycles for the same specimen. Under flexural loading, such trend is seen in every PC and HFRC sample. HFRC samples outperform PC specimens when exposed to identical FT cycles. The peak load of HFRC is higher than that of PC due to the reinforcing fibers, which increase tensile strength, crack resistance and ductility. Furthermore, when compared to PC specimens, more energy is absorbed by HFRC samples. In HFRC(0, 10, 20, 30) the increase in FTE is 7.67 J, 5.4 J, 4.33 J, and 1.31 J, respectively, as compared to PC (0, 10, 20, 30). When compared to PC specimens, FTI of HFRC specimens is more prevalent, whereas FTI of PC specimens is equal to 1 because specimen is broken into two pieces at peak load. In flexural curves, HFRC demonstrates superior performance compared to PC due to its enhanced resistance to bending stresses as well as post cracking behaviour. The higher values or upward trends in the flexural strength of HFRC curves showcase its ability to endure bending loads more effectively than PC. This improvement is attributed to the reinforcing effects of the hybrid fibers, enhancing HFRC's ability to withstand flexural stresses and reduce the likelihood of cracking or failure under bending conditions. Hence, in this way HFRC is better than PC.

4.5 SEM Analysis

Figure 4.8 displays pictures of HFRC specimens that were mechanically loaded during failure tests. These photos are used to study the bonding between the fibres and the concrete matrix. The failure surfaces of the tested HFRC specimens following mechanical testing after the application of freeze-thaw cycles were analyzed through physical observance with naked eye. This physical analyzation demonstrated a strong connection between the fibres and the concrete matrix. There were incredibly few and tiny voids. Concrete broke and disintegrated into minute particles at the maximum load after mechanical testing. It was observed that the fibres holding the fractured concrete fragments together strongly suggested that the fibres and concrete composites have a strong bond.Upon visual observation of the broken samples, it is quite clear that almost 80% of the jute fibres from concrete have been pulled out whereas, most of the nylon fibers were broken. This may be due to the tensile strength of jute and nylon fiber i.e., 393 and 10.45 MPa, respectively [82, 83]. The fibres holding the fractured concrete fragments together suggest that the fibers and concrete composites have a strong bonding. Due to jute and nylon fibres, broken concrete composite pieces are joined together.

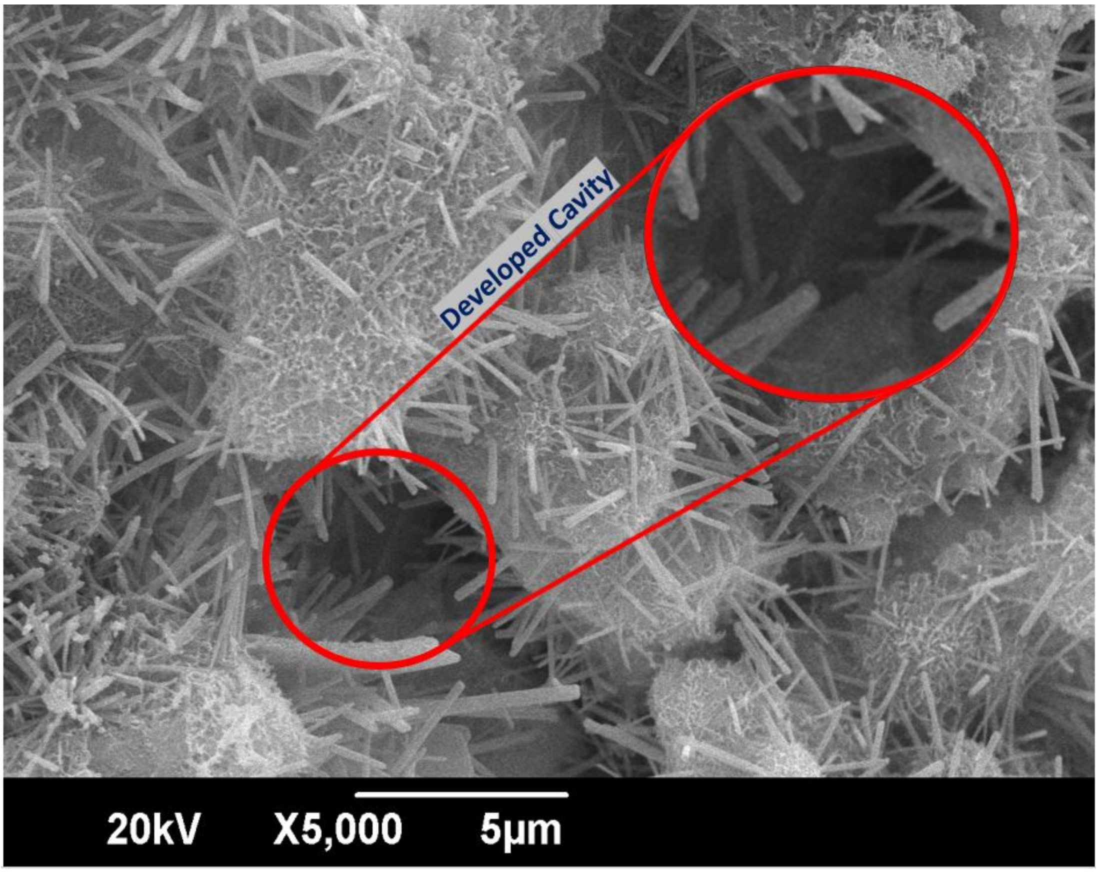

FIGURE 4.8: Image showing Fiber-Concrete Matrix at 5000x Zoom

Figure 4.9 fibre strength illustration makes it evident that even after applying cycles of freeze and thaw cycles ranging from 0 to 30, jute fibres continue to link and bridge with concrete particles. It is clear that even after the application of mechanical loading, the majority of fibres tend to draw away from the concrete rather than breaking apart. Following testing, pullout fibres are 50 mm long, the same length as when HFRC was being prepared. The fact that fibre-related voids are not significantly deeper is a sign of superior concrete mixing and fibre-to-concrete ingredient bonding. Figure 4.9 shows that after the application of mechanical loading, fibres pull away from the test specimens of HFRC and cavities are created. These photos also show that the fibres and concrete are properly bonded. Additionally, it is noted that the fibres and concrete ingredients are mixed uniformly.

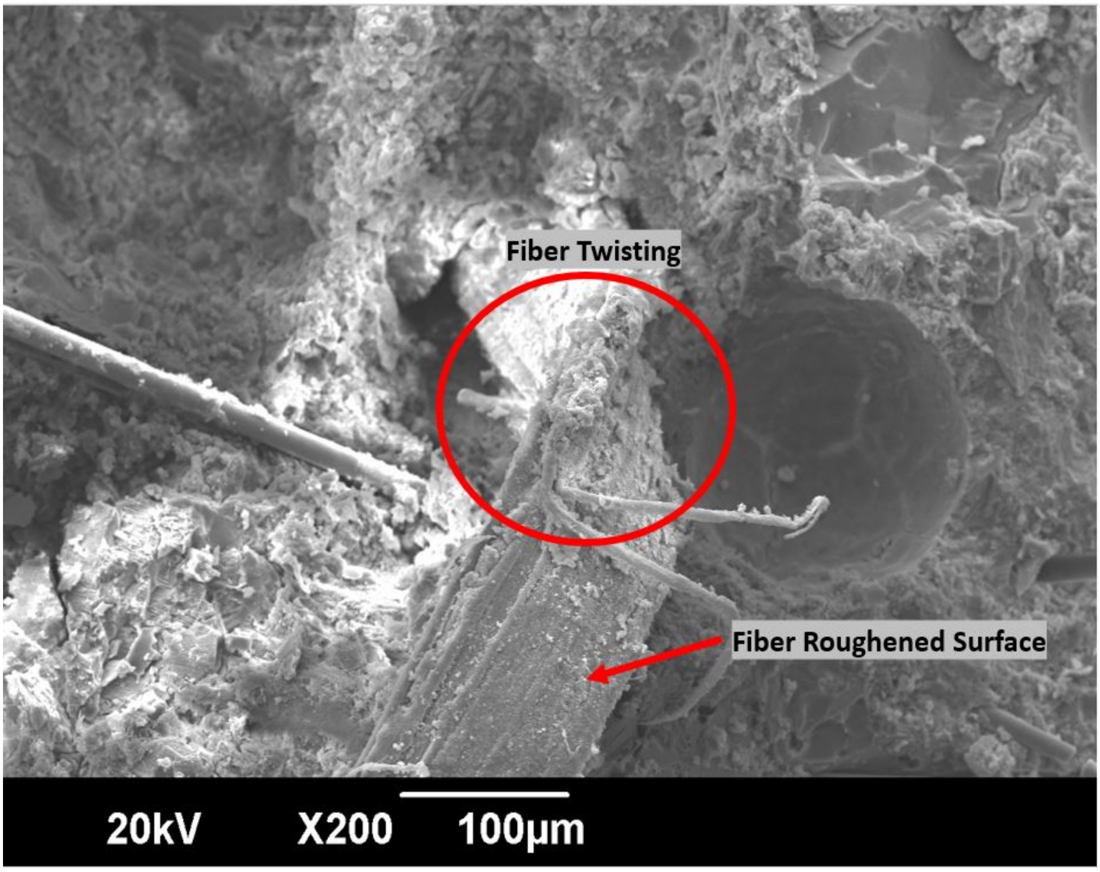

FIGURE 4.9: Image showing Fiber Failure Mechanism

4.6 Summary

In this chapter, dynamic properties and mechanical properties of both PC and HFRC samples are determined. To analyze the behavior of fibres in concrete, photographs of a few chosen HFRC specimens are taken while they are being mechanically loaded. Except for compressive strength, all mechanical parameters of HFRC compared to PC have increased. Whereas different trends in split tensile strength and flexural strength graphs during freeze-thaw cycles are influenced by the type of stress each test measures and the role of fiber reinforcement in crack control and stress distribution. Furthermore, Mass loss of HFRC is more as HFRC has jute and nylon fibers, in which jute fibers absorbs a lot of water while casting and curing as well. While the application of FT cycles on HFRC, mass of water is vaporized away which causes greater mass loss than PC but this mass loss is just due to water absorbed by Jute fibers whereas surface damage of PC samples was more upon application of FT cycles hence, PC cant be recommended over HFRC. As a result, it can be shown that HFRC's qualities are significantly better than PC's. Images demonstrate improved jute and nylon fibre with concrete matrix adhesion.

Chapter 5

Discussion

5.1 Background

Chapter 4 already provides an explanation of the results of testing on mechanical and dynamic properties. In comparison to PC, there has been a noticeable improvement in the HFRC's split tensile energy absorption, flexural strength, energy absorption, and relative dynamic modulus of elasticity (E_d). It is now time to establish a connection between mechanical properties, the percentage of mass loss, and the quantity of FT cycles.

5.2 Comparison of Properties

Seasonal temperature variations initiate concrete degradation and deterioration. Because oof this, changes in mechanical & physical behavior occur. Mass loss occurs as a result of deterioration. Whereas, the decision of recommending HFRC cannot be based on mass loss only. Properties like strength, energy absorption and modulus of rupture must be analyzed for recommending HFRC over PC or vice versa [80]. Because the bulk of the specimen is reduced, the mechanical properties are likewise altered. In compressive testing, no increase in strength is observed in HFRC; instead, a reduction in compressive strength was observed.

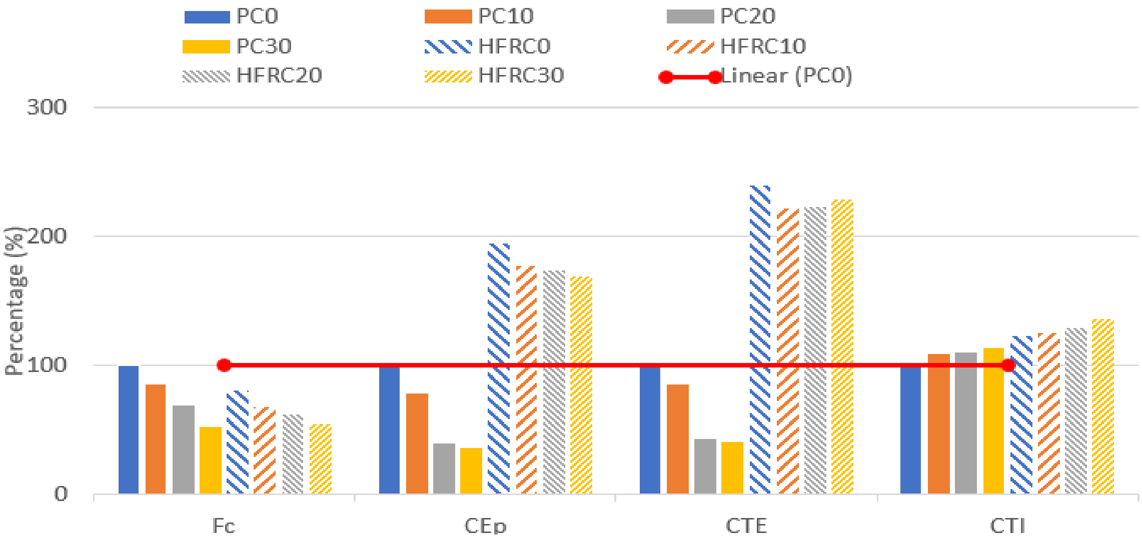

FIGURE 5.1: Comparision of Compression Properties of PC and HFRC

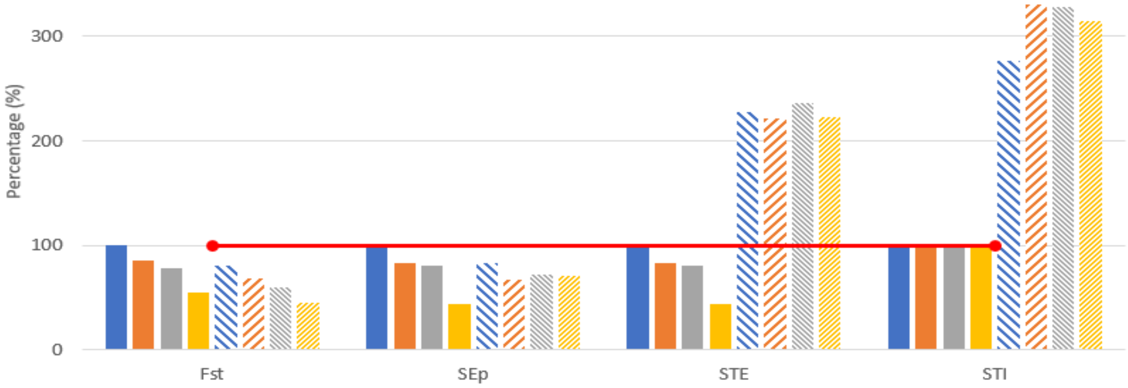

FIGURE 5.2: Comparision of Split Tensile Properties of PC and HFRC

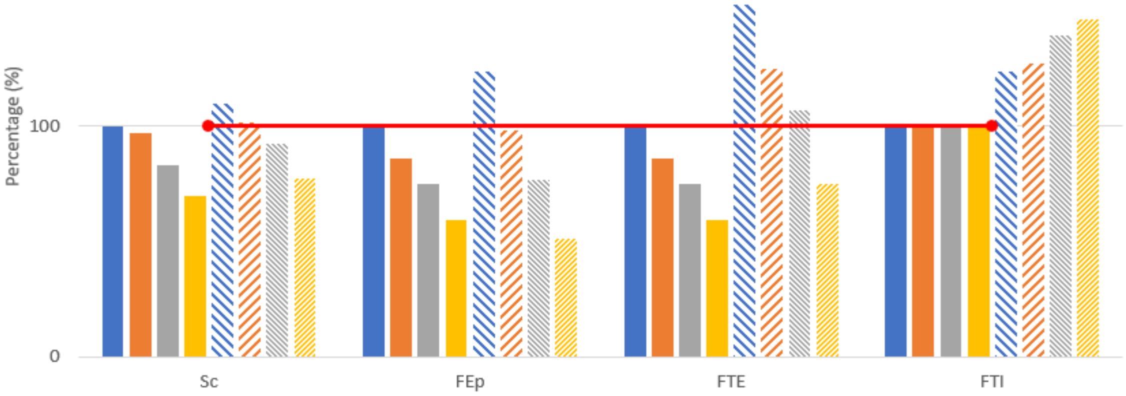

FIGURE 5.3: Comparison of Flexural Properties of PC and HFRC

The surface experience higher mass loss, while the presence of fibers potentially reinforces the inner concrete, core, contributing to enhanced toughness despite the overall decrease in compressive strength. Moreover, it's important to note that mass loss doesn't necessarily correlate directly with changes in flexural & split tensile strength, indicating the need for a further assessment of FT cycles on various mechanical properties. In Figure 5.1, the mechanical properties are compared. When comparing the impact of various freeze-thaw cycles on PC and HFRC specimens, the horizontal line in the bar graph that depicts PC's characteristics at 0 cycles is utilised as a reference.

Figure 5.1 compares and displays the f'c, CEp, CTE, and CTI values for each specimen of the HFRC and PC. Comparing HFRC0, HFRC10, HFRC20, and HFRC30 to PC0, PC10, PC20, and PC30, a reduction in compressive strength of 19 percent, 16 percent, 10 percent, and 3 percent is seen. According to other researchers [28], the use of natural fibres reduces the compressive strength of HFRC specimens. In comparison to PC0, PC10, PC20, and PC30, the CTE of HFRC0, HFRC10, and HFRC30 increased by 0.183, 0.179, 0.234, and 0.245 MJ/m$\hat{3}$, respectively. In comparison to PC0, PC10, PC20, and PC30, the CTI of HFRC0, HFRC10, and HFRC30 increased by 22.3 percent, 16.2 percent, 18.62 percent, and 22 percent. Because of the great strength of the jute fibres utilised, each HFRC specimen's ability to absorb energy is seen to be better than that of the corresponding PC specimen. Against their respective FT cycles, the CTI of HFRC specimens is higher than that of PC specimens.

Figure 5.2 compares and displays the fst, SEp, STE, and STI values of each specimen of HFRC and PC. In comparison to PC0, PC10, PC20, and PC30, the STE of HFRC0, HFRC10, and HFRC30 increased by 127, 140, 156, and 178 percent, respectively. In comparison to PC0, PC10, PC20, and PC30, the increase in STI for HFRC0, HFRC10, HFRC20, and HFRC30 is 176, 230, 228, and 213 percent, respectively. The findings show that HFRC specimens have absorbed more energy than their corresponding plain concrete specimens. While the STI for PC specimens is equal to one, it is larger for HFRC specimens. This is caused by the initial and peak crack loads existing in the same location. Fibers can therefore be used to verify improvements in crack-controlling mechanisms and energy absorption capacity.

Figure 5.3 compares and displays the Sc, FEp, FTE, and FTI values for each specimen of HFRC and PC. In comparison to PC0, PC10, PC20, and PC30, the FTE of HFRC0, HFRC10, HFRC20, and HFRC30 increased by 52.5 percent, 39 percent, 31.8 percent, and 16 percent, respectively. In comparison to PC0, PC10, PC20, and PC30, the FTI of HFRC0, HFRC10, HFRC20 and HFRC30 shows increases of 23.4 percent, 27 percent, 29 percent, and 46.5 percent. Comparing HFRC specimens to their respective PC specimens, an improvement in flexural characteristics is seen. Because the starting and peak crack loads are present at the same location, the FTI of HFRC specimens is greater than one, on the other hand the Flexural Toughness Index of every Plain Concrete sample is equal to one. Therefore, utilising the fibres in concrete is helpful.

5.3 Rigid Pavement Design and its Performance

Vehicles load on concrete road is encountered by the flexural stress of the concrete, and reinforcements are employed to prevent crack propagation. To calculate the thickness of a rigid pavement, the design example by Huang [43] is commonly utilized. According to Merritt et al. [44], the thickness of a rigid pavement is influenced by two parameters, namely the modulus of rupture (MoR) and modulus of elasticity (Ec), with all other parameters held constant. Delatte [45] states that the American Association of State Highway and Transportation Officials (AASHTO) suggests using compressive strength to calculate the modulus of elasticity due to its simplicity and reliability. However, it is essential to note that the modulus of elasticity is not the only factor that impacts rigid pavement performance. To calculate the thickness of a rigid pavement utilizing the Huang [43] method, a series of steps must be taken, including determining values for the design variables, computing the effective modulus of subgrade reaction, calculating critical stresses, determining slab thickness requirements, and verifying fatigue resistance.

The rigid pavement is not greatly affected by modulus of elasticity. As a result, each specimen's compressive strength is utilised to calculate its unique modulus of elasticity. With the exception of compressive strength, flexural strength, and elastic modulus as determined by [35, 36], all parameters in the Huang design example are the same as shown in Table 5.1 for PC and HFRC. The AASHTO equation is used to calculate the concrete pavement's thickness. Each specimen has a unique Elastic modulus, compression stress, and flexural strength. The thickness of rigid pavement necessary against each specimen is determined using the compression stress, flexural stress, and elastic modulus of each specimen as well as example values. Table 5.2 makes it evident that increasing the frequency of FT cycles likewise increases the concrete road thickness needed to withstand their effects. When compared to the corresponding HFRC specimens against the same freeze-thaw cycles, design thickness for PC specimens is higher.

TABLE 5.1: Design Parameters for 1998 AASHTO Rigid Pavement Design Model. [48]

Design Parameter	**Values**
ESAL (W18)	51,00,000
Reliability (R)	95%
Standard Deviation (So)	0.30
Elastic Modulus (Ec)	Variable (psi)
Modulus of Rupture (Sc)	Variable (psi)
Subgrade Reaction Modulus (K)	72 psi/in
Initial Serviceability (Pi)	4.2
Terminal Serviceability (Pt)	2.5
Drainage Coefficient (Cd)	1
Load Transfer Coefficient (J)	3.2

Due to HFRC's high value of MoR and lower values of E compared to the corresponding PC specimens under the same FT cycles, concrete road thickness is reduced for HFRC roads. The value of MoR is governing as compared to E in terms of reduction in pavement thickness [72]. For the same traffic loading, a 23%

Table 5.2: Thickness of Concrete Pavement Using AASHTO Design Equation

Samples	Modulus of Rupture (Sc) (MPa)	Compressive Strength(f'c) (MPa)	Elastic Modulus (Es) (MPa)	Thickness (h) (mm)
PC0	6.40	29.38	25475	200
PC10	6.18	25.01	23500	205
PC20	5.29	20.25	21150	225
PC30	4.44	15.53	18522	245
HFRC0	7.00	23.78	22919	195
HFRC10	6.51	19.92	20977	200
HFRC20	5.90	18.03	19957	210
HFRC30	4.93	16.02	18812	230
Huang[43]	4.51	53	34216	272

increase in PC pavement thickness is required to withstand the effects of thirty FT cycles. Whereas for HFRC, only 17 % thickness increase is required to counter the effects of 30 FT cycles. The road can support additional traffic loading if the thickness of the HFRC pavement is increased by 23 %. Additionally, fibres are utilised to enhance the behaviour of microcracks. According to Khan and Ali [30], fibres increased tensile strength. Each HFRC specimen has much higher tensile strength, energy absorption, and toughness index than PC. It improved the ductility, performance, and durability of concrete. concrete performs better over its lifetime and sustains fewer damages.

5.3.1 Pavement Age Prediction Against IRI

International Roughness Index (IRI) is a measure of pavement performance.Cyclic freezing and thawing processes result in the formation of cracks and uneven surfaces, ultimately increasing the IRI values. It basically quantifies the roughness of road surface as it is measured in m/km and gives a numerical value that represents the roughness of the pavement. Lower values of IRI represents a smoother road surface whereas a higher number indicates a rougher road surface.

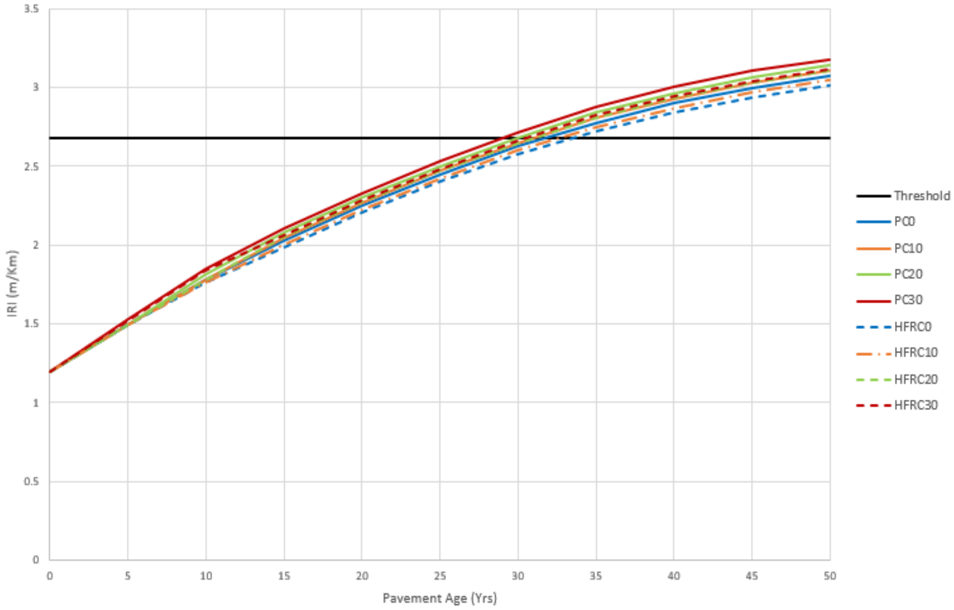

Figure 5.4: Pavement Age Threshold against IRI

In figure 5.4, International Roughness Index (IRI) against Pavement age has been shown for PC0, PC10, PC20, PC30, HFRC0, HFRC10, HFRC20 and HFRC30 as designed in AASHTOware using the mechanistic empirical pavement design approach. The black line is the threshold value as given by AASHTO [47]. It can be seen that performance of HFRC is better as it achieves the threshold value of 2.68m/km later whereas the PC specimens reach this value of IRI early.On comparing PC and HFRC at 0, 10, 20, and 30 cycles, it can be seen that HFRC is reaching the threshold value lately, hence increasing the predicted age of pavement by 6.25%, 4.76%, 3.28% and 5.8%, respectively. This trend is seen due to the damage of FT cycles to samples of PC and resistance by utilization of fibers.

5.3.2 Pavement Age Prediction Against Faulting

Faulting in rigid pavements is another measure of its performance. It is also a quantitative indicator for pavement performance as it is measured in milimeters for the vertical difference between adjacent slabs. A value of 3mm is considered to be the threshold value for faulting. Higher values of faulting indicates poor performance of pavement wheras lesser numbers indicated good performance of pavement. Freeze-thaw cycles can significantly impact faulting in rigid pavement.

As moisture seeps into cracks and joints within the pavement, it can freeze during cold weather, causing the underlying soil to expand and exert increased pressure on the pavement slabs. This added pressure can exacerbate faulting by pushing and tilting adjacent slabs, resulting in more pronounced vertical displacement. Over time, this dual action of Freeze-Thaw cycles and faulting can lead to a more uneven and deteriorated pavement surface, diminishing ride quality and posing structural concerns.A value of 3mm is considered to be the threshold value for faulting.

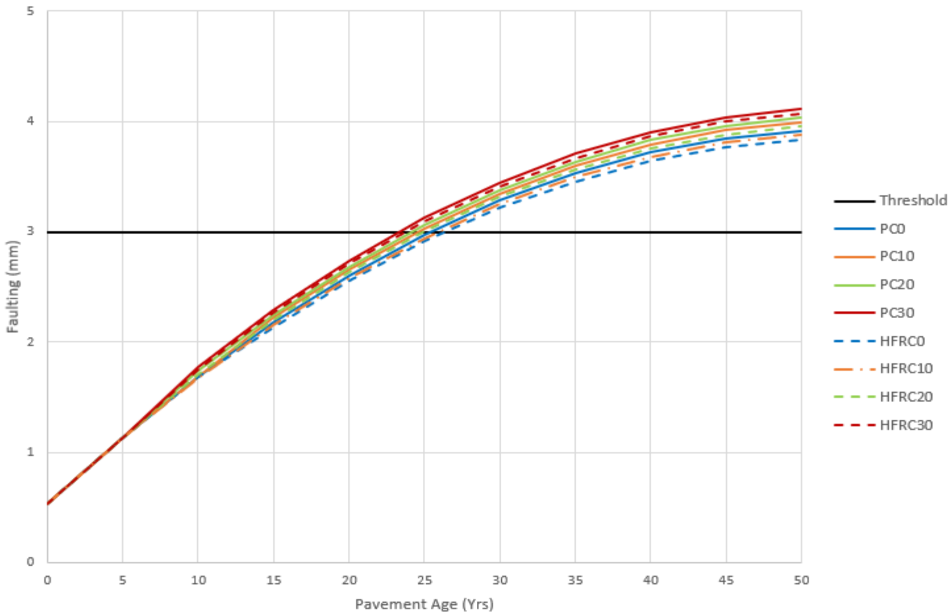

Figure 5.5: Pavement Age Threshold against Faulting

Figure 5.5, shows and displays faulting in rigid pavement against Pavement age for PC0, PC10, PC20, PC30 and HFRC0, HFRC10, HFRC20, HFRC30 as designed in AASHTOware using the mechanistic empirical pavement design approach. The black line is the threshold value as given by AASHTO [47]. The performance of HFRC appears superior since it attains the threshold faulting value of 3mm at a later stage, while the Pavement Concrete (PC) specimens reach this value earlier. But the difference in case of IRI, this difference is lower. On comparing PC and HFRC at 0, 10, 20, and 30 cycles, it can be seen that HFRC is reaching the threshold value lately, hence increasing the predicted age of pavement by 3.7%, 4.6%, 2.5% and 1.3%, respectively. This trend is seen as fibers have not affected the pavement age whereas increasing number of freeze-thaw cycles decrease the percentage difference.

5.4 Utilizing Research Findings in Practical Applications

The utilization of fibers and admixtures in concrete manufacturing proves to be both cost-effective and environmentally friendly. As discussed in previous chapters, Hybrid Fiber Reinforced Concrete (HFRC) exhibits superior mechanical and dynamic characteristics. Notably, HFRC is intended to demonstrate enhanced values in parameters such as toughness index, damping ratio, elastic modulus, and relative dynamic modulus compared to other PC samples. The incorporation of hybrid fibers encourage a strong bond between the concrete mix and fibers, resulting in improved impact-bearing capacity. Furthermore, the use of nylon and jute fibers contributes to the increased resilience of concrete, preventing cracking and spalling. Structural integrity is primarily associated with the inner core of the concrete. Higher mass loss in HFRC might raise concerns, but decision should not rely solely on this factor. Despite elevated mass loss, HFRC offers advantages like increased toughness, energy absorption and modulus of rupture [80]. Evaluating suitability should encompass various properties beyond mass loss for a comprehensive decision. As a conclusion, it can be shown that HFRC's properties are significantly better than PCs in rest of the factors.

Cracking in PC is caused by its brittle nature. When concrete structures experience differential settlement, bending stresses occur, leading to the formation of cracks. To minimize cracking resulting from differential settlement, it is crucial and important to improve the flexural strength of concrete. Moreover, the natural brittleness of concrete contributes to cracking in various concrete structures. To address this issue, it is necessary to enhance the concrete's capacity to absorb energy and its toughness, changing it from being brittle to having the toughness characteristic of FRC. In our current research, we are conducting experiments to investigate how PC and HFRC behave as potential solutions for controlling concrete cracking and spalling due to freezing and thawing cycles. Providing jute and nylon fibers in equal amounts into the concrete lead to an improvement in the flexural strength, energy absorption along with other parameters of concrete.

5.5 Summary

It has been determined how concrete characteristics and cracking relate to one another. The chapter covered the influence of hybrid fibers and their influence on the characteristics of concrete. Higher mass loss is observed in HFRC, but mass loss in concrete due to freeze-thaw cycles does not necessarily dictate its ability to withstand traffic loading (i.e. pavement design). Rather, MoR and E are contributing in design. While mass loss might indicate surface deterioration. Even with surface deterioration, the concrete's core structural properties are quite reasonable. The findings reported here demonstrated that HFRC can more effectively suppress cracking in Concrete pavements than plain concrete Pavement. The Incorporation of fiber in concrete resulted it in a high pre and post-crack energy absorption rate. Hence, it is concluded that further studies are required to assess the long term durability of jute and nylon fibers on increased number of cycles of freeze and thaw, whereas as per current research Rigid Pavement with HFRC can be recommended as an effective solution to the Freeze and thaw associated issues.

Chapter 6

Conclusions and Recomendations for Future-Work

6.1 Conclusion

For the case of concrete pavements against 10, 20, and 30 cycles of freezing and thawing, PC and HFRC specimens are studied. In concrete, jute and nylon fibres in equal amounts are added at a 5 percent by total mass of cement with a 50 mm (2in) length. The thickness of the road pavement is determined from the PC and HFRC data in order to compare the results. The key findings are as follows:

- In HFRC specimens compared to PC specimens, there is a greater percentage of mass loss that ranges from 0.55 percent to 1.93 percent. Hence, this can be linked with short term durability.
- The relative dynamic modulus of elasticity of HFRC decreases slowly than that of PC, so it can withstand more freeze and thaw cycles effectively. In case of beams, PC30 have a drop of 1.48 percent whereas HFRC30 dropped only 0.79 percent.
- Varying influence of freeze and thaw cycles was observed on mechanical properties of PC and HFRC specimens. With more freeze and thaw cycles, mechanical properties of both PC and HFRC decrease.

(a) Compressive Strength at 0 cycles was compromised with the use of fibers but the rate of compressive strength loss in HFRC samples was much slower than in PC samples on 10, 20 and 30 FT cycles.A decrease of 19 percent was observed in HFRC samples.

(b) Split Tensile Strength at 0 cycles was also less in HFRC samples as compared to PC samples Where as the total energy absorption was significantly increased. An increase of 47 J was observed in case of HFRC at 30 cycles.

(c) Flexural Strength of HFRC specimens increased by upto 9.3 percent when compared to PC specimens. Energy absorption was also increased in HFRC specimens.

- In SEM analysis of damaged samples subjected mechanical testing, there is still bonding between fibers and the components of concrete. Cavities have been developed due to pull out of fibers. Twisting effect of fibers was also observed in the SEM images
- On comparing the overall properties of PC and HFRC specimens, it was observed that the energy absorption of all the HFRC specimens have significantly increased whereas strength was increased in case of flexure and reduced in compression & split.
- To withstand the effects of 30 cycles of freeze-thaw, pavement thickness must increase by 23 percent in the case of PC. While utilizing HFRC calls for an up to 17 percent increase in rigid pavement thickness.
- With more and more cycles of freeze and thaw more cracks were observed but overall HFRC specimens performed better as the size of cracks were smaller and lesser.

Based on these findings and the outcomes, concrete pavements can be constructed more affordably and effectively by mixing equal amounts of jute and nylon as hybrid fibres into concrete for construction of rigid pavement.

6.2 Future Work

The recommendations for the future work are as follows:

- Jute and nylon as hybrid fibres long-term durability in concrete must be investigated with variations in content and length of both fibers.
- Finite Element modelling can be helpful to validate the results in order to develop prototypes of such pavements.
- Decay of both jute and nylon fibers should be explored in concrete mix to assess its performance under different environmental conditions.
- Impact of freeze-thaw should be at higher number of freeze-thaw cycles to assess true behaviour against real scenarios.

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