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Mechanical, Dynamic and Absorption Properties of Hybrid Fiber Reinforced Concrete for Rigid Pavements Application

by

Kaynat Arooj

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This effort is dedicated to my respected and affectionate parents, who helped me through all difficult times of my life, always prayed for my achievements, sacrificed all the comforts of their lives for my bright future and blessed me with their ethical support at all times. This is also a tribute to my honorable teachers who guided me to face the challenges of life with patience and courage, and who made me what I am today.

CERTIFICATE OF APPROVAL

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Kaynat Arooj

(MCE193029)

THESIS EXAMINING COMMITTEE

S. No.	Examiner	Name	Organization
(a)	External Examiner	Engr. Dr. Faisal Shabbir	UET, Taxila
(b)	Internal Examiner	Engr. Dr. Ishtiaq Hassan	CUST, Islamabad
(c)	Supervisor	Engr. Prof. Dr. Majid Ali	CUST, Islamabad

Engr. Prof. Dr. Majid Ali
Thesis Supervisor
February, 2021

Dr. Engr. Ishtiaq Hassan
Head
Dept. of Civil Engineering
February, 2021

Dr. Imtiaz Ahmad Taj
Dean
Faculty of Engineering
February, 2021

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(Kaynat Arooj)

Registration No: MCE193029

Abstract

Conventional concrete pavements are frequently recommended because of their relatively long service life compared to flexible pavements. But micro shrinkage cracking is usually observed in normal concrete. This just leads to start of deterioration of pavement from the very early age, thus affecting its intended functionality. Natural fibers are more popular due to their low cost, least hazardous, easy handling and their abundant availability. Hybrid natural fiber reinforced concrete (HNFRC) can help to improve the properties of concrete in different ways by using two different types of fibers with different properties, resulting in minimizing the micro-cracking to a large extend. Fibers like; Jute have the tendency to improve the performance of concrete in terms of energy absorption while, wheat straw are good in energy absorption and possess good tensile strength. The overall aim of this research is to provide sustainable, economical and eco-friendly solution to reduce cracks that on later stages appear in form of large cracks and thus, affect the performance of concrete pavements. Many types of fibers (e.g. steel and artificial fibers) have already been investigated by many researchers for concrete pavements. To the best of authors knowledge, natural fibers are rarely studied for such applications.

Keeping in mind this aspect of natural fibers, the current study is conducted to evaluate the mechanical, dynamic, water absorption, linear shrinkage and mass loss properties of HNFRC, using wheat straw and jute fiber with constant fiber length (jute=50mm and wheat straw=25mm), but varying fiber content in concrete mix. Fiber evaluation through micro-structural analysis has been conducted. To study the influence of jute and wheat straw in improving the properties of concrete, the properties of Plain Concrete (PC) are taken as reference. Mechanical properties, dynamic properties, water absorption and mass loss are determined experimentally. Treated natural fibers (wheat straws and jute) having fiber content of 5% by cement mass are considered. A total number of 36 specimens are prepared with same fiber length of but varying content of both fibers. Thus, composites studied are as C1, C2, C3, C4 and C5. The mix design ratio of both PC and HNFRC is 1:

2: 3 (cement: sand: aggregate) is used for specimen casting. Water cement ratio for PC, C1, C2, C3, C4 and C5 are taken as 0.7. Micro-structural analysis of jute and wheat straw to explore its bond with concrete is also performed.

The obtained results thus show an increase in compressive energy absorbed, splitting tensile strength and flexural strength of HNFRCs. An increase in dynamic properties of properties of concrete is observed. Empirical relation is developed between linear shrinkage and fiber content ratio in HNFRC using experimental data of linear shrinkage and fiber content ratio in concrete. The relation between L/S and fibers content ratio and each of the CS, SS, SPE, and FPE are made because of their observed mutual coherence in experimental outcomes. A good relation between experimental and empirical values is observed. Among the tested HNFRCs, C1, C2 and C3 showed the improved performance. This will help to reduce the rate of cracking in rigid pavement, hence improving its performance. A detailed research program is needed to investigate other aspects of jute fiber and wheat straw hybrid natural fiber reinforced concrete such as durability for commercial implementation in construction industry.

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Abbreviations

CCE	Compressive energy absorption from peak load to final load
CPE	Compressive energy absorption up to a peak load
CS	Compressive strength
CTE	Compressive total energy absorption
CTI	Compressive toughness index
C1	JF=0.5; WS=4.5
C2	JF=1.5; WS=3.5
C3	JF=2.5; WS=2.5
C4	JF=3.5; WS=1.5
C5	JF=4.5; WS=0.5
Ec	Elasticity modulus
Edynamic	Dynamic modulus of elasticity
FCE	Flexural energy absorption from peak load to finale load
FPE	Flexural energy absorption up to a peak load
FS	Flexural strength
FTE	Flexural total energy absorption
FTI	Flexural toughness index
HNFRC	Hybrid natural reinforced concrete
JF	Jute
kN	Kilo Newton
L/S	Linear shrinkage
ML	Mass loss
mm	Milli meter
MPa	Mega Pascal

PC	Plain concrete
RFl	Longitudinal Frequency
RFt	Transverse Frequency
RFr	Torsional Frequency
SCE	Split energy absorption from peak load to final load
SEM	Scanning electron microscope
SPE	Split energy absorption up to a peak load
SS	Split-tensile strength
STE	Split total energy absorption
STI	Split toughness index
STM	Servo hydraulic testing machine
STS	Split tensile strength
W/A	Water absorption
W/c	Water cement ratio
WS	Wheat straw

Symbols

ε_o	Strain at Peak Load
Δ	Deformation / Deflection
ξ	Damping Ratio

Chapter 1

Introduction

1.1 Background

Rigid pavements are preferred over flexible pavements, due to their better functionality and ability to carry heavy loads. But the problems, like cracking [1] and faulting due to environmental issues and loading [2] reduce the functionality of concrete pavements [3]. Concrete being weak in tension, fail under heavy traffic loading, specifically for rigid pavements. Flexural strength property plays an important role in rigid pavement to resist faulting under cyclic loading. The flexural strength of concrete can be enhanced by the addition of fibers, it also avoid the large thickness requirement in pavement [4]. Addition of fibers results in increase in flexural, impact and that of tensile strength property of concrete [5]. Studies revealed the improvement in toughness and that of crack resistance properties of concrete, by adding fibers in it [6-10].

Addition of fibers improves mechanical as well as durability properties of concrete [11-13]. The bonding mechanism between fiber-matrix and the multi-directional fiber reinforcement cause reduction in volumetric changes, hence results in increasing durability. Fibers also enhance the durability of concrete by preventing or minimizing the deterioration rate in concrete [14-17]. Studies have been conducting on utilization of natural fibers in civil engineering applications. Researches on natural fibers for rigid pavement applications are available with very limited scope [18]. Literature proved that natural fibers can be used as construction material. Though, studies on its practical implementation for large scale purposes are still need to be done [19]. This will paid the path towards economical construction of rigid pavements which is significant for under-developing countries. Hence, addition of fibers can enhance the properties of concrete and performance of structure.

1.2 Research Motivation and Problem Statement

Roads are an important and economical source of transportation around the world. Construction of roads requires a major portion of annual budget. Although, the construction cost of rigid pavements is not much, but their repair cost is relatively high. These problems are mainly caused by initial cracking which results in major cracks and potholes at later stages. Thus the problem statement is as follows:

"In concrete mix the process of volumetric changes and drying shrinkage results in micro- cracks. The main reason for volumetric changes is evaporation from surface of concrete and it is common in structures exposed to environmental conditions. This phenomenon results in increase in tensile stresses more than the tensile strength of concrete. If these micro- cracks are not controlled at their initial stage, can cause failure of structure".

1.2.1 Research Questions

Following research questions will be addressed:

- How much tensile/ flexural strength can be increased with how much compromise on compressive strength?
- How much damping can be enhanced?
- Is there any issue in bonding for using hybrid natural fibers in concrete?

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

The overall aim of the research program is to have sustainable and economical rigid pavements, by utilizing locally available natural fibers which have potential to be used as construction material.

"The specific aim of MS thesis research program is to investigate the mechanical, dynamic, mass loss, linear shrinkage and water absorption properties of hybrid fiber reinforced concrete for possibility of rigid pavement applications".

1.4 Scope of Work and Study Limitation

Mechanical, dynamic, mass loss, linear shrinkage and water absorption properties for all type of concrete mix is investigated by taking the average of 2 specimens. The fibers are used with constant length but different content. Dynamic properties are investigated before testing the specimen for mechanical properties. In case of determining mechanical properties, failure is considered when the first crack appears on the specimen after applying the load. SEM is also be performed for both fibers, while SEM is performed for fiber-matrix bond investigation. To develop the empirical relation. Study is limited to mechanical, dynamic, mass loss, linear shrinkage and water absorption properties of hybrid fiber reinforced concrete. Durability of hybrid fiber reinforced concrete is not included in scope. Only fiber of specific region is considered.

1.4.1 Rationale Behind Variable Selection

Fibers are selected based on their local availability and best physical properties among other fibers. Different length of fibers will help to tackle both small and large cracks. While, w/c ration of 0.7% will help to hydrate both fibers and material properly.

1.5 Research Novelty and Research Significance

Patel and Patel [20] determine the mechanical properties of concrete by adding jute fiber in it, the study showed the improvement in mechanical properties of concrete. Farooqi and Ali [21] investigated the reduction in cracks for rigid pavement application, by in-cooperating wheat straw fiber in concrete. Study revealed the effect of wheat straw fiber on improvement of splitting tensile strength index (STI) of concrete. Previous studies conducted on jute fiber and wheat straw shows their potential to improve the properties of concrete, and performance of structure. To the best of authors knowledge, no research has been conducted on utilizing jute and wheat straw as hybrid fiber reinforced concrete (HNFRC) specifically for rigid pavement application. Thus, the current study is aimed to study the basic mechanical, dynamic, mass loss, linear shrinkage and water absorption properties of HNFRC using jute and wheat straw.

Construction industry has a significant impact on environmental pollution. It is the need of time to search new building material with properties to overcome the issues related to material waste in construction industry [22]. Fibers in concrete are used to control cracking; however a single fiber with same length cannot do it effectively [23, 24]. The multi-level cracking in concrete can be controlled by utilizing same or two different types of fibers with different length, size, proportions and properties [25]. Therefore, utilization of two various types of fibers with different lengths as hybrid fiber are way better. The presence of two different lengths of fibers will help to entertain cracks at different levels. The post-peak behavior of stress-strain curve is taken as an important requirement for determining the structural performance.

1.6 Brief Methodology

In this study, the Mechanical, dynamic, mass loss, linear shrinkage and water absorption properties of plain concrete (PC) and hybrid natural fiber reinforced concrete (HNFRC) are examined. The fiber used in this specific study includes wheat straw and jute fiber. The HNFRC is prepared with same fiber length (50 mm and 25mm; for jute and wheat straw, respectively) and variation in fiber content. The mix design ratio for PC and HNFRC is 1:2:3 (cement: sand: aggregate), with w/c ratio of 0.7%. The fibers of jute and wheat straw are added in concrete mixer for the production of HNFRC, according to their content percentage. For production of each type of HNFRC, fibers with total 5% contents by mass of cement are added in concrete with their specific content in respective specimen. The workability of concrete mixes of PC and HNFRCs is computed in fresh state by using the standard procedure of slump cone test. Standard specimens are casted and tested according to ASTM standards.

1.7 Thesis Outline

The thesis contains six chapters. These are:

Chapter 1 includes of introduction. It explains the Background, research motivation and problem statement, overall and specific research aims, scope of work with study limitations, investigation methodology, and thesis outline.

Chapter 2 contains the literature review. It comprises of background, flaws in rigid pavements, governing properties of concrete and their contribution towards pavement performance, durability considerations and design considerations, effectiveness of fiber incorporation for improvement in its properties and summary.

Chapter 3 incorporates the testing methodology. It covers the background, raw materials, fiber treatment, the techniques of PC and HNFRCs mixing and casting, specimen details, testing methodologies, and summary of chapter 3.

Chapter 4 encompasses the results obtained from tests and their analysis. It describes the background, material-properties of the mixes (i.e. PC and HNFRC), mechanical properties (CS, SS, and FS), dynamic properties (E, G, f, and) ML, LS, WA, and behavior of the specimens during the testing, and summary.

Chapter 5 consists of discussion. It consists of background, empirical equations between the linear shrinkage and fiber content ratio of concrete in controlling the rate of cracking in concrete rigid pavements, bond mechanism between fibers and concrete mix, its practical implementation and summary of chapter 5.

Chapter 6 comprises of conclusions and recommendations. Consecutive to the end of chapter 6, all the references are given.

Annexure A explains the details of compressive load-time, splitting-tensile load-time and flexural load-time curves, behavior of tested specimens during the respective loading and the fibers bonding in concrete mix.

Chapter 2

Literature Review

2.1 Background

Rigid pavements are more often recommended over flexible pavements due to their load carrying capacity and serviceability. But their serviceability suffers some major issues, like cracking. The increasing rate of cracking reduces the performance efficiency of rigid pavements. Improvement in mechanical properties (CS, STS and FS) can significantly reduce the cracking. Fibers are being used as an additive in concrete to improve its mechanical properties. Addition of fibers also results in enhanced dynamic properties of concrete against vibration effects. Utilization of natural fibers as construction material is need of time due to their cheap, environmental friendly and local availability. Jute and wheat straw fibers are among locally and abundantly available natural fibers in Asian countries as a crop by-product. Studies have been conducted to evaluate the mechanical properties of jute fiber reinforced concrete and wheat straw fiber reinforced concrete for different civil engineering applications. However, in depth knowledge of mechanical, dynamic, mass loss and shrinkage behavior of HNFRC using jute and wheat is important for its practical implementation in rigid pavements. To the best of authors knowledge, studies on HNFRC using varying content of jute fiber and wheat straw are not conducted up till now.

2.2 Flaws in Rigid Pavements and Its Remedial Solution

The use of rigid pavements has been grown in developing countries over past few years, due to their serviceability [26]. Rigid pavements also offer durability to structural performance [27]. However, the wide use of rigid pavement is still prevented, because of its high construction cost. While, plain concrete being brittle in nature offers low strain capacity as well as low tensile strength. Therefore, rigid pavements often experience fatigue failure due to their exposed surface to environment, which results from combined effects of temperature curl, drying shrinkage, volumetric changes and that of temperature gradient [28]. Rigid pavements with various advantages also have some major drawbacks. If the water cement ratio of concrete is less than the value of 0.40, this value of water will not be enough to completely hydrate the concrete particles [29].The dehydration of concrete particles cause increase in shrinkage phenomenon, which increases the rate of cracking [30]. Figure 2.1 shows the observed cracks in concrete pavement.

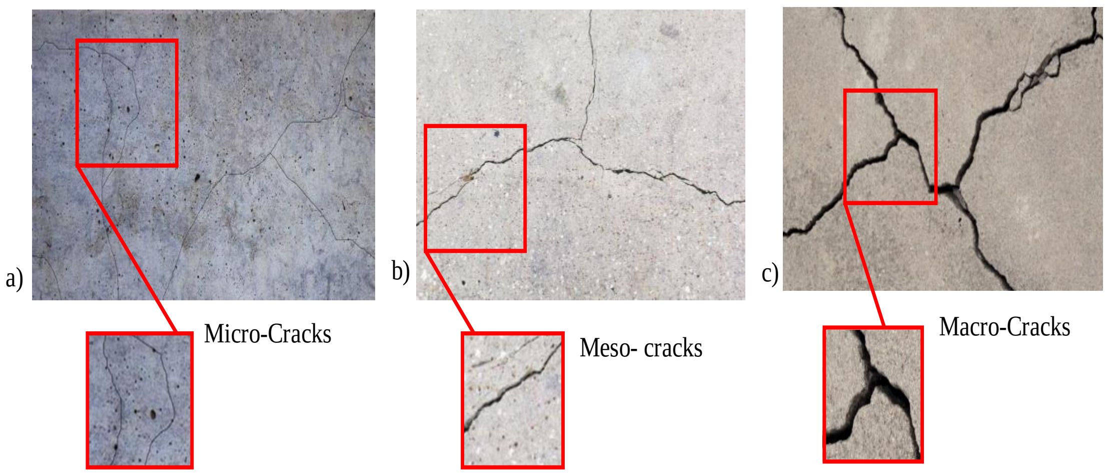

FIGURE 2.1: Observed cracks in rigid pavement; a) micro-cracks, b) meso-cracks, c) macro-cracks [31]

Concrete structure, especially rigid pavements during their long service life suffer from various damages, these damages require repair and maintenance. During the process of drying shrinkage, volumetric changes take place which results in form of micro-cracks even before applying load on structure [32]. Change in volume take place due to the process of evaporation from the surface of concrete [33]. This issue is more common in structures open to environment, which leads to further structural failure [34]. This is a serious point of concern during changing weather conditions [35]. This results in increased tensile stresses as compared to tensile strength of concrete [36]. The repairs of such damages require a high amount and time [37]. The structure after repair also undergoes to some failures due to differential shrinkage, between repaired material and that of concrete substrate. The phenomenon of differential shrinkage can cause high stresses to repaired material and results in de-bonding of repaired material from structural concrete [38].

Avoiding the presence of these cracks appears in form structural failure [39].The aim of rigid pavement is to offer resistance to cracks, developed under loading and environmental conditions [40]. Flexural strength property of concrete plays a vital role in performance of concrete by resisting heavy traffic loading. The trend of using natural fibers in rigid pavements has been growing from past few years [41]. The reason behind their growing demand is their lowing density, renewable property, local availability and low cost as compared to other synthetic fibers [42]. Stress development during the process of drying shrinkage can be reduced by the addition of fibers [43]. Fiber reinforced concrete is now used to enhance the performance of plain concrete for many structural applications. Fiber reinforced concrete, which is composed of fiber and concrete, can enhance the flexural, Compressive, fatigue, tensile, impact and shrinkage properties of concrete [44].

2.3 Governing Properties of Concrete and Their Contribution towards Pavement Performance

A micro-crack appeared on concrete with the passage of time converts into macro crack. Independent of the size of crack, cracking affects the properties of concrete and also the functionality of concrete structure. The crack propagation ends up affecting the strength of concrete [45]. The properties of concrete have significant role in structural cracking [46]. The factors related to design and durability of concrete structure is also affected by the concrete properties up to some limits. Concrete being weak in tension and strong in compression behavior, this is the reason that flexural strength property of concrete is given more importance than that of compressive strength property of concrete for better structural performance [47, 48]. The properties that influence performance of rigid pavement includes; compressive property, splitting- tensile property and flexural property. Among these properties, splitting-tensile property controls the cracking behavior of concrete [49].

The evaluation of cracking in concrete structure is based on two properties of concrete, which includes tensile strength and the tensile strain capacity. The tensile strain capacity is the measure of tensile strain that a concrete structure can withhold without forming cracks throughout the structure. The evaluation of cracking process can do more effectively and easily by considering tensile strain rather than tensile strength property of concrete, the process express forces in form of volumetric changes. A concrete structure under particular loading possesses a relation between tensile load carrying capacity and crack width [50]. The tensile strain capacity of concrete is measured through modulus of rupture [51], this method was initially used by the crop of engineers, to determine the tensile strain resistance ability of concrete [52, 53]. Strains on the outer surface of the test specimens under tension were measured directly.

2.4 Design and Durability Considerations

The early age micro-cracks develop at the surface of concrete during initial 24hrs of concrete placement [54]. The concrete mix is more prone to cracking during initial 24hrs. At this stage, the concrete material does not have enough strength to resist stresses due to shrinkage. Adding some supplementary cementitious materials (SCMs) in concrete mix may increase the process of shrinkage. The water absorption capacity of concrete accelerates due to hydration and pozzolanic reaction in concrete [55]. The water penetration is restricted in un-cracked concrete as compared to cracked concrete [56]. The width of crack is an important parameter of reinforced concrete structure. There is a close relation between crack width and durability of structure. The width of crack depends on the tensile load carrying capacity of concrete under certain loading [57]. The width of crack and pore structural properties help to determine the durability of structure [58].

Under aggressive environmental conditions, the reinforcing steel undergoes deterioration and corrosion due to cracks in concrete. In a cracked unreinforced concrete structure, the ultimate load carrying capacity across the cracks was dependent on tensile load carrying capacity (for small cracks less than about 0.1-0.3 mm in width) [57, 59]. The process of deterioration of concrete can be prevented through improved mechanical and durability properties of concrete. The stresses generate in rigid pavements are due to; compressive strength and flexural strength. The thickness of concrete pavement is controlled by factors like modulus of rupture and modulus of elasticity. The thickness of rigid pavement can be reduced by increasing the flexural strength of concrete. Now- a- days, natural fibers are one of the most used alternate material to enhance the properties of concrete in economical ways [60]. Hence, improved values of these factors and improved properties of concrete can help to enhance performance of concrete.

2.5 Effectiveness of Fiber Incorporation in Concrete for Its Properties Improvement

Concrete is widely used material for different structural applications, like pavements, bridges and other structures. These structures sometimes undergoes loads that are lower than their ultimate load carrying capacity, these loadings may be in form of cyclic loading [61]. Continuous cyclic loading on structure cause fatigue failure, which is the most common structural failure [62, 63]. Under the effect of cyclic loading, micro- cracks starts appearing on the surface of structure, which leads to failure of structure at its extreme stage [64, 65]. The crack propagation results in reduction of overall effective load area of structure [66]. However, small cracks can significantly disturb the functionality of structure and ultimately results in structural failure [67]. In plain concrete, the crack bridging effect is due to the aggregate interlocking. This action of interlocking due to aggregate can be enhanced by the addition of discrete fibers in concrete. Presence of fibers in concrete mix generates forces around cracks that tend to join or restrict the further increase in width of crack [68]. Studies on rigid pavements containing fiber reinforcement reported an increase in toughness, crack resistance capacity of concrete [69]. The factors that control the performance of fiber reinforced concrete, includes type and proportion of fiber in concrete. Different type of fibers shows different behavior in concrete matrix. While, the fiber proportion measures their performance in concrete [70].

Hybrid natural fiber reinforced concrete (HNFRC) is used as a replacement of plain concrete (PC). Macro- fibers helps to tackle macro- cracks and increase toughness of concrete [71]. In hybrid natural fiber reinforced concrete (HNFRC) the forces across cracks are combined effect of aggregate and fibers. During the resistance to crack propagation, fiber experience frictional slippage, pull-out forces, breaking effect and debonding [72]. The presence and surfaces of fibers control the energy dissipation and deformation phenomenon after post cracking [73]. Fiber pull-out from matrix promotes the ductile behavior of concrete because of energy dissipation during the process of post-cracking [74].

The different cracking levels can be controlled by adding different type of fibers of different length in concrete. Figure 2.2 shows the technique of using two various types of fibers with different length and dia as crack arrester at multiple levels. Literature shows an improvement in energy absorption, flexural and that of compressive strength of concrete due to presence of HNFRC [75-77]. Under same loading effect HNFRC showed less corrosive density as compared to plain concrete [78]. The crack increment in any structure can be controlled by confinement effect of fibers [79]. Hybrid fiber reinforced concrete is used as an alternate of plain concrete, due to multi-scale properties of hybrid fibers in concrete, which helps to control cracks from micro to macro level [80]. As the addition of two different bers with different lengths resulted in enhanced performance of structure, by

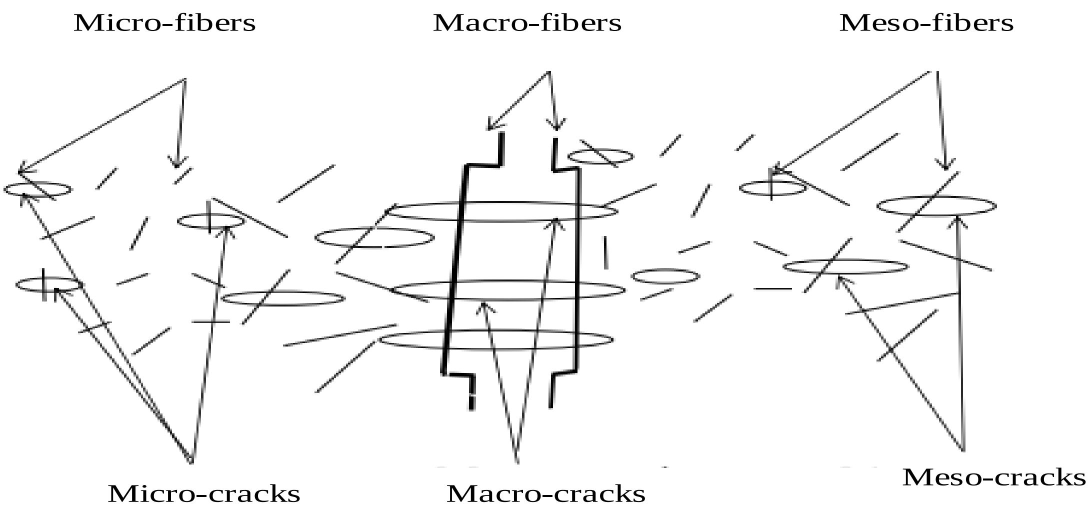

FIGURE 2.2: Concept of hybrid fiber resistance to cracks in concrete; a) micro-cracks, b) meso-cracks[56]

controlling the rate of cracking [56]. The dose of fibers has a significant effect on the performance of concrete as compared to that of fiber ratio, with the statistical relation on tensional toughness, volumetric weight and that of number of fibers [81].

Figure 2.2 shows the working mechanism of fibers with different lengths on multi level cracks. For this specific study, the selected fibers possess the good properties among other locally available natural fibers. The fibers of jute and wheat have good tensile strength, which helps to resist cracking in hybrid fiber-reinforced concrete. The less water absorption property of fibers also restricts the crack propagation, more significantly in rigid pavements due to their exposed surfaces to environment. Literature studies show improved properties of concrete by introducing hybrid fibers in it [82-85]. These properties and also the fracture energy of concrete can be improved even with a minor amount of fibers in matrix [86-88]. Studies on jute fiber revealed that jute has ability to (i) control cracks- propagation, (ii) absorb major portion of post-crack energy (iii) carried a main section of the tensile stress [89]. Researchers are conducting studies to use wheat straw as construction material [90]. Wheat straw is a by- product of crop and available in cheap and abundant amount [91]. The content of wheat straw fiber used in different studies varies from 0.5%-5% by mass of cement [98].While, the volume of jute fiber used to prepare jute fiber reinforced concrete in different researches were 0.25%, 0.50% and 1% [92]. The stiffness of the matrix by using wheat straw fiber content of 0.75%, by volume, was increased by 23% as compared to plain concrete. Although, wheat straw fiber reinforced concrete with enhanced properties were reported by Albahttiti et al. and Merta et al. [98, 99]. Table 2.1 shows the advantages using jute fiber and wheat straw fiber in concrete.

Table 2.1: Advantages of using jute fiber and wheat straw in concrete [93-100]

Fiber	**Improved properties of concrete**	**Reference**
Jute	Increase in CS, STS and FS of concrete by 27%, 12% and 44%, respectively	Chandar, S. P., Balaji, C. J. (2015) [93]
	High breaking tensile strength	Kundu et al. (2012), and Ramaswamy et al. (1983) [94, 95]
	Increase in toughness index and that of flexural strength of concrete.	Joshi, S. et al. (2004) [96]
Wheat straw	Seven times lighter than steel.	Won, J. P et al. (2008) [97]
	Increase in stiffness by 23%.	Albahttiti, M. T. et al. (2013) [98]
	Increase in fracture energy of 5%.	Merta, I. et al. (2013) [99]
	Enhance compressive strength property of concrete	Ashour, T. et al. (2011) [100]

This enhancement in properties of HNFRC as compared to PC may be due to the rough surfaces of jute and wheat straw fibers, which leads to better bonding between fiber and matrix. This interlocking phenomenon between fiber-matrix gives sewing effects to concrete mix, resulting in increased energy absorption capacity through resistance to cracks. Use of wheat and jute fiber in concrete improves the mechanical properties of concrete. Same as mechanical properties, dynamic behavior of hybrid natural fiber- reinforced concrete structure is also important, especially for design purposes. As the dynamic behavior of structure during vibration period can affect the durability and stability of structure in many ways [101]. Different researches have been conducted that deal with the dynamic behavior of fiber-reinforced structure [102], limited studies are available on jute and wheat straw fiber [103]. Thus, for stable hybrid natural fiber reinforced structure dynamic behavior should be given serious considerations under the effects of vibrations. To the best of author knowledge, no research has been conducted to study the effect of jute and wheat straw as HNFRC on mechanical, dynamic, water absorption, linear shrinkage and mass loss. Therefore, in the current study, mechanical, dynamic, water absorption, linear shrinkage properties and mass loss characteristics of HNFRCs composites are experimentally investigated.

2.6 Summary

Cracks reduction can enhance the performance of rigid pavements. The cracking phenomenon can be controlled by improving mechanical properties of concrete. The reduced values of linear shrinkage can minimize the rate of cracking in rigid pavements. Presence of fibers in previous studies has showed the improved properties of concrete, which ensure the positive impact on performance of structure. In this chapter; flaws in rigid pavements, governing properties of concrete and their contribution towards rigid pavement, design and durability considerations and the effectiveness of fiber incorporation in concrete for rigid pavement are discussed in detail.

Chapter 3

Test Methodologies

3.1 Background

Natural fibers are gaining attentions of construction industry from last few years, due to their low cost, environmental friendly nature, easy handling, good mechanical properties and easy availability. The fibers used in this research that includes jute and wheat straw, have good energy absorption, low density and high tensile breaking strength. As stated in the previous chapter that an in-depth research on suitability of HNFRC with various type of fibers for pavements has not been conducted up to now. Therefore, mechanical and dynamic properties of HNFRCs along with the linear shrinkage, water absorption and mass loss are considered in this research. In this chapter, raw materials, fiber treatment, the techniques of PC and HNFRCs mixing and casting, specimen details, testing methodologies are discussed in detailed.

3.2 Raw Materials and Fiber Treatment

The material used to prepare PC includes; ordinary Portland cement, lawrencepur sand, coarse aggregates 12.5 mm down and water. To begin with, jute fiber and wheat straw have been selected due to their local availability and good properties.

To prepare HNFRC, same ingredients are used with different proportions of jute fiber and wheat straw. The fiber used in length of 50mm and 25mm for jute and wheat straw, respectively.

TABLE 3.1: Mechanical properties of jute fiber and wheat straw [104-106]

Parameter	**Jute**	**Wheat straw**
Diameter (um)	20-200	5-7
Density (kg/m3)	1300-1490	1150-1200
Tensile modulus (MPa)	320-800	30-32
Youngs modulus (GPa)	8-78	6.0-6.6
Max. elongation (%)	1-1.8	1-1.13

Table 3.1 shows the mechanical properties of jute fiber and wheat straw [104-106]. The use of natural fibers over synthetic fibers has been increased for industrial applications.

FIGURE 3.1: Considered natural fibers; a) Jute fiber, b) Wheat straw

Different methods are being introduced by researchers to enhance the bond strength capacity between fiber and matrix in concrete, by improving the surfaces of natural fibers. These treatments include both physical and chemical modification of fiber surface.

The fiber treatment adopted for this specific study is the water treatment, which is the simplest and easy treatment method and is reported by various researchers. For this purpose, the raw fibers of jute and wheat straw are cut into required length of 50mm and 25mm, respectively. Jute fibers cutting are done by combing the fiber and straighten them to avoid varied length. The cutted fibers were then soaked into water for about 24hrs. Raw fibers, prepared fibers and fiber cut length for both fibers is shown in Figure 3.1a and 3.1b for jute fiber and wheat straw, respectively. To study the resistance force of fibers against tensile failure in form of fiber pull-out force and fiber breakage, fiber length of 50 mm and 25mm is taken based on assumption that hypothetically half the length of jute fiber and some of the length of wheat straw will remain embedded to tackle minor cracks, when concrete will undergo ultimate failure and spall up to 25 mm.

3.2.1 SEM Analysis of Treated Natural Fibers

The SEM analysis of fibers in conducted to obtain information related to failure analysis of inorganic materials, chemical composition, qualitative analysis and external texture and structure of fibers. Figure 4a shows the SEM image of wheat straw the diameter range from 5um- 7 um, while Figure 4b shows the microstructure of jute fiber comprising of nano strands with value of diameter for jute fiber ranging from 20 um-200 um. Figure 3.2a and 3.2b shows the SEM image of swelled tubular strand edges of jute fiber and wheat straw due to enough water absorption.

The SEM analysis of wheat straw as given in Figure 3.2a shows external and internal layers of wheat straw. The outer frictional surface of wheat shows that the rough surface of wheat straw results in frictional effect between concrete and

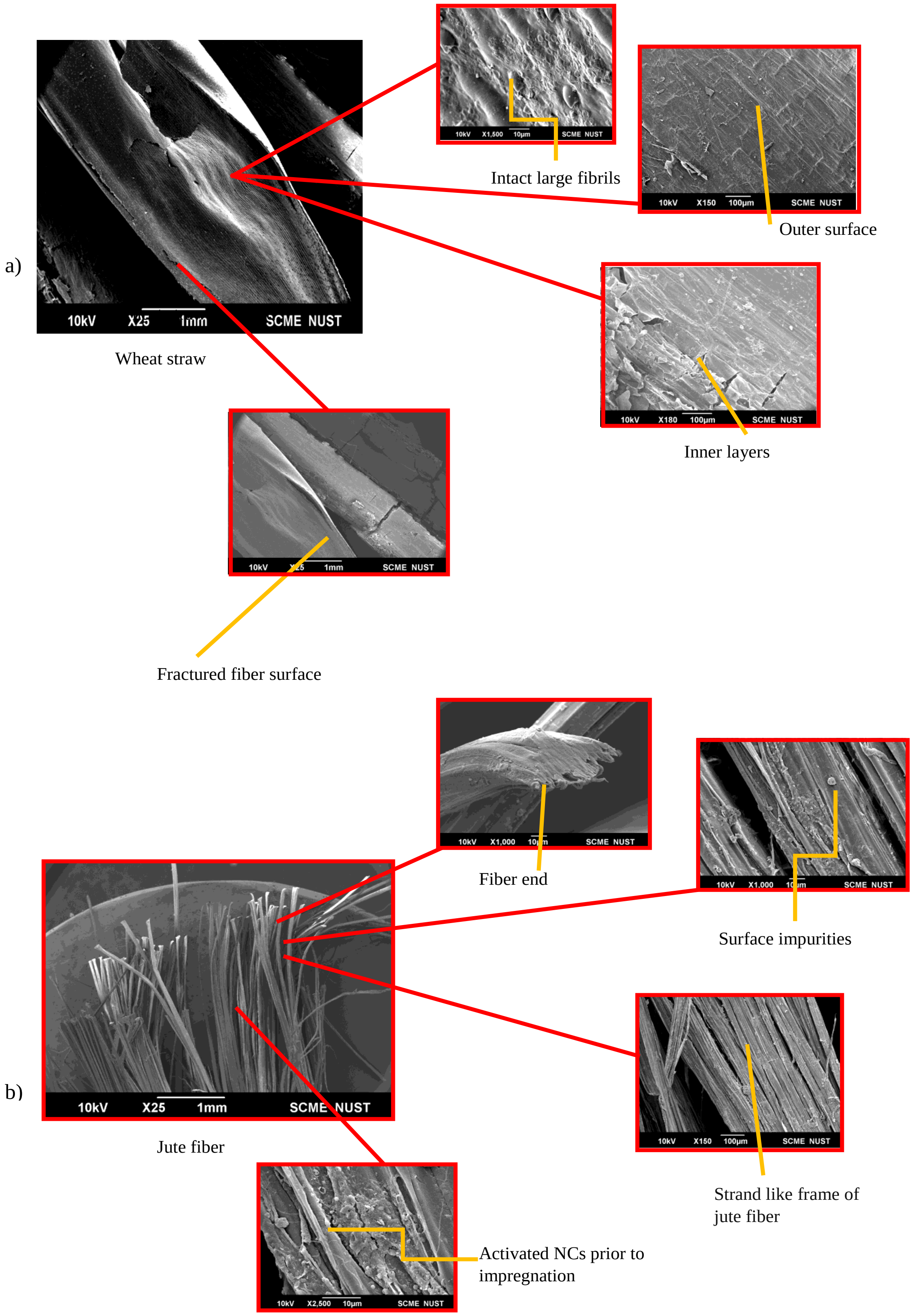

FIGURE 3.2: Fibers structural exploration through SEM; a) wheat straw, b) jute fiber

fiber which resist the pull-out force. While, the internal layers with less pores shows the low water absorption property of wheat straw as compared to jute fiber. Figure 4b shows the impurities present at the surface of jute fiber and presence of nano-porous carbon with roughed surface and fiber ends. These rough surfaces of natural fibers resist the forces that extract them from matrix by developing frictional effect.

3.3 Mix Design and Casting Procedure

The mix design ratio of 1:2:3 (cement: sand: aggregate) is used for preparation of both PC and HNFRC, with w/c ratio of 0.7. A saturated surface dry condition is missing. Therefore, a relatively high w/c ratio is used for the concrete mix. It may also be noted that no bleeding is observed during slump test and filling of moulds (this may insure no loss in strength of HNFRCs). In case of HNFRC, the variation is only the addition of fibers 5% by mass of cement. The fiber added in concrete are same in length 50mm and 25mm for jute fiber and wheat straw respectively, but their content vary in concrete. Table 3.2 shows the concrete mix proportion used to prepare specimens of PC and HNFRCs. Concrete mixer is used to prepare both PC and HNFRC. For the production of PC, the raw ingredients along with water are poured into the mixer and the mixer is rotated for about 3 minutes. After that the slump test is conducted to check the workability of the concrete before pouring it into the moulds. For the preparation of HNFRCs, one third part of the material is poured into the mixer in layers, and the process is repeated to complete the material for specific number of moulds or specimens. For the preparation of HNFRCs, the mixer is rotated for about three minutes to mix the material along with calculated fibers proportions in its dry state for proper material mix-up. Then, one third of the water are added in mixer and the mixer is rotated for about three minutes to prepare the required number of specimen. The remaining water is added into mixer and the mixer then again rotated for about 3 minutes. Before pouring the concrete mix into mould, workability test is performed. All the HNFRCs mixes are observed to be workable at that time and are evenly dispersed. The workability test performed for HNFRCs is same as that for PC. Standard procedure of filling the moulds in three different layers and then tempering each of the layers with the 25 blows by using 16 mm diameter rod is followed. With standard procedure of moulds filling, the technique of lifting up and dropping the mould down from a height of about 165mm- 230mm is adopted in case of HNFRCs, to completely remove the air voids. All the specimens of PC and HNFRCs are prepared following the same procedure. Among the available techniques the method with best suitability to enhance the slump of HNFRC is recommended. All the specimens are cured for the period of 28 days.

Table 3.2: Details of fiber content and concrete mix proportion in different concrete mixes

—	[Mix	proportions	(kg/m^3)]	[Fiber	proportion	(kg)]
Mix	**Cement**	**Fine aggregates**	**Coarse aggregates**	**Water**	**Jute fibers**	**Wheat straw**
PC	402.2	858.8	1412.6	297.7	0	0
C1	317.6	678.4	1116.1	297.7	0.03	0.31
C2	336.5	717.4	1180.4	297.7	0.10	0.24
C3	355.9	761.0	1251.6	297.7	0.17	0.17
C4	374.6	800.2	1316.1	297.7	0.24	0.10
C5	393.4	836.5	1381.1	297.7	0.31	0.03

3.4 Specimens

For the splitting tensile strength, compressive strength, water absorption and mass loss test the cylinder of diameter 100mm and height of 200mm are used, both for PC and that of HNFRCs. In case of, flexural strength and linear shrinkage, beamlets of size 100 mm 100 mm 450mm are used. As per ASTM C39, to calculate the properties of concrete, an average of two readings is taken both for PC and HNFRCs. A total number of 36 specimens are casted; these are 24 cylinders and 12 beam-lets. Specimens are marked to distinguished them based on fiber proportion. ASTM C143/C143M15a is followed to determine workability of both PC and HNFRCs in their fresh state. For the determination of density, ASTM C642-13 is taken in consideration. Due to non- availability of respective standard same standard is followed for both workability and densities determination. Due to retention and that of confinement effect, reduced slump values are observed in HNFRCs as compared to slump value of PC.

The slump values of PC and HNFRCs (i.e. C1, C2, C3, C4 and C5) are 43mm, 27mm, 25mm, 22mm, 19mm and 17mm, respectively, for same w/c ratio. The reduced value of 27mm, 25mm, 22mm, 19mm and 17mm has been noticed in slump test of C1, C2, C3, C4 and C5, respectively, as compared to that of PC. The slump values of C1, C2, C3, C4 and C5 reduced by 37.2%, 41.9%, 48.3%, 55.8% and 60.4% than that of PC. The reduced value of slump in C5 is due to highest jute fiber (J=4.5%, W=0.5%) content in particular specimens, as jute fiber tends to have high water absorption property. The presence of fibers in HNFRCs caused a decrease in densities due to low fiber weight of HNFRCs than that of PC. The observed densities of PC, C1, C2, C3, C4 and C5 are 2204 kg/m3, 2194 kg/m3, 2162 kg/m3, 2149 kg/m3, 2142 kg/m3 and 2139 kg/m3 respectively. Hence, the densities of C1, C2, C3, C4 and C5 are reduced by 1%, 1.4%, 2.5%, 2.8% and 3%, in comparison to that of PC. Among specimens of HNFRCs, the specimens of C4 and C5 show lowest density values. As jute fiber have low unit weight as compared to that of wheat straw.

3.5 Testing Methodology

The mechanical properties, dynamic, water absorption, loss in mass and linear shrinkage properties are measured against PC and HNFRCs. These setups are used as per standards. To avoid the humans errors an average of two reading is taken. The ASTM standard also allow the average of two readings. Figure 3.3a, 3.3b and 3.3c shows the setups to perform these tests.

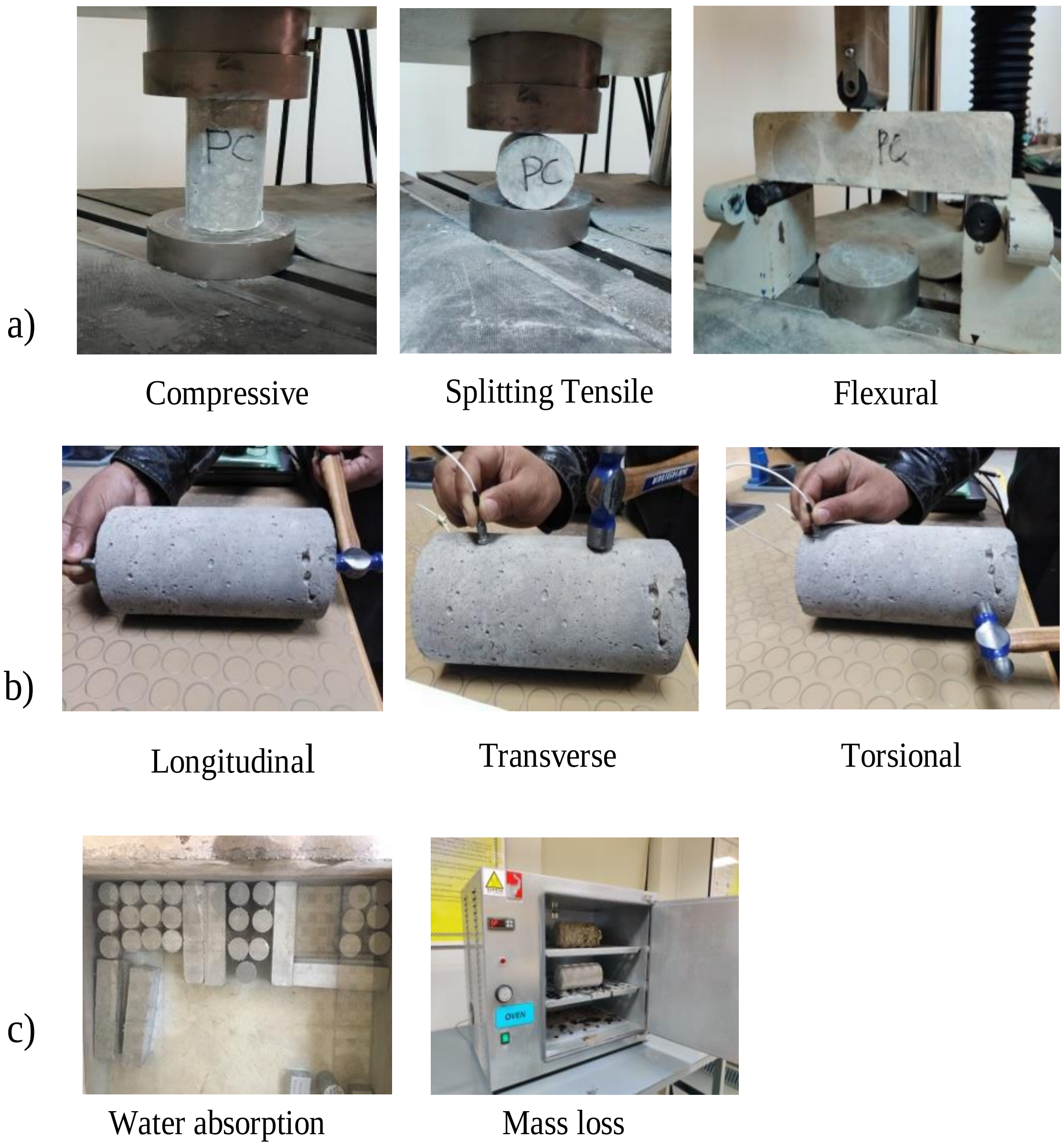

FIGURE 3.3: Tests setups; a) mechanical properties, b) dynamic properties, c) miscellaneous

3.5.1 Determination of Mechanical Properties

For the determination of compressive strength, splitting tensile strength and flexural strength of PC and HNFRCs, UTM (Universal Testing Machine) is used, according to ASTM standards. For the compressive strength (CS), compressive behavior, compressive pre-crack (CPE) and post-crack energy (CCE), strain at maximum stress (o), compressive total absorbed energy (CTE)and the compressive toughness index (CTI) of both PC and HNFRC, according to ASTM C39 / C39M-17.For uniform load distribution over cylinder capping of cylinder with plaster of paris is done. For the determination of splitting- tensile strength, splitting-tensile behavior, splitting tensile pre-crack/post-crack energies, and splitting-tensile toughness index properties of both PC and that of HNFRCs ASTM C496/C496M-11 standard is followed. ASTM standard C293 / C293M-16 is followed to determine the flexural properties of PC and HNFRCs

3.5.2 Determination of Dynamic Properties

Dynamic properties of the cylinders and beam-lets specimens of PC and HNFRCs are determined as per ASTM standard C215-14 to find frequencies used to find damping ratio, relative modulus of elasticity (Pc) is calculated and the dynamic modulus of rigidity as well as dynamic Poissons ratio as per ASTM C666/C666M-1.

3.5.3 Water Absorption, Linear Shrinkage and Mass Loss Tests

The determination of water absorption in done by following ASTM-C642. The test is conducted by drying the specimens in oven, and then placing the dried specimen in water at room temperature and then boiled under water for a time period of about 5hrs. Same procedure is followed for the calculation of W/A rate of all concrete mix specimens. Since, no document is available to determine the linear shrinkage of concrete specimen. For this purpose, ASTM standardC157/C157M-08 is followed to obtain the linear shrinkage value of specimens for both PC and HNFRCs, by measuring the variation in length of specimens (OPSS LS-435 standard). With exemption that sizes of beam lets specimen are about 100 mm x 100 mm x 450 mm, and in view of that, gauge length reference bar is being used. One specimen from each type of concrete mix is placed in heating oven and the temperature is raised at an average value of 3^{o}C/min from 20^{o}C to 100^{o}C. The reason behind the highest temperature value of 100^{o}C is to take realistic data. The temperature of 100^{o}C is maintained for about 1 hour. The specimens are then allowed to cool-down in oven, to prevent the thermal shock due to sudden temperature variation. The average cooling rate followed is 3^{o}C/min. After the cooling of specimens, the mass loss of specimens is determined [107].

3.5.4 SEM Analysis of Damaged Surfaces of HNFRC

Micro structural analysis of tested broken specimens is conducted. The micro-level analysis of HNFRC specimen helps to examine the bonding effect between fiber and matrix. The main purpose of SEM analysis is to investigate the failure mechanism of fiber-matrix bond.

3.6 Summary

The mix design ratio used for the preparation of PC and HNFRCs is 1:2:3.The same w/c ratio of 0.7 is used for both PC and HNFRCs. The proportion of fiber in concrete is 5% by mass of cement, while varying the content of both fibers to prepare HNFRC specimens of different content type, with same fiber length of 50mm and 25mm for jute and wheat straw, respectively. A total number of 36 HNFRC specimens are prepared, 24 cylinder and 12 beam-lets. For testing of both PC and HNFRC specimens, ASTM standards are followed. The test performed on concrete (PC and HNFRC) includes; slump, density, determination of mechanical properties, determination of dynamic properties, water absorption, and mass loss test. The obtained results are discussed in next chapter (i.e. chapter 4).

Chapter 4

Test Results And Analysis

4.1 Background

The mix design ratio of 1:2:3 is used for casting specimens of both PC and HNFRCs. The w/c of 0.7 is used for all specimen type. For preparation of HNFRCs (C1, C2, C3, C4 and C5), fiber is added 5% by mass of cement, according to their ratio. Fibers are used with different length of 25mm and 50mm for wheat straw and jute fiber, respectively. This chapter is based on detailed results obtained after testing all specimens of PC and HNFRCs.

4.2 Mechanical Properties

4.2.1 Properties under Compressive Loading

Figure 4.1a show the stress train curve of PC and HNFRCs. While, Figure 4.1b shows the fracture pattern of specimens of the PC and HNFRCs under the compressive loading. This phenomenon is shown in three stages; at initial cracks, at peak and ultimate load. The first crack appeared at the surface of respective PC specimens and that of HNFRCs (i.e. C1, C2, C3, C4 and C5) is observed at 80%, 88%, 87%, 84%, 82% and 87% of their respective peak loads. The width of cracks in HNFRCs is much less than cracks in PC. The crack width at peak load is 80 mm, 70 mm, 65mm, 60 mm, 63mm and 55 mm in PC and HNFRCs, respectively. The phenomenon of cracking can be clearly seen in given images in Figure 4.1b. However, PC broke down into two pieces after its first crack, while those HNFRCs specimens remains together due to the bridging effect of fibers present in concrete mix. The values of CS, CPE, CCE, CTE, and CTI of PC and HNFRC are given in Table 4.1.

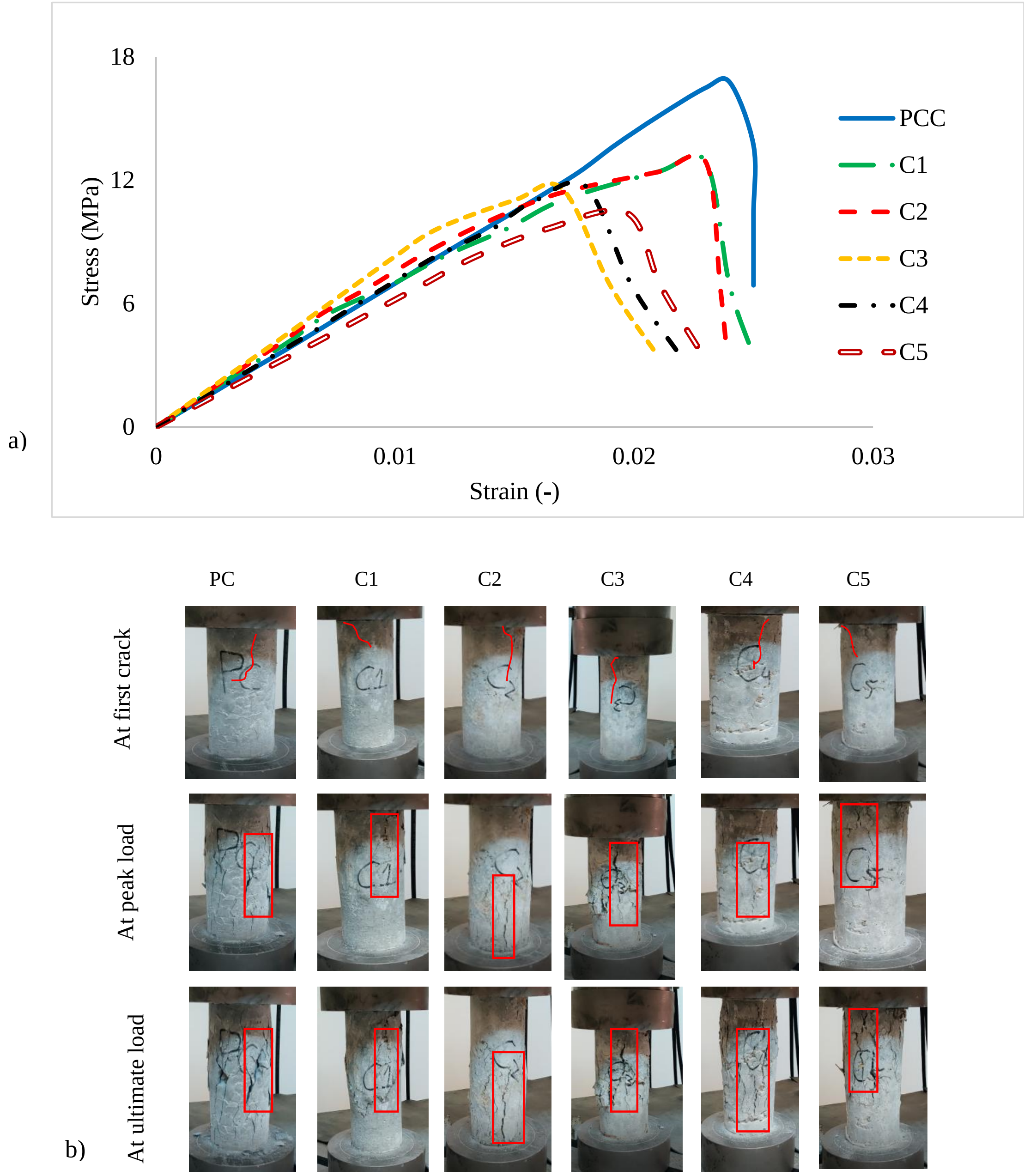

FIGURE 4.1: Compressive behavior of HNFRCs and PC; a) typical stress-strain curves, b) crack propagation

The CS values of 13.32MPa, 8.80MPa, 8.26MPa, 8.18MPa, 7.40MPa and 7.03MPa are experienced in specimens of PC and HNFRCs, accordingly. A reduction in CS value of 33.93%, 37.98%, 38.58%, 44.44% and 47.22% is observed in case of HNFRCs than PC. It cause decrease in CS of HNFRCs could be due to the presence of less dense fibers. While, the most reduced CS of C5 could be due to presence of large amount of jute fibers due to their low density. The values of strain against maximum stress are 0.013, 0.016, 0.012, 0.011, 0.009 and 0.007, for PC and HNFRCs, respectively. The specimens of PC and that of C1 somehow show the same results of strain against their maximum stress. This ensures that specimens of C1 have high value elongation property that allows them to with stand the matrix together and resist the shattering forces. And the reduced values of strain in other specimens of HNFRCs could be due to slippage effect of jute fibers in concrete matrix. The values of CPE of PC and HNFRCs are 0.12MPa, 0.22MPa, 0.23MPa, 0.22MPa, 0.24MPa and 0.24MPa, respectively.

Table 4.1: Compressive strength properties of PC and HNFRCs

Specimen Parameters	**CS (MPa)**	ε_0 **(-)**	**CPE (MPa)**	**CCE (MPa)**	**CTE (MPa)**	**CTI (-)**
PC	13.32±2.31	0.013±0.001	0.12±0.08	0.08±0.02	0.2±0.09	1.67±0.73
C1	8.80±1.60	0.016±0.003	0.22±0.10	0.31±0.13	0.53±0.17	2.25±0.94
C2	8.26±2.34	0.012±0.002	0.23±0.12	0.29±0.06	0.52±0.21	2.28±1.03
C3	8.18±2.11	0.011±0.001	0.22±0.09	0.27±0.09	0.49±0.18	2.32±0.89
C4	7.40±3.35	0.009±0.003	0.24±0.04	0.30±0.15	0.54±0.16	2.43±1.25
C5	7.03±2.08	0.007±0.001	0.24±0.13	0.33±0.10	0.57±0.23	2.53±0.87

Note: CS = Compressive strength, o = Strain at the maximum stress, CPE = Compressive absorbed pre-crack energy, CCE = Compressive cracked absorbed energy, CTE = Compressive total absorbed energy, CTI = Compressive toughness index.

When compared with CPE value of the PC reduction in values of HNFRCs is observed in C4, while an increase in CPE of C1, C2, C3 and C5 is observed. The values obtained against CCE of PC and HNFRCs are 0.08MPa, 0.31MPa, 0.29MPa, 0.27 MPa, 0.30MPa and 0.33MPa, respectively. The values of CCE increased for the specimens of HNFRCs as compared to that of PC. The increased values of CCE in case of C1, C4 and C5 are due to the enhanced post crack energy absorption which resulted from the presence of high content of specific fiber in these specimens and outperformed the performance of other fiber due to its structure and high strength property. While, a reduction in values of C2 and C3 is due to the presence of equal abundant amount of two different fibers which cause increase in the air voids and resulted in reduced post crack energy absorption values of these specimens.

The values observed for CTE of HNFRCs are 0.53MPa, 0.52MPa, 0.49MPa, 0.54MPa and 0.57Mpa, while, for the specimens of PC the value of CTE are 0.2Mpa. These shows an increase in values of C1, C2, C3, C5 against CTE of PC, in case of C4 the values of PC and C4 for CTE are same. The enhanced values of CCE and CTE could be due to the adding up of fibers in concrete that improved the post crack energy absorption ability of the concrete. The value of CTI for PC and that of HNFRCs are 1.67, 2.25, 2.28, 2.32, 2.43 and 2.53, respectively. Comparing the CTI value of PC increased values of the CTI of HNFRCs is observed. The addition of fibers in concrete has limited the crack propagation. The increase in CTI values of HNFRCs is due to the presence of large amount of fibers in concrete that resist the crack width against stresses produced. Therefore, of high post-crack energy absorption of HNFRCs cause increase in toughness indices of HNFRCs as compared to that of PC.

4.2.2 Properties under Split Tensile Loading

The load-time curve under the split- tensile loading is given in Figure 4.2a. While, Figure 4.2b shows the cracking behavior of specimens of PC and HNFRCs under split loading. The loading pattern is given for initial crack, the cracks at the peak loading with the cracking pattern at ultimate loading. The specimens of plain concrete and HNFRCs showed cracks at their corresponding peak load values of 100%, 99%, 98%, 95%, 93% and 91% (see the upper five photos of Figure 4.2b), respectively. The widths of cracks in HNFRCs are much less than those in PC. The lengths of cracks observed in HNFRCs are about 60 mm, 66mm, 75mm, 78mm and 70 mm, respectively. While, the specimen of PC break down into two pieces at it initial crack without any time space. On the other hand, the specimens of HNFRCs remain interact due to the bridging effect between fiber and concrete matrix. At peak load value, the width of cracks in HNFRCs is less (see middle four photos of Figure 4.2b than the specimen of PC that breaks into two pieces at its first crack. The crack width at this stage in case of HNFRCs is enlarged up to the value of 65 mm, 71 mm, 75mm, 78mm and 81 mm. The specimens of HNFRCs have given the values even at ultimate load opposing the behavior of the PC and the width of cracks observed at ultimate loading are 74 mm, 81 mm, 75mm, 78mm and 91 mm (see the bottom four photos in Figure 4.2b).

According to previous studies on fiber concrete and expectations, the width of cracks and the cracking phenomenon in HNFRCs was less than PC. This expresses the bridging effect of fibers in concrete mix which reduce the brittle behavior of concrete by reducing the crack width. Thus, by the addition of fibers in concrete the post cracking behavior of concrete especially in case of split loading can be improved. To observe the failure mechanism in HNFRCs specimens after loading the specimens has been intentionally break. To determine the splitting tensile strength (SS) of specimens, highest load value is taken into consideration. The area under curve up to value of initial crack is defined as splitting-tensile absorbed energy before crack (SPE). While, area after initial crack value is taken as the splitting-tensile post-crack absorbed energy (SCE). It is important to note that the value in both the cases of SPE and SCE is same for PC specimens as it breaks into two pieces after first crack. The total area under the curve is taken as splitting-tensile total absorbed energy (STE). The percentage between the splitting-tensile total absorbed energy and that of splitting-tensile pre-crack absorbed energy is taken as splitting-tensile toughness index (STI).

Table 4.2 shows the data obtained from load deflection curve against SS, SPE, SCE, STE, and STI of plain concrete and that of HNFRCs. The values of SS for the specimens of PC and HNFRCs are 1.87MPa, 1.93 MPa, 1.95 MPa, 1.91MPa,

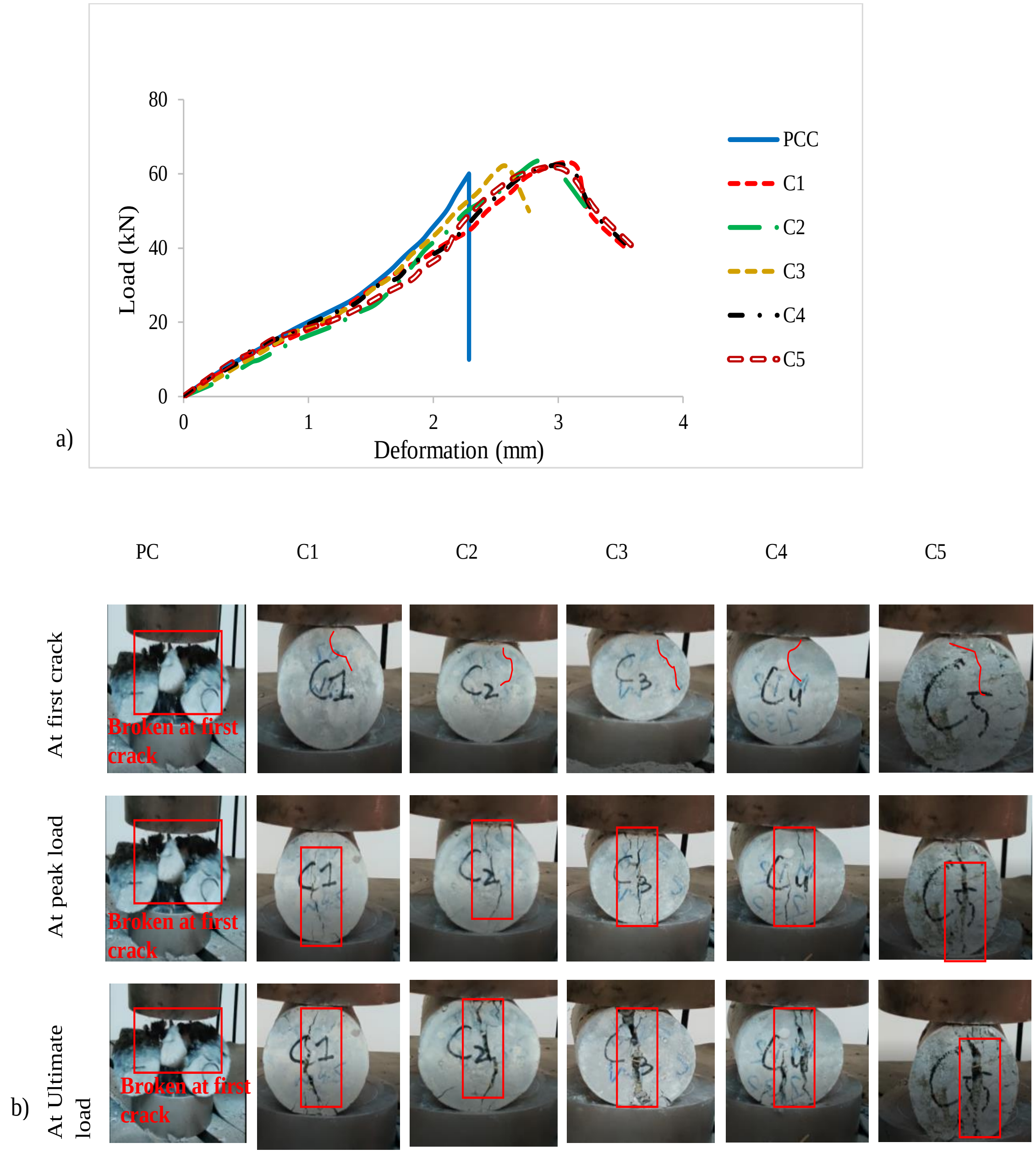

FIGURE 4.2: Splitting tensile behavior of HNFRCs and PC; a) splitting tensile strength, b) concrete failure mode

1.90MPa and 1.88MPa, respectively. An increase of 3.21%, 4.28%, 2.14%, 1.6% and 0.53% is observed in SS of HNFRCs as compared to that of PC. The values of PC and HNFRCs obtained against SPE are 45.67 kN.mm, 77.87 kN.mm, 74.38 kN.mm, 70.88 kN.mm, 74.37 kN.mm and 77.86 kN.mm, accordingly. As compared to SPE of the PC, the values for HNFRCs are reduced by 70.51%, 62.9%, 55.2%, 62.84% and 70.84%, respectively. The reduced SPE values of HNFRCs could be due to the high content of less dense natural fibers in a mix design ratio used in a same manner as that for PC. The most decreased values of SPE of C4 and C5 are because of negative effect of high jute fiber content in them which is low dense and resulted in decreased bonding capacity of concrete matrix. These results in decreased shear resistance value of C4 and C5 caused resistance to early crack formations and decreased SPE. While, in case of C1, C2 and C3 presence of wheat straw due to their structure and small dosage enhanced the resistance towards shear forces by avoiding early crack generation.

TABLE 4.2: Splitting tensile strength variation of PC and HNFRCs

Specimen Parameters	**SS (MPa)**	**SPE (kN.mm)**	**SCE (kN.mm)**	**STE (kN.mm)**	**STI (-)**
PC	1.87±0.87	58.7±5.0	-	45.67±5.0	1.00±0.72
C1	1.93±1.02	62.1±3.0	15.33±2.0	93.20±2.5	1.20±0.86
C2	1.95±0.94	66.3±5.0	10.26±1.7	84.64±4.0	1.15±0.58
C3	1.91±0.73	68.7±6.0	5.19±1.5	76.07±5.5	1.13±0.67
C4	1.90±1.02	74.37±4.0	8.64±2.0	83.01±3.0	1.11±0.49
C5	1.88±0.84	86.5±5.0	12.09±3.4	89.95±4.0	1.16±0.69

Note: SS = Splitting-tensile strength, SPE = Splitting-tensile absorbed pre-crack energy, SCE = Splitting-tensile post-crack absorbed energy, STE = Splitting-tensile total absorbed energy, STI = Splitting-tensile toughness index.

For this propose, relatively high value of SPE is observed in C1, C2 and C3 as compared to that of C4 and C5. The values obtained for SCE of the PC and HNFRCs are 0 kN.mm, 15.33 kN.mm, 10.26 kN.mm, 5.19 kN.mm, 8.64 kN.mm and 12.09 kN.mm, accordingly. Comparing the SCE of PC a clear 100th times increased value of SCE is seen in case of specimens of HNFRCs. And among all, C1, C2 and C3 have shown the best values of SCE. These values of SCE have proved the post crack energy absorption behavior of HNFRCs than that of PC due to the fiber bridging effect in specimens f HNFRCs. The values noticed against STE of PC and HNFRCs are 45.67 KN.mm, 93.20 KN.mm, 84.64KN.mm, 76.07 KN.mm, 83.01 KN.mm, and 89.95 KN.mm, respectively. As compared to STE value of PC an increase of 104%, 85.33%, 66.56%, 81.7% and 96% is observed in case of C1, C2, C3, C4 and C5 of HNFRCs. The values of STI observed for both PC and HNFRCs are 1, 1.20, 1.15, 1.13, 1.11 and 1.16, respectively. An increase of 20%, 15%, 13%, 11% and 16% is noticed in STI of HNFRCs as compared to that of PC.

4.2.3 Properties under Flexural Loading

Figure 4.3a displays the area under load- deflection curve. While, Figure 4.3b shows the cracking pattern of PC and HNFRCs (C1, C2, C3, C4 and C5) specimens under flexural loading and this can be seen at first crack, peak load and the ultimate load point. The upper first five photos show the cracking phenomenon at first crack of PC and HNFRCs. The specimens of PC and HNFRCs shows their first crack at their peak load value of 100%, 98%, 99%, 95%, 93%, and 92%. The crack length of about 60 mm, 50 mm, 55mm, 58mm and 50 mm is observed case of C1, C2, C3, C4 and C5, respectively. The width and length of initial cracks in HNFRCs is less than that of PC. In case of PC, it was seen that the specimen of PC broken into two pieces at its first crack, while, beam-lets of HNFRCs does not shatter into pieces due to bridging effect of the fibers. The specimens of HNFRCs show less number of cracks and width as compared to that of PC, at their peak load. At peak load values, cracks in HNFRCs further enlarge up to 81 mm, 84 mm, 84mm, 89mm and 77 mm, respectively, (refer to the middle four photos in Figure 4.3b). While, at the ultimate load value, the cracks in HNFRCs extends up to 93 mm, 95 mm, 92mm, 93mm and 81 mm, respectively, (refer to bottom four photos in Figure 4.3b). In flexural test, the cause behind pull-out behavior and the fracture of specimens are somehow same as explained under heading of splitting tensile property of PC and that of HNFRCs. The value of modulus of rupture (MoR) is computed by taking the highest value of the load against deflection obtained from load-deflection curve. The area under the load-deflection curve up to occurrence of first crack is taken here as flexural observed energy before crack occurrence (FPE) value. It can be seen through graph and figure that value of load under the definition of initial crack and the crack at the peak load is same for specimens of PC, because it broke into two pieces at its first crack. The area under the load-deflection curve from initial cracking load to ultimate load is taken as flexural post crack energy absorption (FCE). The total area under load-deflection curve comes under the definition of total flexural absorbed energy (FTE). The values of flexural toughness index (FTI) are thus obtained by taking the ratio of flexural total absorbed energy and the flexural pre-crack absorbed energy.

a)

b)

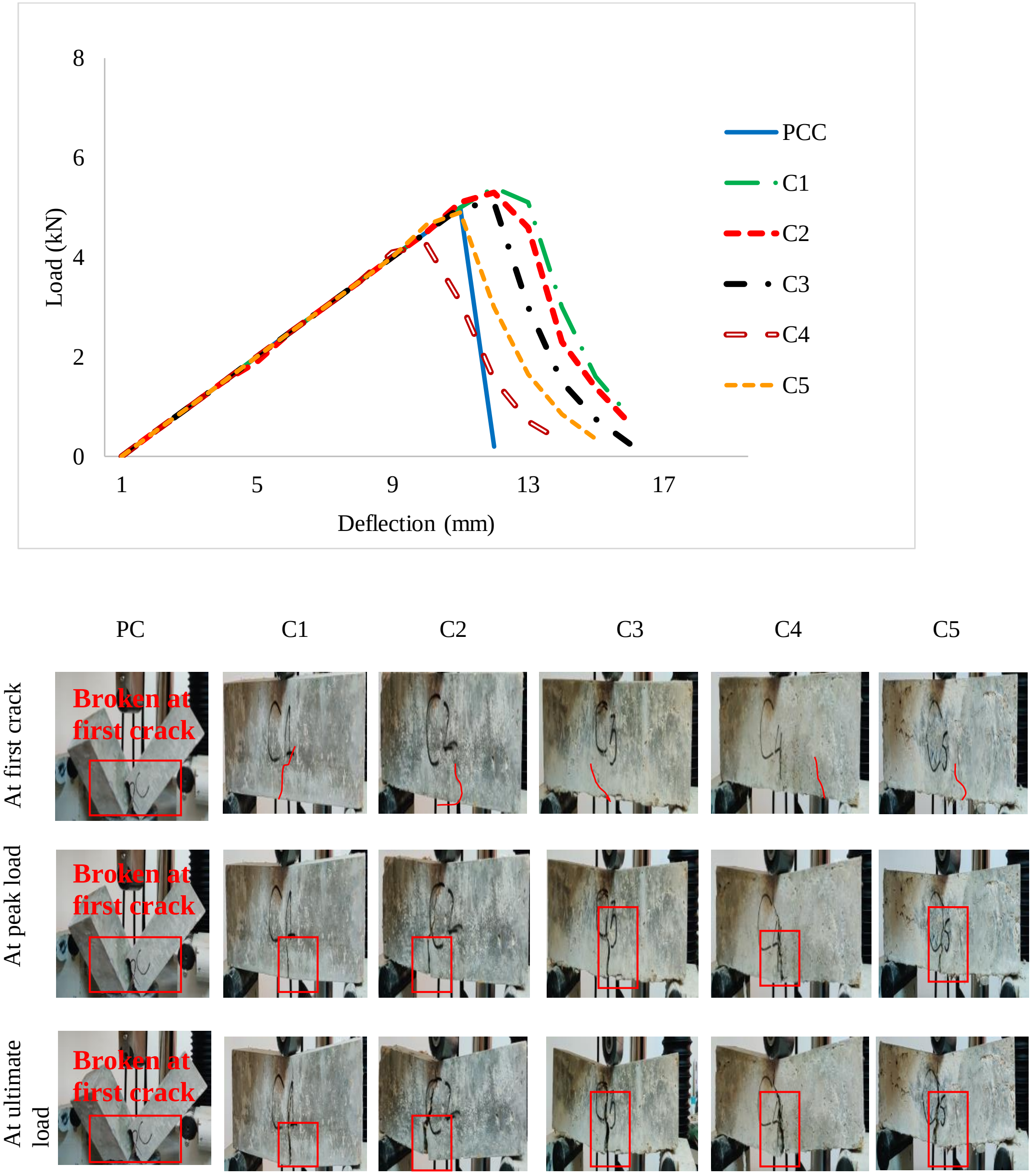

FIGURE 4.3: Flexural behavior of HNFRCs and PC; a) typical load- deflection curves, b) crack propagation under loading

Table 4.3 displays the values of MoR, o, FPE, FCE, FTE, and FTI of PC and that of HNFRCS obtained from load-deflection curve under flexural loading. The values obtained against MoR of PC and HNFRCs (C1, C2, C3, C4 and C5) are 2.17 MPa, 2.61 MPa, 2.63 MPa, 2.39MPa, 1.96 MPa and 2.19 MPa, respectively.

The values of MoR in case of C1, C2, C3 and C5 increased by 20.27%, 21.19%, 10.13%, 0.92% than that of PC. The increased values of MoR in these specimens are due to the enhanced post crack energy absorption and that of bridging effect

TABLE 4.3: Flexural strength values of PC and HNFRCs

Specimen Parameters	**MoR (MPa)**	Δ_0 **(mm)**	**FPE (kN.mm)**	**FCE (kN.mm)**	**FTE (kN.mm)**	**FTI (-)**
PC	2.17±0.95	0.763±0.52	3.43±1.23	-	3.43±1.54	1±0.04
C1	2.61±1.05	1.397±0.68	1.31±0.71	3.54±1.23	4.849±2.08	1.37±0.37
C2	2.63±0.92	1.316±0.23	0.78±0.42	3.58±1.59	4.355±1.83	1.22±0.71
C3	2.39±1.24	1.189±0.77	1.51±0.86	2.62±1.03	4.120±2.13	1.58±0.48
C4	1.96±1.08	1.02±0.53	0.4±0.13	1.65±0.98	2.035±0.88	1.24±0.64
C5	2.19±1.01	0.794±0.42	0.98±0.38	1.67±0.93	2.65±0.79	1.59±0.85

Note: FS = Flexure strength, o = Deflection at the maximum load, FPE = Flexural absorbed pre-crack energy, FCE = Flexural post-crack absorbed energy, FTE = Flexural total absorbed energy, FTI = Flexural toughness index.

of fiber due to appropriate jute fiber content in them. While, the reduced value of 9.67 observed in case of C4 as compared to that of PC. This reduction in MoR of C4 is due to the less strength and bridging capacity, this may be due to the voids present in these specimens due to the presence of both fibers in abundant amount. The value of deflection against peak load in case of PC and HNFRCs is observed to be 0.763 mm, 1.397 mm, 1.316 mm, 1.189mm, 1.02mm and 0.794 mm, respectively. The larger value of deflection is observed in specimens of C1, C2, C3 and C4 than that of PC and C5. The reason behind this could be the high fiber pull-out ratio in these specimens. The values of FPE obtained from load-deflection curve for PC and HNFRCs are 3.43kN.mm, 1.31kN.mm, 0.78kN.mm, 1.51KN.mm, 0.4KN.mm and 0.98 kN.mm, respectively. The decreased values of FPE are observed for HNFRCs as compared to PC by 61.8%, 77.25%, 55.97%, 88.3% and 71.42%. The reason behind most reduced values of C4 and C5 could be the high ratio of jute fiber due to their less dense property, which disturbs their proper distribution in matrix. The values of FCE of HNFRCs obtained from load-deflection curve are 3.54kN.mm, 3.58kN.mm, 2.62kN.mm, 1.65 kN.mm and 1.65 kN.mm, respectively.

The FCE value is not obtained for PC as it breaks down into two pieces at its peak load and first crack. The values of FTE for PC and HNFRCs are 3.43 kN.mm, 3.849 kN.mm, 4.355 kN.mm, 4.120 kN.mm, 2.035 kN.mm and 2.65 kN.mm, respectively. The increased value of FTE is observed in case of C1, C2 and C3 by 41.37%, 26.97% and 20.11%, correspondingly, than the FTE value of PC. While, decrease in value of FTE are observed in case of C4 and C5 by 40.67% and 22.74%, as compared to that of PC. The values obtained against FTI in case of PC and HNFRCs are 1, 1.37, 1.22, 1.58, 1.24 and 1.59, respectively. In case of the FTI of PC an increase of 37%, 21.99%, 58%, 24% and 59% is observed in FTI of HNFRCs. The high values of post-crack energy and the better post crack behavior results in improved flexural toughness indices of HNFRCs. C1 is recommended based on its best properties among other specimens. The presence of jute developed a bridging effect with somehow acceptable properties in specimens of C2 and C3, which is important to hold the cracking in rigid pavements. But due to presence of jute with large length and hybrid concrete the fibers creates bridging mechanism which resist the cracking and caused enhanced energy absorption for post-crack behavior of HNFRCs specimens [56].

4.3 Dynamic Properties

Dynamic properties of PC and HNFRCs are determined to investigate the effect of impact on properties of concrete specimens. The dynamic properties of all type of specimens are determined according to ASTM standard C215-14 and ASTM standard C666/C666M-15. The dynamic properties of HNFRCs are determined by following the same standard due to non-availability of specific standard. An average of two reading is taken for appropriate results. Table 4.4 shows the determined dynamic properties of concrete. The damping ratio of HNFRCs in case of cylinders is increased by 12.8%, 23%, 19.2%, 54.3% and 77.9% than that of PC. The damping ratio of HNFRCs beam lets is increased by 109%, 65.5%, 112%, 168% and 210.6% than that of plain concrete specimens. The increase in damping ratio shows that the specimens of concrete containing fibers have an ability to sustain the loading impact in form of damping on them as compared to that of plain concrete specimen.

Table 4.4: Dynamic properties of PC and HNFRCs

Specimen	RFl (Hz)	RFt (Hz)	RFr (Hz)	Damping ratio (%)	Dynamic modulus of elasticity (GPa)	Dynamic modulus of rigidity (GPa)	Poisson ratio (-)
Cylinder							
PC	2873±338	2604±476	2594±618	1.09±0.34	8.4±1.5	2.9±1.32	0.28±0.12
C1	4253±278	4261±00	4261±50	1.23±0.53	17.1±2.3	6.6±2.27	0.50±0.24
C2	3639±850	4527±664	3728±618	1.34±0.62	18.5±2.5	4.9±1.03	0.52±0.18
C3	4128±734	3684±375	3906±476	1.30±0.91	12.4±3.7	5.4±1.85	0.44±0.09
C4	3684±450	3209±524	3184±438	1.68±0.82	9.3±1.9	3.6±0.98	0.33±0.17
C5	4128±338	3584±225	3637±102	1.94±1.02	11.8±2.0	4.7±2.03	0.36±0.013
Beam							
PC	1287±180	1065±133	1078±85	2.06±1.04	13.7±4.1	2.7±0.97	0.40±0.12
C1	1420±79	1365±223	1420±107	4.31±2.10	21.3±3.0	4.4±1.93	0.58±0.32
C2	1553±68	1509±302	1464±331	3.41±1.52	28.2±6.2	5.1±2.09	0.52±0.27
C3	1420±105	1376±228	1366±64	4.37±1.87	22.5±3.1	4.3±1.08	0.54±0.19
C4	1287±117	1376±209	1358±76	5.52±2.43	21.2±5.7	4.0±2.06	0.62±0.23
C5	1376±84	1331±104	1320±93	6.40±3.41	19.7±3.4	3.7±0.89	0.54±0.20

Note: An average of two readings is taken.

The cylinder specimens of HNFRCs experienced an increase in dynamic modulus of elasticity by 103.6%, 120.2%, 47.6%, 10.7% and 40% as compared to that of plain concrete. While, in case of HNFRCs beam lets an increase of 55.5%, 105.8%, 64.2%, 54.7 and 43.8% is observed than the specimens of PC. The cylinder specimens of HNFRCs shows an increased modulus of rigidity values of 6.6 GPa, 4.9 GPa, 5.4GPa 3.6GPa and 4.7GPa, while for PC the value is 2.9 GPa. While, the beam-lets specimens of HNFRCs shows increased values of 4.4GPa, 5.1GPa, 4.3GPa, 4.0GPa and 3.7GPa respectively, than that of PC. This concluded results of dynamic properties shows that the specimens of fiber content C1, C2 and C3 have performed better In comparison with other specimens of HNFRCs and that of PC against dynamic properties, which shows their performance against loading effects. So the specimens of C1, C2 and C3 can improve the efficiency of pavement performance against loading impact.

4.4 Water Absorption, Linear Shrinkage and Mass Loss

Water absorption is given as process of liquid transportation through the capillary action and is given as total mass of absorbed water divided by actual mass of the specimen after oven dry (ASTM standard C642-13). Table 4.5 shows the values of water absorption percentage of PC, C1, C2, C3, C4 and C5; these are 2.44, 2.68, 2.82, 3.05, 3.78 and 3.89, respectively. The HNFRCs specimens show an increase of 9.83%, 15.57%, 24.99%, 54.9% and 59.4% as compared to that of PC. The water absorption values of C4 and C5 are relatively higher than other type of concrete specimens; the reason could be that high requirement of water absorption of jute fibers. The results thus obtained from water absorption tests concluded that due to less water absorption and acceptable value of slump, C1, C2 and C3 could be better choice against prevention of cracks in rigid pavements due to suitable amount of fibers in specimens. Table-4.5 shows the results obtained after measuring the linear shrinkage of PC and HNFRCs.

TABLE 4.5: W/A and L/S (%) of PC and HNFRCs

Parameters/Mix	**PC**	**C1**	**C2**	**C3**	**C4**	**C5**
W/A	2.44	2.68	2.82	3.05	3.78	3.89
L/S (% decrease)	0.082	0.073	0.079	0.091	0.112	0.156

Note: LS is reported to the nearest 0.001% of gauge length (ASTM C157/C157M-08)

The values of PC and HNFRCs are 0.082, 0.073, 0.079, 0.091, 0.112 and 0.156, respectively. An increased LS value of 90.25%, 36.60% and 10.98% is observed in case of C5 and C4 and C3, respectively, when compared to the value of PC. While, a reduced value of 10% and 3.66% is experienced in LS of C1 and C2, correspondingly. The reduced LS values of C1 and C2 may be due to presence of randomly distributed fibers and less voids as compared to all other type of fibers. An in- creased LS value of specimens could be due to high W/A capacity and also due to loss of capillary water from specimens. While, C3 shows a very minor difference from that of PC. C1, C2 and up to some extent C3 shows better performance than those specimens of PC, C4 and that of C5 and the reason behind lower values of LS is high tensile strength values of C1 and C2. This change in length is caused by the process of wetting and drying, so the decrease in values of LS of C1 and C2 indicates their better performance towards cracks prevention by reducing tensile stress that generates under the process of drying and shrinkage. Hence, it can be concluded that C1 and C2 can helps to reduce tensile stress ultimately limiting generation of cracks in rigid pavements.

Table 4.6: M/L (%) of PC and HNFRCs under elevated temperature

Concrete mix	**Temperature 50 (^{o}C)**	**Temperature 75 (^{o}C)**	**Temperature 100 (^{o}C)**
PC	-0.037	-0.043	-0.103
C1	-0.046	-0.051	-0.129
C2	-0.058	-0.060	-0.142
C3	-0.062	-0.068	-0.157
C4	-0.069	-0.074	-0.184
C5	-0.072	-0.079	-0.192

The percentage change in mass is defined as change in mass of specimens under increasing temperature and is done by heating the specimen up to 100oC, gradually increasing the temperature 3C/min. This gradual change gives time to water to escape from specimen. The change in mass loss is given in Table 4.6. It was cleared that specimens reduce mass gradually with increasing temperature. The steeper value of mass loss was observed in case of PC from -0.037±0.01, -0.043±0.01, -0.103±0.01 for 50^{o}C, 75^{o}C and 100^{o}C. While, for HNFRCs higher values of mass loss were observed due to high water absorption properties of fiber in these specimens. The mass loss in case of HNFRCs was gradual and even at high temperature of 100oC the loss in ass doesnt form any larger cracks or spalling. The internal pressure generation in concrete was controlled by melting of fibers and formation of micro cracks in concrete, which reduce the process of spalling and lamination at high temperature and the same phenomenon, is reported by [108].Thus, it is clear from investigation that fiber control the sudden mass loss and spalling in concrete by bridging, melting and formation of micro-cracks by reducing internal pressures.

4.5 SEM Analysis of HNFRC

SEM analysis of HNFRC specimen show that there are airs voids present in concrete mix, as shown in figure given below. Needle like Ettringite structure can be observed in high magnification. Both jute and wheat straw can be seen in broken specimen of HNFRC under SEM analysis. In Figure 4.4 circumferential de-bonding can be seen around fibers. The presence of two different fibers in concrete mix causes a high amount of air voids. The embedded jute fiber length shows that length cause increase in pull-out force and improved fiber length. The SEM analysis given in Figure 4.4b shows the fiber resistance to pull-out forces and its bond in concrete matrix. The roughed and damaged surface of fibers shows their resistance towards debonding and pull-out. The SEM images show the bulged out of concrete matrix, the fibers in concrete shows twisted behavior rather than the disintegration of fibers. This phenomenon shows their elastic property. It can be clearly seen from the images that the fibers remain in concrete even under high loading and pull-out forces, this shows their bridging effect and resistance to pull-out which significantly enhance the properties of HNFRC.

4.6 Summary

The mechanical, dynamic, waster absorption, mass loss and the linear shrinkage properties of the plain concrete and HNFRCs are determined with mix design ratio of 1:2:3 and using w/c ratio of 0.7. HNFRCs show an increase in MoR and better post-crack energy absorption behavior when compared with PC. The presence of natural fibers in HNFRCs results in increased value of water absorption in comparison to that of PC. While, a reduction in LS of C1 and C2 is observed when compared with PC. C1, C2 and that of C3 outperformed all other concrete specimens by enhancing both mechanical and dynamic properties of concrete. These concrete mixes also reduced the LS of concrete specimen which ensure their crack controlling property.

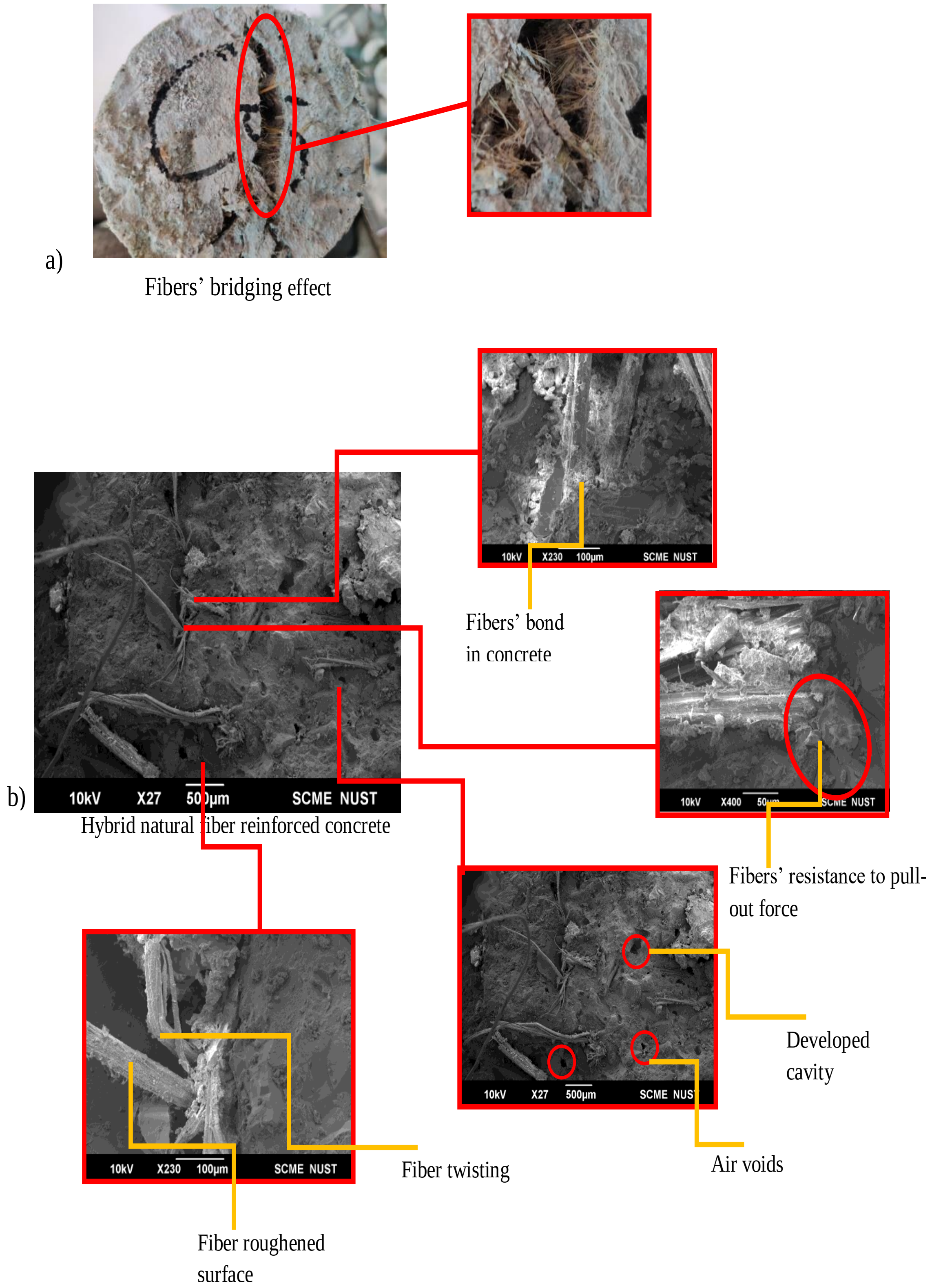

FIGURE 4.4: Fiber matrix bond; a) fragmented bridging in tested specimen, b) SEM images

Chapter 5

Discussion

5.1 Background

The testing results obtained gave quantitative results of impact of fiber ratio on properties of hybrid fiber reinforced concrete having wheat straw and jute fibers. Stress-strain, load- deflection and load deformation graphs represent effect of fibers on mechanical properties and that of dynamic properties of HNFRCs. This data obtained is further utilized to develop an empirical relation between mechanical and dynamic properties of HNFRC. Furthermore, discussion on utilization of HN-FRC in real life applications is made in this chapter.

5.2 Empirical Relation between Linear Shrinkage and Splitting Tensile Absorb Energy

The performance of structure can be judged by its mechanical, dynamic, water absorption, mass loss and liner shrinkage properties. These properties of concrete are affected by different factors like material properties and content used. These factors result in cracking and faulting and then affecting performance of structure.

Linear shrinkage is one of the major causes of cracking in concrete pavements. The cracks in concrete are also related to the splitting tensile property of concrete and the amount of energy absorbed by the specimens. An empirical relation is developed between LS and splitting tensile strength energy absorption before cracking. It can be a performance indicator, especially when the natural fibers are introduced in concrete.

$LS = (SPE/200)^{2.25} - - -5.1$

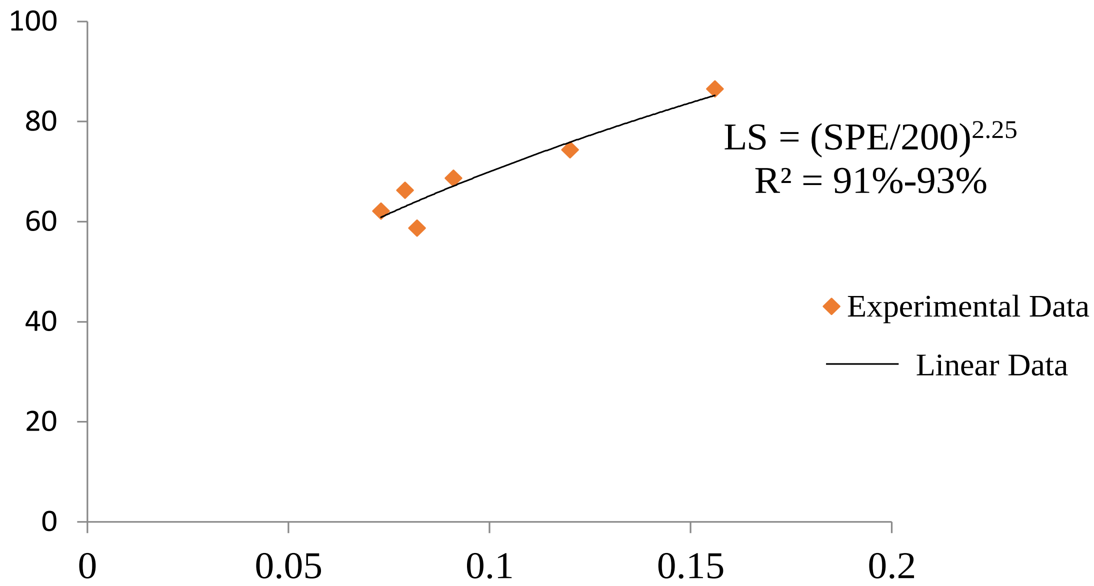

FIGURE 5.1: Developed empirical relation between linear shrinkage and splitting tensile energy absorption before cracking

This is done by generalizing the coefficients and that of exponents of the input variables to numerically predict the value of linear shrinkage (%).Where SE(abs) is the splitting tensile energy absorption before cracking in particular specimen, LS is the linear shrinkage in the particular specimen type. Figure 5.1 shows the graph obtained from empirical relation between LS and splitting tensile energy absorption before cracking. The value of R2 varies from 91%-93%, which is an accuracy indicator of developed equation. Table 5.1 shows that values obtained from experimental working in comparison with the values obtained from empirical equation and their percentage difference. The values obtained from empirical equations are somehow close to that of experimental data obtained. Therefore, it can be concluded that LS in hybrid natural fiber reinforced concrete can be calculated with above written equation. The value of R2 varies from 93%-97%, which is an accuracy indicator of developed equation.

Table 5.1: Linear shrinkage values from experimental data and empirical equations with their percentage difference

Specimen	**Linear Shrinkage and Splitting Tensile Energy Absorption**	**Linear Shrinkage**	**Linear Shrinkage**	**Linear Shrinkage**
–	(J)	Experimental Results (%)	Empirical Results (%)	Difference (%)
PC	58.7	0.082	0.063	23.17
C1	62.1	0.073	0.072	1.37
C2	66.3	0.079	0.083	5.06
C3	68.7	0.091	0.090	1.37
C4	74.37	0.11	0.11	0.00
C5	86.5	0.156	0.152	2.56

5.3 Rigid Pavement Design and Performance

In rigid pavement design, modulus of elasticity and modulus of rigidity are the two main factors that control the thickness of rigid pavement. These two parameters are also used by AASHTO and ACPA StreetPave software. So, by increasing the values of modulus of elasticity and modulus of rupture and keeping all others factors constant, the thickness of concrete pavement can be reduced [109]. According to Delatte [110], ASSHTO recommends determination of modulus of elasticity from compressive strength of specimens. As modulus of elasticity has no major effect on thickness of concrete pavement. Therefore, it can be calculated by the compressive strength of concrete specimens. Table 5.2 shows the calculated thickness values for HNFRCs specimens in comparison with PC. The values of MoR (Modulus of Rupture) and MoE (Modulus of Elasticity) are different for each concrete mix. The thickness of concrete pavements is calculated manually using ASSHTO pavement equation which can be written as; The values of all the parameters will be constant except Ec = Elastic modulus of concrete (psi) Sc =

Flexural strength of concrete (psi), which are variable and obtained from experiment. The other parameters are;W18 = Traffic load in equivalent standard axle loads (5.1 106 ESAL's), ZR = Standard normal deviation for desired reliability (The value corresponding to reliability (R) of 95% is -1.645, SO = Overall standard deviation (0.30) ΔPSI = Serviceability index of 2.5 with initial serviceability of 4.2, Cd = Drainage coefficient , J = -3.2 for Load transfer coefficient, k = 72 for sub grade reaction modulus (psi/in).

$$\log_{10}W_{18} = Z_R S_o + 7.35\log_{10}(D+1) - 0.06 + \frac{\log_{10}\left[\frac{\Delta PSI}{4.5-1.5}\right]}{1 + \frac{1.624\times10^{7}}{(D+1)^{8.46}}} + (4.22 - 0.32\rho_t)\left[\frac{S'_c C_d\left[D^{0.75} - 1.132\right]}{215.63j\left[D^{0.75} - \frac{18.42}{\left(\frac{E_c}{k}\right)^{0.25}}\right]}\right]$$

Constant

TABLE 5.2: Pavement thickness design of rigid pavement using ASSHTO equation

Material	Modulus of rupture (MoR)	Compressive strength (fc)	Elastic modulus (E)	Thickness from ASSHTO equation (h1)	Thickness from ASSHTO equation (h1)
—	(psi)	(psi)	(psi)	(inch)	(mm)
PC	314.65	1931.4	2505018.7	15.13	384.3
C1	378.45	1276.0	2036105.1	13.59	345.2
C2	381.35	1197.7	1972644.7	13.51	343.2
C3	346.55	1186.1	1963068.7	14.22	361.2
C4	284.2	1073.0	1867130.7	15.76	400.3
C5	317.55	1019.35	1819853.9	14.85	377.2

The low thickness value of rigid pavement is obtained in case of C1, C2, C3 and C4as compared to that of PC and C5. While, the most reduced thickness values with better mechanical and dynamic properties are observed in case of C1 and C2. While C3 and C5 also shows less thickness as compared to PC but a little higher than that of C1 and C2. The possible reason could be the high content of wheat straw in these specimens that results in increased values of MoR. As modulus of rupture (MoR) plays an important role in reducing the thickness of concrete. It can be seen through Table 11 that specimens of C1 and C2 reduced the thickness most which reduced its material requirement resulting overall cost reduction of the project. Therefore, the high wheat straw content in concrete enhances the performance of rigid pavement in both economic and structural manners. It is need of time and that of under-developing counties to introduce material that efficiently improve the performance of structure and demand low non-renewable natural resources and low financial requirement.

5.4 Practical Implementation

Concrete in different civil engineering applications also undergoes various types of loadings including dynamic loading and mechanical loading. These loading affect the performance efficiency of concrete and are controlled by factors like tensile strength, compressive etc. In rigid pavement applications, the failure caused by cracking which is mainly due to linear shrinkage, water absorption and tensile strength is generally resisted through the tensile and flexural properties of concrete [111]. This cracking in concrete can be controlled if the value of induced stresses is less than the value of tensile strength of concrete [112]. The phenomenon of differential settlement can also cause cracking in rigid pavements which can be controlled by enhancing the flexural strength property of concrete. Hence, the mechanical as well as dynamic loadings should be given proper consideration to avoid damages in concrete. In this study, the behavior of PC and HNFRCs is evaluated using jute and wheat straw fibers with variation in their content. The specimens of C1, C2 and C3 has shown better performance towards pavement application by enhancing mechanical properties of concrete in comparison with PC and other HNFRCs specimens. It is also important to know that the specimens of C4 and C5 have also performed better as compared to PC. While, C1, C2 and C3 can reduce the cracking phenomenon due to enhanced flexural and tensile strength properties of concrete. These can also be seen through the relation between damping ratio values and that of energy dissipation values obtained from experimental data. As the resonance produced during a seismic events can cause failure of structure (bridges, etc) [113]. The enhanced values of damping ratio in case of HNFRCs shows their impact towards oscillating system due to high energy absorption of these specimens as compared to that of PC. The improved properties of HNFRCs showed its crack reduction ability, the practical implementation of this investigated material will results in increased functionality, durability and efficiency of pavement. Farooqi and Ali [114] constructed first fiber reinforced rigid pavement, which ensure its practical implementation and performance.

FIGURE 5.2: Wheat straw fiber reinforced concrete pavement [114]

Figure 5.2 shows the laying and constructed fiber reinforced concrete. The construction of fiber reinforced rigid pavement has proved that fibers for the application of rigid pavement are effective and can be possible implemented with effective properties. Due to their abundant availability, easy handling, efficient properties fibers are most studied and used additive material in concrete these days. The only drawback in their practical implementation is their non-availability in readily available form for large scale use. If the processed fibers are given to the construction industry with enough awareness, consumption of different natural resources can be minimized with reduction in overall cost and increase in performance and life of structure, especially for rigid pavements.

5.5 Summary

The relation between properties of concrete and cracking has been evaluated. The chapter discussed the impact of fibers and their proportions on the properties of the concrete. The results discussed here showed that HNFRCs can control the cracking in rigid pavement in better way as compared to that of plain concrete. The fibers in concrete results in high post-crack energy absorption. As per final recommendations, C1, C2 and C3 can perform effectively to control the rate of cracking in rigid pavements.

Chapter 6

Conclusions and Recommendations

6.1 Conclusion

The current study explores the behavior of HNFRCs with different fiber contents of jute and wheat straw. These variations in fiber content are taken as scale to measure their appropriate fiber ratio in concrete to decrease the cracking rate in rigid pavements. The properties of plain cement concrete are taken as reference. Hybrid natural fiber reinforced concrete with various fiber content are prepared by adding 5% fiber content by mass of cement, while 50 mm and 25mm length is used for jute and wheat straw, respectively. The mix design ratio of 1:2:3 is used for both PC and HNFRCs. Following conclusions are drawn from conducted study:

- Fibers in hybrid natural fiber reinforced concrete improve the mechanical properties of concrete in many ways, by enhancing the values of energy absorption, toughness index and its strength. The properties enhanced by the percentage with their effect on performance of structure are as followed;

  – A decrease in CS value of 33.93%, 37.98%, 38.58%, 44.44% and 47.22% is experienced in case of HNFRCs when compared with PC. The cause of reduction in CS of HNFRCs could be due to the presence of less dense fibers. These shows an increase in values of C1, C2, C3, C5 against CTE of PC, in case of C4 the values of PC and C4 for CTE are same. From CTI of PC increased values of CTI of HNFRCs are observed.

– An increase of 3.21%, 4.28%, 2.14%, 1.6% and 0.53% is observed in SS of HNFRCs as compared to that of PC. As compared to STE value of PC an increase of 63.78%, 39.46%, 20.86% and 18.37% is observed in case of C1, C2, C3 and C4 of HNFRCs, while a decrease of 16.67% is noticed for specimens of C5. An increase of 20%, 15%, 13%, 11% and 16% is noticed in STI of HNFRCs as compared to that of PC.

– The values of MoR in case of C1, C2, C3 and C5 increased by 20.27%, 21.19%, 10.13%, 0.92% as compared to PC. The increased value of FTE is observed in case of C1, C2 and C3 by 41.37%, 26.97% and 20.11%, respectively, when compared to the FTE value of PC. While, decrease in value of FTE are observed in case of C4 and C5 by 40.67% and 22.74%, as compared to that of PC. In case of the FTI of PC an increase of 37%, 21.99%, 58%, 24% and 59% is observed in FTI of HNFRCs.

- The damping ratio of HNFRCs in case of cylinders is increased by 12.8%, 23%, 19.2%, 54.3% and 77.9% than that of PC. The damping ratio of HNFRCs beam lets is increased by 109%, 65.5%, 112%, 168% and 210.6% than that of plain concrete specimens. The increase in damping ratio shows that the specimens of concrete containing fibers have an ability to sustain the loading impact in form of damping on them as compared to that of plain concrete specimen.

- An increase in value of WA is observed in case of C1, C2, C3, C4 and C5 by 9.83%, 15.57%, 24.99%, 54.9% and 59.4% than PC. Increased LS value of 70%, 48% and 1.08% is observed in case of C5 and C4 and C3, respectively, as compared to PC. While, a reduction of 22.83% and 6.52% is obtained in LS of C1 and C2, accordingly. No explosive spalling was observed in specimens of HNFRCs, which ensure its performance towards temperature.

The specimens of C5 observed the most mass loss due to high demand of water absorption for jute fibers.

- The fibers of jute show more resistance to pull-out force as compared to that of wheat straw due to their large embedded length and frictional surface. The voids in HNFRC are more as compared to that of PC due to presence of fibers in concrete which induced air bubbles in concrete specimens.

- The empirical relation developed between linear shrinkage and split tensile pre-crack energy absorption of hybrid natural fiber reinforced concrete and that of PC. This will help to determine the rate of shrinkage by using the split tensile pre-crack energy absorption of specimens.

- The specimens of C1, C2, C3 and C5 shows reduction in rigid pavement thickness as compared to that of PC due to increased value of modulus of rupture. While, increase in thickness is observed in case of C4 which shows its properties and uneconomical use for rigid pavements application.

- The enhanced properties of specimens and the effect of hybrid natural fibers on thickness of rigid pavement show their economical and durable construction compatibility to use for practical implementation, especially for under developing countries.

From investigated HNFRCs the specimens of content type C1, C2 and C3 are seems more efficient in controlling rate of cracking in rigid pavements. The reason could be the better bonding of fiber with specific fiber content in concrete mix.

6.2 Future Work

Thus, jute and wheat straw in hybrid fiber concrete have potential to enhance properties of concrete by varying their content in concrete mix. Following works should be given consideration for future working to understand the behavior of HNFRCs in further detail:

- HNFRCs should be studied with varying fiber lengths for each of the constant fiber content.
- HNFRC should be study with same fibers obtained from different origins.
- Fiber decay in concrete mix should be explored to evaluate its performance under different environmental conditions with passage of time.

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Annexure A

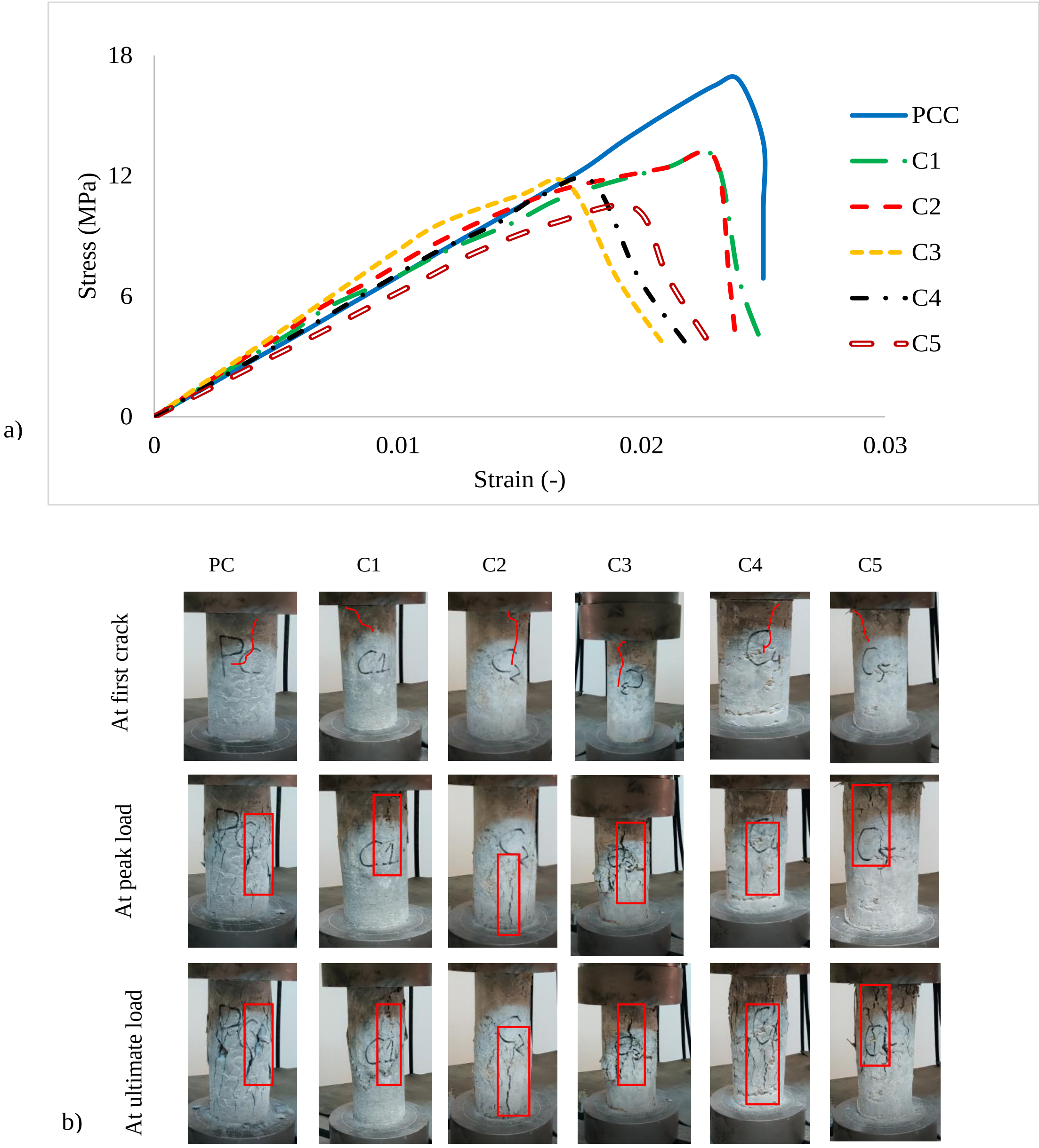


FIGURE A.1: Compressive behavior of HNFRCs and PC; a) typical stress-strain curves, b) crack propagation

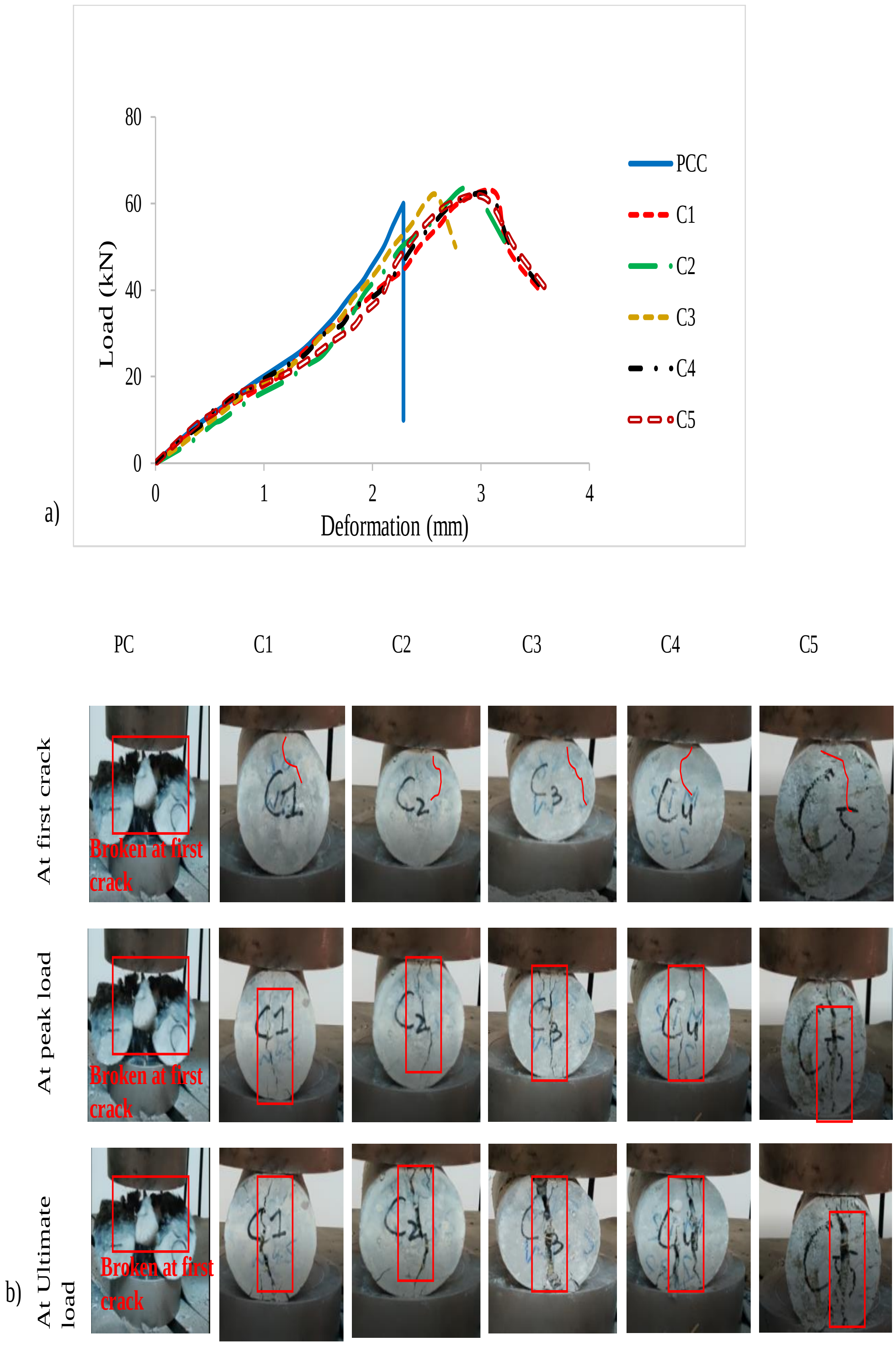
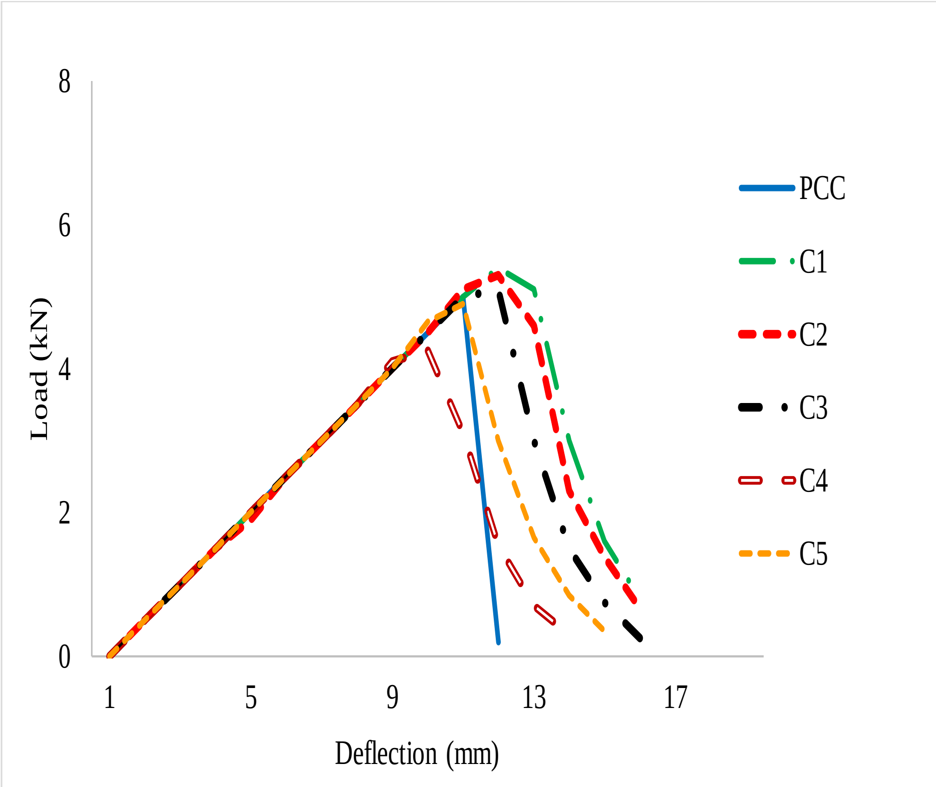


FIGURE A.2: Splitting tensile behavior of HNFRCs and PC; a) splitting tensile strength, b) concrete failure mode a)



b)

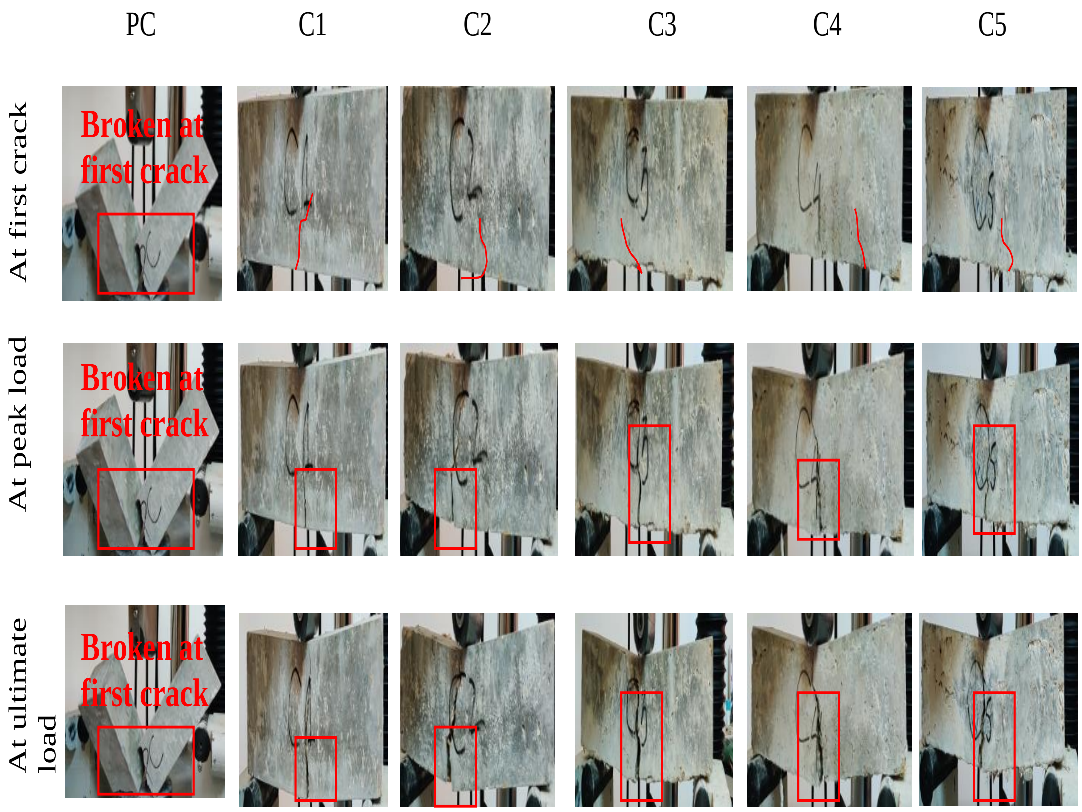


FIGURE A.3: Flexural behavior of HNFRCs and PC; a) typical load- deflection curves, b) crack propagation under loading

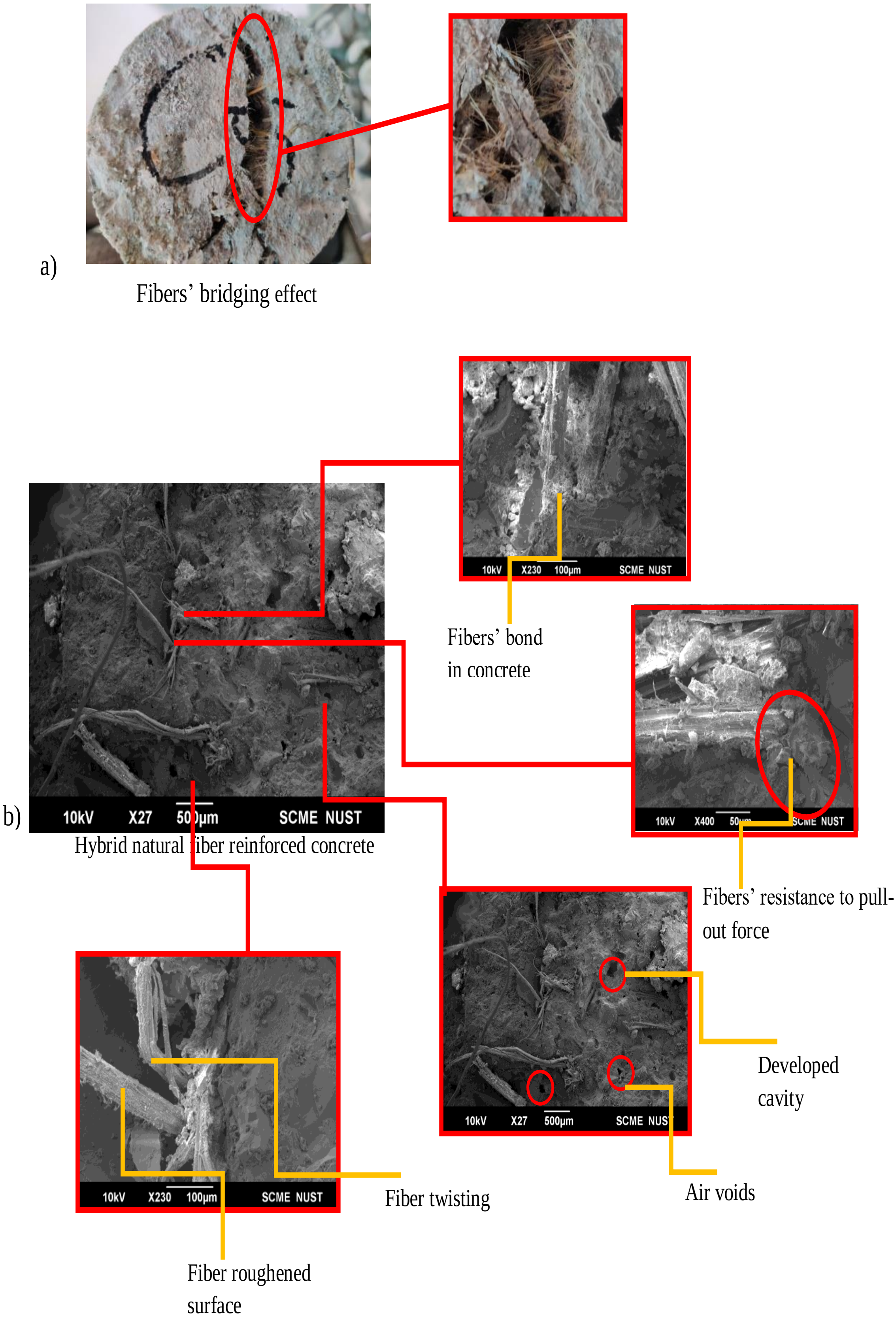


Figure A.4: Fiber matrix bond; a) fragmented bridging in tested specimen, b) SEM images