CAPITAL UNIVERSITY OF SCIENCE AND TECHNOLOGY, ISLAMABAD

Mechanical, Dynamic and Absorption Properties of Concrete with Hybrid Natural Fibers of Varying Lengths

by

Muhammad Abrar

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

in the

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I want to dedicate this achievement to Allama Khadim Hussain Rizvi (R.A), my mentor, who's teachings always encourage me in every step of my life.

CERTIFICATE OF APPROVAL

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Muhammad Abrar

Registration No: (MCE203017)

THESIS EXAMINING COMMITTEE

S. No.	Examiner	Name	Organization
(a)	External Examiner	Dr. Faisal Shabbir	UET, Taxila
(b)	Internal Examiner	Dr. Muhammad Usman Farooqi	CUST, Islamabad
(c)	Supervisor	Dr. Majid Ali	CUST, Islamabad

Dr. Majid Ali
Thesis Supervisor
April, 2022

Dr. Ishtiaq Hassan
Head
Dept. of Civil Engineering
April, 2022

Dr. Imtiaz Ahmad Taj
Dean
Faculty of Engineering
April, 2022

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List of Publications

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Muhammad Abrar

(MCE203017)

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Abstract

Concrete has drawbacks like spalling, cracking, brittleness and non-eco-friendly nature. As far as concrete has high strength in compression, it is weak in tension. Cracking is one of the severe drawbacks of concrete. While non-eco-friendly nature of concrete is the basic reason to find some material for making concrete as sustainable as it can be. On the other hand, agricultural wastes are abundantly produced every year especially in developing counties. Due to their ecofriendly nature, natural fibers in developing countries are gaining attention as sustainable construction materials for cleaner production. The splitting tensile and flexural properties of concrete can be improved by using natural fibers in concrete. One kind of fiber can enhance the properties up to some extent while the use of two different fibers together can provide the combined effect of both fibers. Hybridization of smaller and longer length fibers can help in bridging cracking and can provide better results. Jute fiber (JF) and wheat straw (WS) fiber are the agricultural wastes which are widely available in developing countries like Pakistan, India and Bangladesh. These natural fibers can be used as sustainable construction materials and have ability to make construction environment friendly. The overall goal of this study is to use agricultural wastes (instead of burning) for sustainable construction. The specific aim of this research is to improve the properties of concrete by the utilization of agricultural wastes like jute and wheat straw as sustainable construction materials

In this research the natural fibers are added in concrete to enhance the properties for improving performance of concrete for applications in civil engineering construction industry. JF and WS fibers are used in concrete as hybrid natural fibers. For this purpose, four cylinders and two beamlets are casted for plain concrete (PC). Similarly, jute and wheat straw fiber reinforced concrete (JWS-FRC) samples are prepared by the addition of JWS-FRC. JF are taken 0.5% by mass of cement and wheat straw fibers are taken as 4.5% by mass of cement. The lengths of JF used for hybridization are 25 mm, 50 mm and 75 mm. While, the WS is used with approx. 12.5 mm and 25 mm lengths for hybridization of fibers. The water cement ratio (W/C) of 0.6 is used with mix design ratio 1:2:3 (cement: sand:

aggregates) for the preparation of PC. The 0.7 W/C is used along with mix design ration 1:2:3 for the preparation of fiber reinforced concrete (FRC). The Slump, dynamic, mechanical, water absorption (WA), linear shrinkage (Ls) and mass loss (ML) are performed to check the influence of varying lengths combinations of hybrid natural fibers on the properties of concrete.

Slump results showed that JWS-FRCs have less value of slump as compared to PC. The decrease in slump value is observed with the increase in JF lengths in different combinations. The results have shown that JWS-FRCs have dominant dynamic, tensile and flexural properties as compared to PC. The JWS-FRC with optimum JF lengths of 50 mm and wheat straw fibers of 25 mm have shown better performance against dynamic loading. The decrease in compressive strength (C-S) of JWS-FRC was observed as compared to PC. While, the JWS-FRCs with WS of longer lengths showed more (C-S) as compared to the JWS-FRCs with shorter wheat straw lengths. The increase in splitting tensile and flexural strengths is observed as compared to PC. The JWS-FRCs with 50 mm jute and 25 mm wheat straw fibers have maximum splitting tensile and flexural strengths. The CTI, STI and FTI are enhanced by the use of hybrid fibers as compared with PC. The WA of JWS-FRCs is increased when the lengths of JF and WS are increased. On the other hand, linear shrinkage is decreased by enhancing the lengths of JF and WS fibers. Hence, it is concluded that the optimum lengths are 50 mm jute fiber and 25 mm wheat straw fibers to achieve good results under splitting tensile, flexural loading and dynamic loadings. For application in compression members 75 mm jute fiber with 25 mm wheat straw fibers have shown better properties than all other JWS-FRCs.

Keywords: Agricultural Wastes, Jute Fiber, Wheat Straw, Fiber Reinforced Concrete, Sustainable Construction Materials.

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Abbreviations and Symbols

CE1	Compressive Pre-Crack Energy Absorption
CE2	Compressive Post-Crack Energy Absorption
C-S	Compressive Strength
CTI	Compressive Toughness Index
Ed	Dynamic modulus of elasticity
FE1	Flexural Pre-Crack Energy Absorption
FE2	Flexural Post-Crack Energy Absorption
FRC	Fiber Reinforced Concrete
F-S	Flexural Strength
FTI	Flexural Toughness Index
HNF	Hybrid natural fibers
JF	Jute Fiber
JWS-FRC	Jute and Wheat Straw Fiber Reinforced Concrete
Ls	Linear Shrinkage
ML	Mass Loss
MOE	Modulus of Elasticity
PC	Plain Concrete
Rd	Dynamic Modulus of Rigidity
RFL	Response Frequencies Lateral
RFR	Response Frequencies Rotational
RFT	Response Frequencies Transverse
SE1	Splitting-Tensile Pre-Crack Energy Absorption
SE2	Splitting-Tensile Post-Crack Energy Absorption
S-S	Splitting-Tensile Strength

STI	Splitting-Tensile Toughness Index
STM	Servo-Hydraulic Testing Machine
W/C	Water-Cement Ratio
WA	Water Absorption
WS	Wheat Straw Fibers
ζ	Damping Ratio
Δ	Defection

Chapter 1

Introduction

1.1 Background

Since past century, concrete has been used as primary binding material in civil engineering construction industry. So, concrete is considered as backbone material for construction [1]. Being widely used material, although it has advantages, it also has drawbacks. Concrete is a brittle material which is stronger in compression phase and weaker in tension [2], [3].

The service life of structure is reduced due to micro-cracking caused by brittle nature of concrete. It introduces durability concerns because of higher penetration of intruding agents [4]. Due to these characteristics, cannot be relied on concrete. To achieve sustainable material and to enhance properties and performance, there is need to add fibers in concrete. Toughness and tensile strength of concrete is enhanced by addition of fibers [5]. In past few decades, different natural fibers have been used in concrete for attaining specific desired properties, enhancing early strength, accelerating setting time and reducing content of cement in concrete. Therefore, the eco-friendly and high performance materials have to meet with the characteristics such as economy, safety, sustainability and environment friendly [3]. Fiber reinforced concrete (FRC) provides high toughness, energy absorption and good tensile strength. Owing to these facts FRC with short discrete fibers which have considerable length as compared to their diameter has to be studied for attaining these advantages.

Synthetic fibers are not eco-friendly and have harmful effects on human life. They do not undergo easily biodegradation. Wheat straw is a by-product and obtained from wheat crop as a waste material whereas jute fiber is also natural plant fiber. Both are eco-friendly and have no harmful effects on human life. Wheat straw and jute fibers provide advantages like local availability, non-toxicity and low cost [6]. Burning phenomenon of wheat straw in fields produces carbon dioxide (CO_2) [7]. Concrete also emits CO_2 and require large amount of energy for its production [8].

Utilization of hybrid natural fibers (HNF) can reduce content of cement being used in production of concrete. Development of cracks can be countered by use of natural fibers in concrete. On the other hand, the tensile strength, energy absorption can also be increased by short discrete fibers [9]. Many researchers reported the enhancement of resistance against fatigue, cracking and spalling along with increase in flexural strength. Hence, the performance of concrete can be improved for desired applications. Utilization of varying length hybrid fibers in concrete can lead to reduction in macro and micro cracking by introducing bridging effect in concrete. In fact, the addition of natural can enhance numerous mechanical, dynamic and absorption properties of concrete.

1.2 Research Motivation and Problem Statement

Concrete is the primary construction material in this modern age. Although it has many flaws, it cannot be replaced with any other material which may overcome the flaws like lack of tensile strength, lack in flexural strength, low resistance against impact loading result from blast or collision of greater mass body. So, the aim of this study is to mitigate or reduce the impact of these above-described short comings to serve humanity. Because failure of concrete structure can lead to loss of valuable human lives and also the huge loss of money. So, there is need to avoid failure of the concrete when subjected to different types of loadings. On the other hand, burning or dumping of agricultural wastes is also causing environmental pollution.

The use of short discrete natural fibers has been reported to enhance the desired properties of concrete and to avoid its failure. With the development of this world, there is need to introduce new materials and ways in construction industry like high-performance and sustainable materials of construction. The main concern of this research program is to introduce agricultural wastes as sustainable construction materials for enhancing the properties of concrete. For mitigating the flaws of concrete; avoiding structural failures to save human lives. This is the continuation of the research which was applied on rigid pavements and provided better properties [10].

This current study is aimed to take a step forward for utilization of agricultural wastes materials in a useful way to enhanced mechanical and dynamic properties for different structural applications. Based on the relative comparison, this research work is limited to experimental investigations. Moreover, this study may help the researchers to provide a way of thinking and guidelines and to use agricultural wastes in concrete by an effective way. In this way these wastes can be avoided from burning or dumping which is time taking, costly and harmful process for our environment.

"With the growing age, urbanization is increasing, resulting in the increase of construction material like concrete which is not environment friendly. Burning of agricultural wastes also emits Carbon dioxide (CO_2). Agricultural wastes like jute and wheat straw fibers can be utilized in concrete to improve the physical properties of concrete. The use of varying length short discrete natural fibers can lead to reduction of micro and macro-cracking in concrete resulting enhancing the ability to withstand loads, improving tensile strength and toughness.

The hybridization of varying length natural fibers i.e., wheat straw and jute fibers may provide better results by their combined effect. There is no such study that has been conducted which relates to the effects of varying length wheat straw and jute fibers on the mechanical, dynamic and absorption properties of concrete. Construction can never be stopped but the agricultural wastes can be utilized to enhance the properties, saving environment and providing the sustainable materials for sustainable development.

1.2.1 Research Questions

- What is combined effect of varying length jute and wheat straw fibers on the dynamic properties of concrete?
- How much splitting tensile and flexural strength can be enhanced in comparison to compromise with compressive strength after incorporation of varying length hybrid natural fibers?
- What is effect of hybrid natural fibers on the post-crack energy absorption?
- What is the effect of the hybrid fibers on the compressive toughness index, splitting-tensile toughness index, and flexural toughness index?

1.3 Overall Objective of the Research Program and Specific Aim of this MS Research

The overall goal of this research program is to take a step forward towards the development of sustainable concrete for various construction and civil engineering applications. As concrete has many flaws and these flaws affect the performance of structure. Also, provide a platform for utilization of wheat crop waste material i.e., wheat straw instead of burning or dumping with jute fibers by hybridization because it is reported to have good potential to be used in concrete.

"The specific aim of this MS research work is to study the mechanical, dynamic and absorption properties of varying length hybrid natural fibers (jute and wheat straw) reinforced concrete and its comparison with plain concrete (PC) properties.

1.4 Scope of Work and Study Limitations

The workability mechanical properties, dynamic properties and absorption properties are investigated by taking 2 specimens for each property of jute and wheat straw fiber reinforced concrete (JWS-FRC). Dynamic properties are studied before investigating the mechanical and absorption properties. After appearance of first crack on specimen, it is considered as failure after load application. Other miscellaneous properties like linear shrinkage, mass loss and visual inspection of broken specimens are also examined in this current study.

The study is purely limited to mechanical, dynamic and absorption properties of JWS-FRC having different length combinations of jute and wheat straw hybrid fibers. In this scope of study, durability of JWS-FRC is not included. Resistance against impact loading and influence on performance is not considered. Carbon footprint of waste utilization regarding jute and wheat straw fibers is not in the scope of this work. It is the continuation of research on the recommendations of [10] so the detailed study on the fibers properties is not considered. The fibers are used with different length combinations after hybridization but keeping the percentage content of fibers as fixed.

1.4.1 Rationale Behind the Variable Selection

Fibers are selected based upon the superiority of physical properties comparison to others. Both fibers are locally available. Fibers of different lengths may help for bridging micro as well as macro-cracks and they may provide good physical properties as investigated by [10].

1.5 Novelty of Work, Research Significance and Practical Implementations

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 [11]. 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 [12]. 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. This work may contribute for understanding the hybridization of agricultural wastes by different lengths combinations. 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. To the best knowledge of the authors, no such research has been reported which include the hybridization of jute fiber (JF) and wheat straw (WS) of different lengths and further use in concrete. As a result of this, there is need to explore the varying lengths hybridization of JF and WS and their effects on mechanical, dynamic and absorption properties of concrete. This may result in production of a better material to be used in civil engineering and construction industry.

Despite of having many flaws like low tensile and flexural strength and less resistance against lateral loading concrete is also not an eco-friendly material. On the other hand, burning or dumping of agricultural wastes is also causing environmental pollution. The fiber reinforced concrete made of natural fibers have shown better properties as compared with PC. The hybridization of natural fibers have shown better results as compared to sole fibers [14], [15]. The main concern of this research program is to introduce agricultural wastes as sustainable construction materials for enhancing the properties of concrete. For mitigating the flaws of concrete; avoiding structural failures to save human lives. This is the continuation of the research which was applied on rigid pavements and provided better properties [10].

The previous research includes the hybridization of jute and jute and wheat straw fibers by varying contents. There is need to use different length combination of optimum fibers contents recommended by that study. This current study is aimed to take a step forward for utilization of agricultural wastes materials in a useful way to enhanced mechanical and dynamic properties for different structural applications. After analysis of the results, different combinations of JWS-FRCs can be proposed having different jute and wheat straw lengths combinations. These recommendations can be made for specified properties and applications in construction industry. Moreover, this study may help the researchers to provide a way of thinking and guidelines and to use agricultural wastes in concrete by an effective way.

1.6 Brief Methodology

In this experimental study, the basic mechanical, dynamic and absorption properties of plain concrete (PC), jute and wheat straw fiber reinforced concrete (JWS-FRC) are determined in laboratory. For the preparation of fiber reinforced concrete (FRC), wheat straw and jute fibers are used. The varying lengths of 25 mm, 50 mm and 75 mm of jute fibers are used in the preparation of the FRC. These lengths are selected based upon the literature survey [12,46,64,87,109]. Whereas, 12.5 mm and 25 mm lengths of wheat straw are used in FRC. Proportion of wheat straw is kept fixed as 4.5% and 0.5% for jute fibers in all JWS-FRCs as recommended by [10]. The use of 4.5% of fiber by mass of cement is taken and this content is also being used by other researchers [106-108]. Tap water (at normal temperature) is used for preparing the PC and all JWS-FRCs. Two different water-cement ratios are used for manufacturing different types of specimens. 0.6 water-cement ratio is used for making PC and 0.7 water-cement ratio is used for all JWS-FRCs. The water cement ratio for the JWS-FRCs is increased due to the more water absorption property of the jute and wheat straw (natural fibers) as reported in literature [16,17].

The workability plays an important role in the hardened properties of concrete and for easy handling pouring and transporting the concrete [18]. So, the workability of fresh PC and all JWS-FRCs is determined by slump cone test. All specimens are casted as per the ASTM standards. After the workability test, total 42 number of specimens of PC and JWS-FRC are casted. Two beamlets and four cylinders are casted for each combination of JWS-FRC. From these four cylinders, two are used for testing compressive properties and two are used for testing splitting tensile properties of PC and JWS-FRCs. Flexural properties of every type of JWS-FRC are explored by three-point loading setup on casted specimens of beamlets. A servo-hydraulic testing machine is used to conduct the different types of mechanical tests. The flow chart present in **Figure 1.1** shows the brief description of current study.

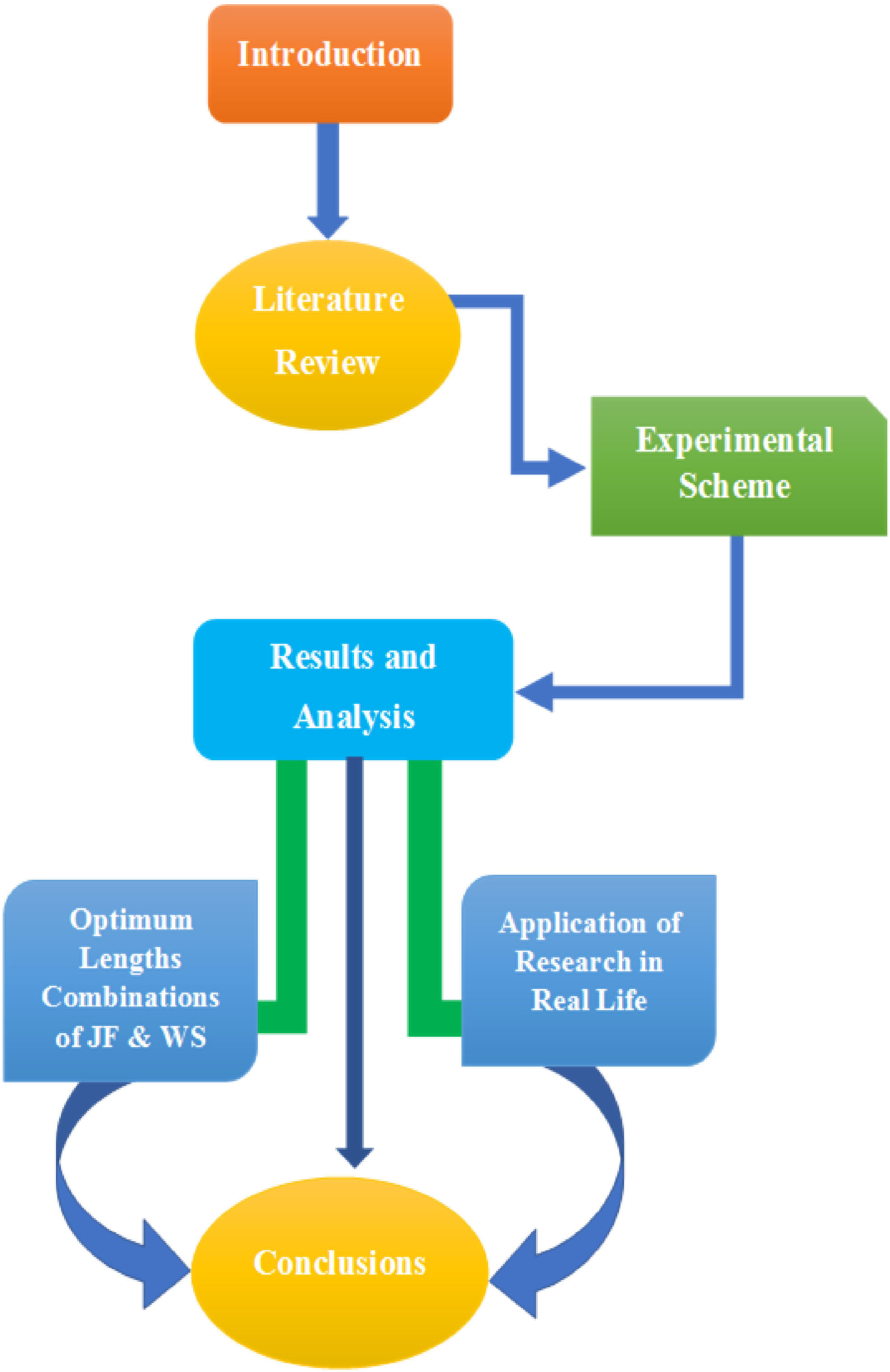


FIGURE 1.1: Flow Chat of Current Research

Before performing the mechanical and other miscellaneous properties like linear shrinkage mass loss and water absorption, dynamic properties are investigated with the help of accelerometer and a hammer. Response frequencies longitudinal (RFL), response frequencies transverse/lateral (RFT), and response frequencies rotational/tortional (RFR) are noted by attaching the accelerometer to the specimens and applying for recording frequencies as per the specific setup of desired frequencies.

These recorded frequencies are then used to determine the dynamic properties of both PC and all types of casted JWS-FRC specimens. The fractured surfaces of broken specimens are closely examined to check the proper mixing of short discrete fibers in concrete, bond of fibers with surrounding matrix, fibers pull out and fiber breakage for both jute and wheat straw hybrid fibers.

1.7 Thesis Outline

The thesis contains six chapters. These are:

Chapter 1 includes the introduction. It covers the background, research motivation and problem statement, overall and specific aims of this research, scope of work with study limitations, brief methodology, and thesis outline.

Chapter 2 contains the literature review. It comprises of background, agricultural wastes, sustainable construction materials, latest trends in use of agricultural wastes as construction materials, hybridization of different fibers, use of varying lengths natural fibers in concrete, flaws in concrete and their remedies and summary.

Chapter 3. This chapter consists of the experimental scheme, raw ingredients in concrete, mix design casting of specimens, testing, and summary of chapter 3.

Chapter 4 includes the results obtained from tests and their analysis. It describes the background, dynamic properties and mechanical properties of the mixes (PC and JWS - FRCs), miscellaneous properties (water absorption, linear shrinkage, and mass loss), fractured surfaces of tested specimens, and summary of chapter 4.

Chapter 5 explains the guidelines for practical implementation, it has background, optimum combination of jute and wheat straw fiber lengths, application of this research in real life, and summary of chapter 5.

Chapter 6 consists of conclusions and future recommendations.

Chapter 2

Literature Review

2.1 Background

Since ancient times, fibers are being used for enhancing the mechanical strength parameters and performance of composites. Utilization of natural fibers is preferred due to their eco-friendly and low-cost nature. Agricultural wastes are generated in millions of tons every year. It is need of time to use these wastes for useful purposes. It has been proved that the fiber reinforced concrete provides better results as compared to conventional concrete. There is need to explore the potential of agricultural wastes as sustainable construction material and their effects when used as hybrid material in concrete for a positive step towards sustainable development.

2.2 Agricultural wastes

Agricultural wastes (agro wastes) are the byproducts or surplus of crops which are abundantly present in developing countries [19]. These wastes need much land to be dumped or disposed. Agro wastes produce about 9% of the total energy production. On the other hand, agro wastes provide around 35% of the total energy consumption in developing countries. World produces about 2.9 billion of crop straw annually and 66% of these straws are burnt as source of energy [20]–[22]. Open burning of wheat straw is the wastage of natural resources and causing air pollution; severe threat to highway traffic, impairing human health and safety [23], [24]. Agricultural wastes include bagasse straw, olive stones, grapes seeds, cotton stalks [25]–[27], pine sawdust [28], pecan, almond, hazelnut, sunflower shells [29], [30], jute, wheat straw, rice straw, rice husk, corncob and cassava rhizome etc. [31]. It was found that about 59% of the gross residue of rice crop contains rice straw whereas 20% is rice husk [32].

According to food and agricultural organization united states 2017, the world produces about 3.8 million tons of buckwheat straw and the issue of recycling of this straw is a matter of concern. Worldwide rapeseed production in 2017 was 72.6 million tons and stem or branches of this agricultural waste can be used as construction material [33]. About 200,000 million of waste is generated from date palm. This palm waste is charred and released as agro waste which can be utilized in production of sound absorbing panels [34].

About 3.3 million tons of jute was produced in world annually whereas India and Bangladesh produced approximately 1.9 to 1.4 millions of jute per year [33]. Jute is the second largest fiber which is used in textile and Bangladesh produce 33% of the total world's jute production [35]. Palm agricultural waste is produced during the production of palm oil. For one unit of palm oil, 10 units of dry biomass are generated. Lignocellulosic fiber can be extracted from fruit mesocarp and empty fruit bunches [36]. These palm fibers have more rigidity as compared to wood and have thicker cells [37].

Pakistan is the eighth largest wheat producing country and produce approximately 27 million tons of wheat per year. Due to this high wheat harvest, Pakistan produces a large amount of wheat straw. About 1.5 kilogram of wheat straw is produced for every one-kilogram wheat grain. Therefore, Pakistan produces 16 million ton of wheat straw waste annually [38]. The most of the wheat straw is disposed in open areas or burnt [103-105]. Due to this reason, safety health and esthetic problems are generated. Cultivation of coconut produce coconut fiber as fibrous waste. Approximately 30 million tons of coconuts are produced every year. Coconut husk generate 70% of pith and 30% fiber [39]. Agricultural waste is the most concerning problem for world regarding conservation of global environment in present days. These wastes sparked researchers to use waste fibers instead of manmade fibers due to their ease of handling and environment friendly properties. Only 10% of agricultural waste biomass is used as alternative raw material [40]. There is need to utilize this waste in useful manner for cleaner production.

2.3 Sustainable Construction Materials

In last 100 years, concrete production had imposed adverse ecological effects on environment. So, it is exerting contrary effects than benefits. Billions of tons of concrete are produced every year which emit carbon dioxide during mixing process and require large quantity of raw materials. The cement industry generated 7% of the total carbon dioxide of the world [41]. The agricultural and industrial wastes produced in urban and rural areas need proper disposal. The recycling of wastes to useful products is the solution of the crises of dumping wastes. The byproducts like silica fume, fly ash, granulated blast slag and palm oil fuel ask had been used as sustainable construction materials [42]–[45].

These materials can be utilized in concrete for further use in different structural elements. Jute fiber was used by [46] as sustainable material for pavement application for freeze-thaw conditions. It was observed that the jute fiber reinforced concrete reduced the freeze-thaw effect. By the incorporation of jute fibers, the pavement with reduced thickness showed same results as compared with the pavement laid by the conventional concrete. The wheat straw has good properties to be used in cement composites. **Table 2.1** shows the studies conducted on the wheat straw fiber reinforced concrete.

Wheat straw had been used by different researchers for application in concrete [13], [50]. A biobased composite i.e., wheat straw concrete was developed for the purpose of thermal insulation. The outcomes indicated that the biobased composite developed by using wheat straw showed excellent hygric properties. These properties can ensure the building's hygrothermal comfort [51]. Wheat straw was used in cement-based mortar for attaining sustainable cement mortar. Under the impact compression loading the specimen did not separate apart but only showed discrete cracking. The overall mechanical properties were enhanced with no change in thermal properties [52].

TABLE 2.1: Results Obtained by Incorporation of Wheat Straw in Composites

Fiber	**Mertrix**	**Fiber Eeinforced Composite Properties**	**Values Obtained**	**Application**	**References**
Wheat Straw	Cement mortar	Max. bending loading	2.4-2.9 kN	-	[47]
	Concrete	Residual tensile strength	i) 1.88 MPa (0.47mm defection) ii) 1.33 MPa (3.02 mm deflection)	Ground Floor	[48]
	Cement concrete	Compressive strength	31.7 MPa	Building Material	[49]
		Fracture energy	111-133 MPa		
		Notch tensile strength	3.3-3.7 MPa		

Sisal fiber was used as sustainable construction material for making eco-friendly ultra-high-performance concrete. Sisal fibers delayed the setting time by restraining the hydration process and autogenous shrinkage was also reduced [53]. Coconut, sisal, jute and sugarcane natural fibers can be used as sustainable construction materials and enhance the tensile as well the compressive properties of concrete [54].

Agricultural wastes like sugarcane bagasse and coffee husk were used as partial replacement of crushed stones to prepare concrete blocks. The thermal, physical and mechanical properties were increased by the use of coffee husk and sugarcane bagasse. Sugarcane bagasse. showed superior properties as compared to coffee husk to be used as sustainable construction material for blocks. By addition of 5% sugarcane bagasse, the concrete block showed improved compressive strength and all the required properties for commercial usage [55].The agricultural wastes and by products can be used in concrete for useful purposes and for also enhancing the required property of concrete or mortar by choosing appropriate natural fiber as sustainable construction material.

2.4 Latest Trends in Use of Agricultural Wastes as Construction Materials

In the current era, sustainable development is a key consideration. Every step taken to achieve the goal of sustainable development has its own importance. In this worldwide effort to achieve sustainable solutions, the focus is on reduction of wastes, which is ultimately providing contribution to global warming. Now a days, re-using and re-cycling are the major concerns, which take the attention of people to counter environment related issues [56-59].

During past few years, remarkable interest has been developed on using natural fibers/agricultural wastes in cement composites for attaining alternate sustainable, eco-friendly building materials. Also, natural fibers have considerable potential to be used as reinforcement for countering the conventional flaws in concrete. Agricultural waste natural fibers are used in brittle cementitious composites to enhance the toughness and well as the energy absorption [60]. Many researchers have used natural fibers as an alternate material for various applications. These agricultural wastes/natural fibers which are used in cementous composites are bamboo, banana, vakka, palm, jute, hibiscus cannabinus, abbaca leaf, sisal, coir, date, malva, pineapple leaf, hemp, ramie bast, wheat straw, sansevieria leaf, kenaf bast etc. [49,61–63].

Natural fibers are cheap and locally available abundantly in many countries. For improving the properties of cementous composites, agricultural waste natural fibers can be used a renewable low-cost construction material. Beside this quality of low cost and availability, natural fibers are easy to be handled as compared with artificial fibers. Hybridization of both natural fibers provide better results as reported by [111]. They can also contribute in the sustainable development as they have low cost and other desired properties for being used in cement composites [62]. An experimental study was carried out for using date palm agricultural wastes as sound absorbing construction. The samples of 25 mm, 35 mm, 45 mm and 55 mm were made. It was found that the samples of 55 mm thickness showed maximum sound absorption [34].

Natural fibers have good properties to be used in concrete. The properties of some natural fibers are given in **Table 2.2**. It can be observed from table 2.2 that the JF and WS have better properties than other natural fibers. Dynamic and mechanical properties of coir fiber reinforced concrete were determined by [64]. The optimum content was observed as 5% and optimum length as 5 cm. There was considerable increase of 910% in the compressive toughness of coir fiber reinforced concrete. Bamboo fiber was used in asphalt road to enhance road performance along with improving cracking resistance. The fatigue resistance and dynamic modulus were enhanced by bamboo fiber [65].

Bamboo sheet twinning tube was developed and used as column along with recycled aggregates. Results revealed that residual bearing capacity, compressive strength and ductility was considerably enhanced [66]. Hemp concrete was prepared to check the hygrothermal performance of hemp concrete as compared with conventional concrete.

Table 2.2: Natural Fibers and their Properties

Sr. No	Fibers	Properties	References
1	Wheat Straw	High energy absorption, high toughness index, strong, high water absorption capacity, easily available.	[13]
2	Jute fiber	Lighter than steel, higher breaking strength, easily available, high energy absorption,	[69]
3	Coconut fiber	High toughness index, high damping ratio, economical, good flexural strength	[64]
4	Flax fiber	High tensile strength, elongation property up to 2.7-3.2%, biodegradable, cost effective	[70]

It was found that hemp concrete can improve the energy efficiency of building and can reduce the environmental impacts [67]. Agricultural wastes can be used as insulating material by incorporation with other composites [68].

2.4.1 Hybridization of Different Fibers

Hybridization of natural fibers is accomplished to get the combined effect of two or more fibers. For this purpose natural fibers are used in concrete to enhance the desired properties of concrete. Boumaaza et al. [71] used sisal, flax and jute fibers of 5mm, 10 mm and 20 mm lengths. The results revealed that the addition of sisal, flax and jute fiber by the hybridization considerably enhanced the flexural properties of concrete. The maximum flexural strength was obtained by the hybridization of 20 mm length fibers. FRC having fiber length of 5-20 mm had shown improvement of flexural strength up to 13% [71].

However, FRC having fiber length of 25 mm to 75 mm had shown improvement in flexural strength up to 38% [12,46,64,87,109]. Thus, FRC with fiber lengths of 25-75 mm is better. A study was carried out by the usage of hybrid fibers with the combination of hybridization of 0.3%, 0.4% and 0.5%. The hybridization of natural fibers by the optimum content of 0.3% showed maximum strengths. The hybridization of natural fibers of two different length was carried out. It was found that the hybrid natural fibers after the hybridization provide better flexural strength as compared to the conversional concrete [72]. The combined effect on concrete after the hybridization depends upon the chemical composition and the ingredients present inside the fibers. **Table 2.3** shows the elements present in wheat straw and jute fibers.

Hybrid natural fiber reinforced concrete is used as a replacement of plain concrete (PC). Macro fibers helps to tackle macro-cracks and increase toughness of concrete also the flaws and their remedial measures with varying length natural fibers [79]. In hybrid natural fiber reinforced concrete, 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 de-bonding [80]. The presence and surfaces of fibers control the energy dissipation and deformation phenomenon after post cracking [81]. Fiber pull-out from matrix promotes the ductile behaviour of concrete because of energy dissipation during the process of post-cracking [82].

TABLE 2.3: Composition of Jute and Wheat Straw Natural Fibers

Fiber	**Element**	**Percentage Weight**	**References**
Wheat Straw	Oxygen	28.65-42.4	[73]
	Carbon	43.51-63.6	[74]
	Potassium	0.00-1.79	[75]
	Silicon	0.04-7.01	[76]
	Calcium	0.42-20.57	[77]
Jute Fiber	Moisture	∼12.6	[78]
	Pectin	∼0.2	[78]
	Wax	∼0.50%	[78]
	Ash	0.5–2	[78]
	Cellulose	61–71	[78]
	Hemicelluloses	13.6-20.4	[78]
	Lignin	Dec-13	[78]

Fiber reinforced concrete continue to make more loads until the fibers present in fiber reinforced concrete break. An experimental study was carried out by using hybridization of jute, coconut, sisal and sugarcane. The presence of cellulosic natural fibers enhanced the tensile and compressive strengths of fiber reinforced concrete by varying the content of these fibers. By the hybridization of jute and sisal fibers, the compressive strengths were enhanced by 11.6% and 22.2% respectively. The results revealed these natural fibers can be used in pavements and flooring slabs as sustainable construction materials [54].

2.4.2 Use of Varying Lengths Natural Fibers in Concrete

Varying length natural fibers are used in concrete to create the bridging effect, short and long fibers resist the macro as well as micro-cracking [83]. Many researchers reported that by the use of optimum lengths and content, it can improve the mechanical properties and physical properties like flexural strength, splitting tensile strength and impact resistance [84], [85]. Micro and macro cracks are formed during the hydration and hardening process of concrete. When specimen is subjected to external loading the propagation of these cracks starts which result in failure of structure. The varying length natural fibers can bridge the micro as well as macro cracks and can resist the propagation of micro cracks towards macro cracks [86]. The crack bridging mechanism of fibers is shown in **Figure 2.1**.

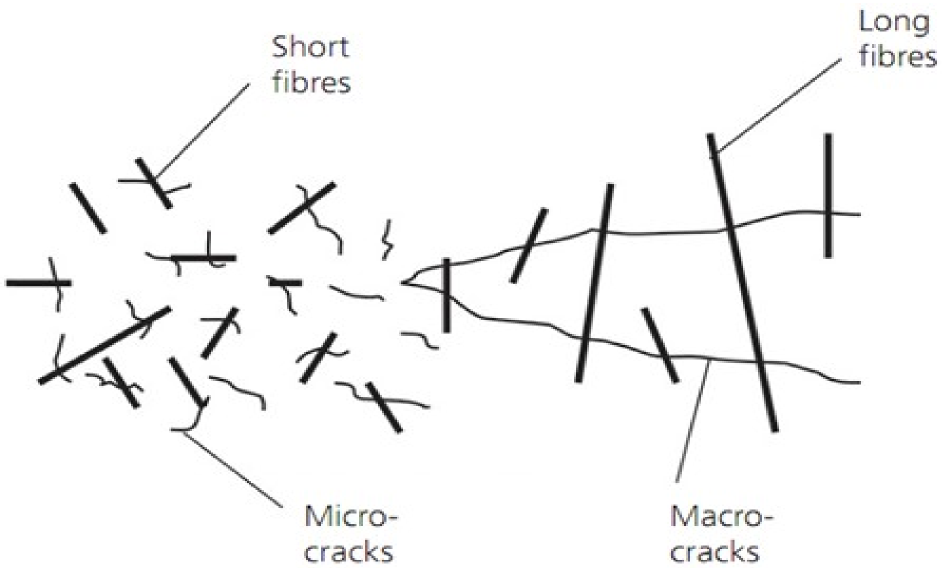


FIGURE 2.1: Crack Bridging Mechanism of Varying Lengths Natural Fibers [86]

[6] conducted a study on varying length natural fibers. The results revealed that the fibers lengths used for reinforcement is directly proportional to the mechanical strength. [87] performed experimental research on the effect of coconut fibers content and length in concrete. Coconut fibers of 25 mm, 50 mm and 75 mm lengths were used in that research. It was observed that the fibers of 50 mm length enhanced the energy absorption and toughness of concrete. So, the optimum lengths of natural fibers in concrete play an important role in attaining energy

absorption and toughness. [88] carried out a study to find out the influence of fibers length and content on the crack resistance of fibers. Results showed that the addition of low content like 1% and longer lengths increased the tensile strength of natural fiber reinforced concrete. For the use of longer lengths of natural fiber the low content like 0.5% was found effective.

2.4.3 Flaws in Concrete and their Remedies

Being widely used material, although concrete has advantages, it also has drawbacks. Concrete is a brittle material which is stronger in compression phase and weaker in tension [3]. During the hydration of concrete, cracks appear on the surface of concrete which may cause the reduction in strength of concrete. When external load is applied these cracks lead to failure of structure [86]. Natural fibers have good potential to be used in concrete. They act as the cracks arrestor and try to bridge cracking. The advantage of the usage of different lengths natural fibers is to bridge micro as well as macro cracking. Conversional concrete has low toughness and energy absorption as compared to fiber reinforced concrete [89]. During the splitting tensile loading the conventional concrete splits into parts while the bridging effect of fibers tend to take more loading until the fiber breakage occurs. The energy absorption and toughness of structure is important factor while making earthquake resistant structures [90].

The low tensile strength of concrete is always needed to be reinforced. The binding material like cement has adverse ecological effects which produce environmental concerns [91]. For the sustainable development and to reduce energy consumption varying lengths natural fibers can be utilized in concrete. The evaluation of cracking in concrete structure is based on two properties of concrete, which include 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 [92]. The tensile strain capacity of concrete is measured through modulus of rupture.

2.5 Summary

From the above discussion, it is concluded that the use of agricultural wastes can improve the properties of concrete. The hybridization of two fibers can provide a combined effect as compared to sole fiber. It is important to improve the mechanical and dynamic properties of concrete to resist the crack propagation. Agricultural wastes which are causing serious issues to our environment. Burning or dumping of agricultural wastes is a matter of concern. These wastes have ability to be utilized in concrete. From this literature, it is concluded that the flaws of concrete can be mitigated by agricultural wastes. Hybrid natural fibers can improve the splitting tensile and flexural strength of concrete. The hybridization of varying length natural fibers can arrest the micro as well as macro cracking resulting in improvement of concrete performance.

Chapter 3

Experimental Scheme

3.1 Background

The agricultural wastes are abundantly available in subtropical regions. The use of agricultural wastes natural fiber in concrete is increasing with time due to their easy handling, easy availability, cheap and environment friendly nature. In this research, jute and wheat straw fibers are used as reinforcement in concrete. From the previous chapter, natural fibers have been used by many researchers in concrete for enhancing desired properties. While, the hybridization of jute and wheat straw with different lengths combinations is still not explored. For this purpose, slump cone test, mechanical tests, water absorption, linear shrinkage and mass loss tests are considered. These tests are taken into count to check the influence of different wheat straw and jute fibers lengths combination on concrete. Also, the analysis of fractured surfaces of broken specimens is performed. In this chapter, raw ingredients, treatment of jute fiber, methods of mixing PC and JWS-FRCs, casting procedures and methodology of testing are discussed in detail.

3.2 Raw Ingredients of Concrete

For the production of normal plain concrete (PC), ordinary Portland cement and Margalla crush along with locally available sand are used. The maximum size of the aggregate is 20 mm used for manufacturing both plain concrete and fiber reinforced concrete (FRC). Commercially available cut length wheat straw fibers are used. 12.5 mm and 25 mm lengths of WS are selected based upon their commercial availability. Jute fibers are taken in raw form. Firstly, the jute fibers are combed properly to achieve straight fibers for ease of cutting and further use in concrete. Then these fibers are cut into desired lengths of 25 mm, 50 mm and 75 mm. No additional treatment is being made because of no visual impurities on both fibers. The aspect ratio of wheat straw is 2.5 and 5. The properties of jute and wheat straw fibers are given in **Table 3.1**.

Table 3.1: Properties of Jute and Wheat Straw Natural Fibers [93]–[98]

Parameters	**Jute**	**Wheat Straw**
Diameter (um)	20-200	05-07
Density (kg/m3)	1300-1490	1150-1200
Tensile modulus (MPa)	320-800	30-32
Youngs modulus (GPa)	08-78	6.0-6.6
Max. elongation (%)	1-1.8	1-1.13
Water absorption (%)	281	(-)
Elongation (%)	1.5-1.8	5.4
Specific gravity (g/cm3)	1.3	0.9-1.18

FIGURE 3.1: Images of Jute Fibers (Raw, Treated, Cut Lengths Used) and Wheat Straw

Figure. 3.1 shows the jute and wheat straw fibers; treatment process of jute fibers is also present in this image. For the preparation of FRC, wheat straw and jute fibers are used. The varying lengths of 25 mm, 50 mm and 75 mm of jute fibers are used in the preparation of the FRC. Whereas, 12.5 mm and 25 mm lengths of wheat straw are used in FRC. Proportion of wheat straw is kept fixed as 4.5% and 0.5% for jute fibers in all JWS-FRCs as recommended by [10]. Tap water (at normal temperature) is used for preparing the PC and all JWS-FRCs. Two different water-cement ratios are used for manufacturing different types of specimens. 0.6 water-cement ratio is used for making PC and 0.7 water-cement ratio is used for all JWS-FRCs.as reported by [12]. The water ratio for the JWS-FRCs is increased due to the more water absorption property of the jute and wheat straw (natural fibers) as reported in literature [16,17]. The W/C for PC is 0.6 to 0.7 as reported by [12]. The higher W/C ratio caused bleeding in concrete and may reduce the C-S as reported by [112].

3.3 Mix Design and Casting of Specimens (W/C Ratio, Slump Test and Density Determination)

For preparation of PC, mix design ratio of 1:2:3 (cement: sand: aggregate) is used. Fixed proportions i.e. 4.5% wheat straw and 0.5 % jute fiber are added in the mixture for the manufacturing jute and wheat straw fiber reinforced concrete (JWS-FRC). All the materials are placed in the drum mixture for preparing the PC mix. Then water is added, in mixture machine, 30-45 seconds after start of rotating the mixture machine. The mixture machine is rotated for the five minutes. The slump cone test is performed after preparation of PC.

For the manufacturing of JWS-FRC, the materials are placed in the form of layers to achieve the good mixing of hybrid fibers within the concrete. Three set of layers are used to make a good mix of the JWS-FRC. One third set of layers of aggregates, sand, wheat straw, jute fiber and cement are placed in the mixer machine. Then the second and third set of layers of aggregate, sand, jute fibers, wheat straw and cement are placed with the same approach. Then the mixture machine is turned on to start rotating. And the two third water is added with the start of machine. After the three minutes continuous rotation of mixer machine, remaining one third quantities of water is added and mixture machine is kept rotating for further two minutes and slump cone test is performed to check the workability of the fresh JWS-FRC. Same approach was for the remaining the types of JWS-FRCs with fixed amount of the jute and wheat straw fiber.

Slump cone test is used to investigate the workability or consistency of the manufactured PC. The slump test for the PC and JWS-FRCs is always performed before the pouring in molds. According to ASTM standard C143/C143M-15a, slump cone test is performed to evaluate the workability of the fresh concrete. Slump cone of bottom diameter of 200 mm (8 in), top diameter of 100 mm (4in) and height of 300 mm (12 in) is used to perform the test. The cone mold should be of non-absorbent.

Tamping rod is hemispherical from both ends with the diameter of 16 mm (5/8 in) and length not more than 600 mm (25 in). The cone is filled with three equal volumetric layers of concrete. After the placing the first 1/3-layer, compaction is done by total 25 times randomly dropping tamping rod on surface of the layer from height of 25 mm (1 in).

Similarly, further two layers of cone are filled and compacted with the help of tamping rod. Removed the extra amount of concrete with striking of the tamping rod and made it smooth by screeding and rolling the rod over it. Later, slump cone is lifted vertically upward. The cone is placed upside down beside the concrete of slump cone's mold. Tamping rod is placed over the up-turned slump cone in such a way that length of reach over the slump concrete with help of the ruler. The value of slump is measured carefully as shown in **Figure 3.2 a**.

To the best of the authors' knowledge, there is no standard test available that help to find the workability of fresh JWS-FRC. Hence, the same procedure and test standard is used for the determination of the workability all JWS-FRCs. The relation between the observed slump values and determined hard densities is shown in **Figure 3.2 b**.

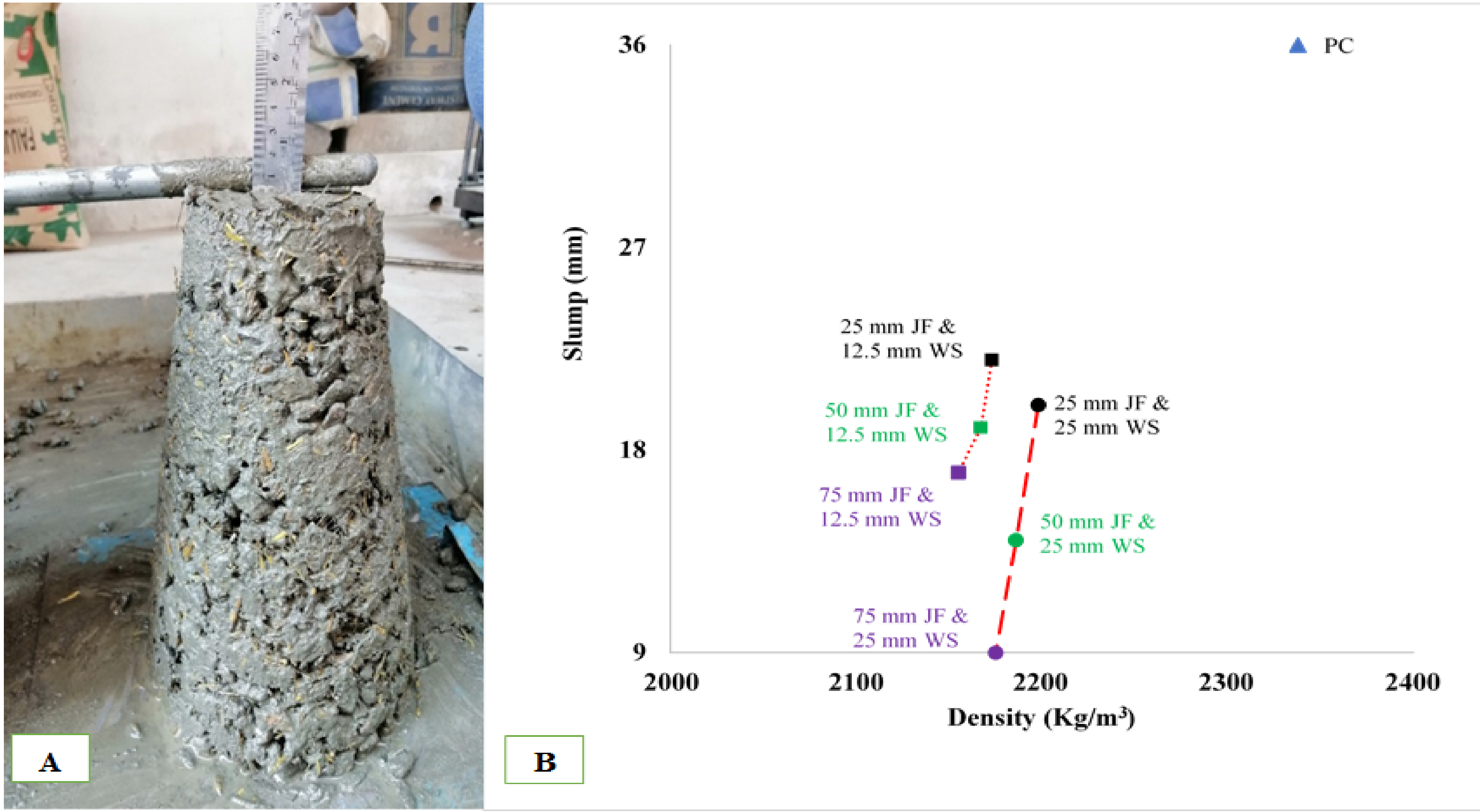


FIGURE 3.2: a) Measuring Value of Slump of JWS-FRC, B) Relationship between Slump of Fresh Concrete and Density of Hard Concrete.

Table 3.2: Specimens Labelling, Density and Slump of Fresh Concrete, Density of Hard Concrete

Labelling of Specimens	**C:S:A***	**Addition of Percentage of Fibers by mass of cement***		**Fiber lengths (mm)**		**W/C (-)**	**Slump of Fresh concrete (mm)**	**Density of hard concrete (kg/m3)**
		Jute fiber	**Wheat straw**	**Jute fiber**	**Wheat straw**			
PC	1:2:3	0	0	0	0	0.6	36	2337
JWS-FRC1	1:2:3	0.5	4.5	25	12.5	0.7	22	2173
JWS-FRC2	1:2:3	0.5	4.5	50	12.5	0.7	19	2167
JWS-FRC3	1:2:3	0.5	4.5	75	12.5	0.7	17	2155
JWS-FRC4	1:2:3	0.5	4.5	25	25	0.7	20	2198
JWS-FRC5	1:2:3	0.5	4.5	50	25	0.7	14	2186
JWS-FRC6	1:2:3	0.5	4.5	75	25	0.7	9	2175

**The cement sand, aggregates ratios and percentage fiber content are taken from the recommendations of the previous researcher [10]*

It can be seen that the PC has maximum density and slump value. Whereas keeping the fixed 12.5 mm length of WS and changing JF lengths as 25 mm, 50 mm and 75 mm the value of slump is decreased along with the value of density. Similarly, by the keeping fixed WS of 25 mm and changing lengths from 25 mm, 50 mm and 75 mm there is decrease in slump and density of JWS-FRCs as compared to PC. The combination of 12.5 mm fixed WS is shown with dotted lines and 25 mm long WS combination is shown with dashed line.

The jute fibers with 25 mm, 50 mm and 75 mm length are shown with black, green and purple colors respectively for better demonstration. For measuring the densities, an average of two specimens is taken for each mix design. The volume of the beamlets is determined in terms of m^3 by taking the internal volume of the molds that are used for the casting of the beamlets. After the final setting time of the concrete, molds are then removed and the mass in kilograms of each specimen is noted by using the weighing balance. The least count of weighing balance used for the determination of the masses is 5 grams. The densities are found by taking ratio of weight (kg) and volume (m^3). The determined values of densities and slumps are shown in **Table 3.2**. To the best of the authors' knowledge, there are no such standard tests available to find out the workability and density of fresh JWS-FRCs. Hence, the same procedure and test standards are used for the determination of the workability and densities of all JWS-FRCs.

3.4 Testing Methodology

In this section of testing methodology, slump test, dynamic test, mechanical test, water absorption test, linear shrinkage test, mass loss, are performed to determine the different properties of concrete against these above-mentioned tests. All these tests are performed as per the ASTM standards or referred by the previous researchers. The average of two samples is taken for every test. **Figure 3.3a** and **3.3b** shows the test setups of dynamic tests and mechanical tests.

For the purpose of determining dynamic properties of plain concrete and jute, and wheat straw fiber reinforced concrete, longitudinal, lateral, and rotational frequencies are observed with the help of accelerometer and a hammer. Three different types of test setups are used for the determination of each type of above-mentioned resonance frequencies.

In longitudinal frequency setup, accelerometer is attached to the one cross-sectional side of the specimen (either beamlet or cylinder) and hammer is striked to the other cross-sectional side of the specimen. For measuring the transverse frequencies, the accelerometer is placed on the length of specimen 25 cm away from cross-sectional edge and then stroke of hammer is given parallel to the accelerometer on the other edge of specimen. To determine the tortional frequencies by third type of test setup, accelerometer is attached as the same way as it is arranged in longitudinal setup. But then the stroke of hammer is given on the length of specimen which is perpendicular to the accelerometer.

Compression, split tensile and flexural testings are performed to explore the mechanical properties of PC and all kinds of JWS-FRCs. To perform compression test, cylinder specimens are placed vertical between the test machine so that it acts as a prototype of compression member or a column. Cylindrical specimens are laid down between the testing plates for performing splitting tensile test. So, that the splitting tensile properties may be observed by this setup. Average of the values of two specimens is taken to get precise value of any results obtained from these tests. In this way, average of obtained results from dynamic and mechanical properties is taken to get precision and to check deviation in results.

3.4.1 Dynamic Testing

Dynamic test is performed before the destructive (mechanical) testing of the specimens as per ASTM 215-14 **Table 3.3**. Response frequencies lateral (RFL), response frequencies transverse (RFT) and response frequencies rotational (RFR) are determined with the help of hammer and accelerometer. The test is conducted on both cylinder and beamlets. For determining the RFL, the accelerometer is attached to once side of cross section of cylinders and beamlets while a strike of hammer is given to the opposite side of the cross section of specimens.

Table 3.3: Testing Standards and Studied Parameters

Test	Followed Standards	Focused Parameters	Additional Parameters Considered for Study
Compressive properties	ASTM C39	compressive strength (C-S)	Stress–strain curves, compressive pre-crack energy absorption (CE1), compressive post-crack energy absorption (CE2), compressive total energy absorption (CTE), compressive toughness indexes (CTI) and modulus of elasticity (MOE).
Splitting-tensile properties	ASTM C496	Splitting- tensile strength (STS)	Load-deformation curves, splitting-tensile pre-crack energy absorption (SE1), splitting-tensile post-crack energy absorption (SE2), splitting-tensile total energy absorption (STE) and splitting-tensile toughness indexes (STI).

Continued Table: 3.3 Testing Standards and Studied Parameters

Test	**Followed Standards**	**Focused Parameters**	**Additional Parameters Considered for Study**
Flexural properties	ASTM C78 ASTM C1609	Fexural Strength (F-S)	Load-deflection curves, flexural pre-crack energy absorption (FE1), flexural post-crack energy absorption (FE2), flexural total energy absorption (FTE) and flexural toughness indexes (FTI).
Dynamic properties	ASTM C215-14	Resonant frequency longitudinal (RFL), Resonance frequency transverse (RFT), Resonance frequency torsional (RFR), damping ratio	No additional parameters studied
	ASTM C1548	Dynamic modulus of elasticity (DME), Dynamic modulus of rigidity (DMR), Poisson ratio.	No additional parameters studied

Continued Table: 3.3 Testing Standards and Studied Parameters

Test	Followed Standards	Focused Parameters	Additional Parameters Considered for Study
Water absorption, linear shrinkage and mass loss	ASTM C642-13,	Density, Water absorption (%)	No additional parameters studied
	ASTM C157M-08	Linear shrinkage (percentage decrease)	No additional parameters studied
	ASTM C1792/1792-14	Mass loss verses time	Mass loss by gradually increasing temperature.
Role of fibers in concrete	(Affan & Ali, 2022)	Broken surfaces of specimen, failure mechanism of fibers, and bonding of fiber with the surrounding matrix	Fiber breakage and fiber pull out in case of hybrid fibers.

The accelerometer observes the frequencies and transfer the record of these frequencies to the computer attached with it. The procedure of RFT and RFR attaching the accelerometer and strike location of hammer is different for cylinders and the beamlets. In case of cylinders, for RFT, the accelerometer is attached at side showing face of length of cylinder at least 25 cm away before the edge. Then a strike of hammer is given at same side showing face on the center of cylinder's length.

For RFR, the accelerometer is attached at top showing face of length of cylinder with same space from the edge like RFT. The strike is given at perpendicular accelerometer on opposite edge of the cylinder length. In case of the beamlets, for RFT determination, accelerometer attached at one side of length at same margin, used for cylinders, on length of beamlets from edge. Strike of hammer is given at center of length of same side at which accelerometer is attached.

For RFR, the accelerometer is attached at top corner of rectangle (side face of the beamlet). A strike is given at other side bottom corner of same side of rectangle in such a way that line joining the point of hammer's strike and accelerometer make the diagonal of the rectangle. From these observed frequencies, the damping ratio, dynamic modulus of elasticity, dynamic modulus of modulus of rigidity and poisson's ratios are calculated. These calculated properties support to understand the behavior and resistance of PC and all types of JWS-FRCs against the dynamic loading. These properties are key to the design of structure undergoing the dynamic loadings and earthquake.

3.4.2 Mechanical Testing

a) Compression Test

A servo-hydraulic testing machine (STM) is used for the determination of the compressive strengths of PC and all JWS-FRCs. The test is performed according to ASTM C39 on cylinders of PC and JWS-FRCs. In this test properties determined are included as compressive strength (C-S), compressive pre-crack (CE1) and post-crack energy (CE2), compressive total absorbed energy (CTE), and the compressive toughness index (CTI) of PC and JWS-FRCs. To distribute the load uniformly throughout the cylinder the caping of the cylinder is done with the plaster of paris.

b) Splitting Tensile Test

ASTM C496M-02 standard is used for the splitting-tensile test. The same machine STM is used for performing the test. The test is performed on the cylinders of PC and JWS-FRCs. The capping of cylinders is not required in the case of the splitting-tensile test. From this test, load-deformation curves, splitting-tensile strength (STS), splitting-tensile pre-crack energy absorption (SE1), splitting-tensile post-crack energy absorption (SE2), splitting-tensile total energy absorption (STE), and splitting tensile toughness indexes (STI) are calculated.

c) Flexural Test

The flexural test is performed on the basis of standards ASTM C78. The three-point loading mechanism is adopted. The test is performed on the beamlets of PC and JWS-FRCs. The studied parameters in this test are load-deflection curves, flexural strength (F-S), flexural pre-crack energy absorption (FE1), flexural post-crack energy absorption (FE2), flexural total energy absorption (FTE), and flexural toughness indexes (FTI).

3.4.3 Miscellaneous Testing (Water Absorption, Mass Loss and Linear Shrinkage)

To calculate the water absorption properties of PC and JWS-FRCs, the ASTM C642 standard is followed **Table 3.3**. First of all, specimens are dried in the oven and then these dried specimens are placed, at room temperature, in water. This method is used to determine the water absorption property of all types of specimens. For the evaluation of linear shrinkage, ASTM C157 / C157M-08 is followed by observing and measuring the variations in the length of specimens (OPSS standard LS-435).

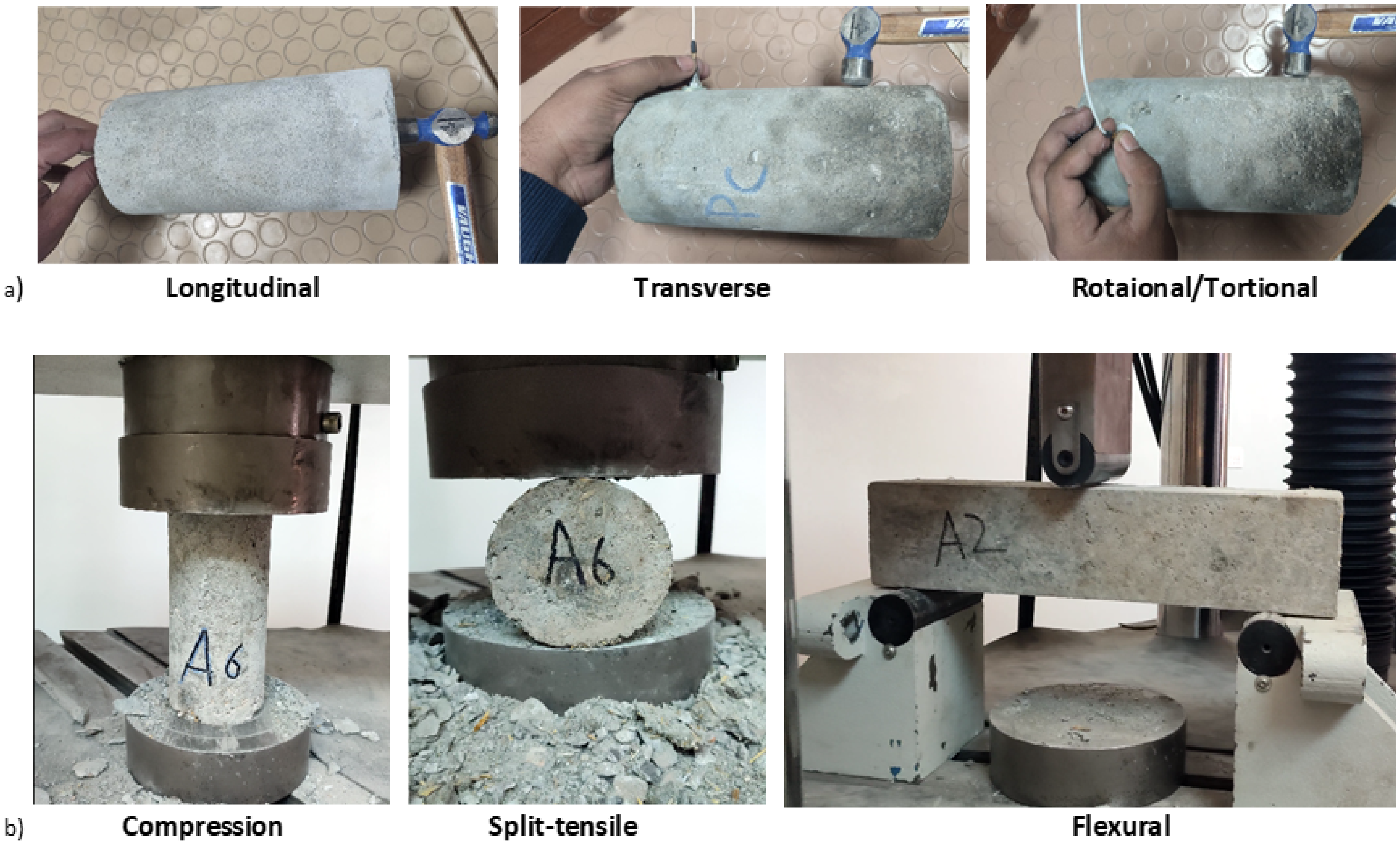


Figure 3.3: Test Setups a) Dynamic Test, b) Mechanical Test

For this purpose, a line of 6 inches is marked as a reference on the length of specimens before conducting the test. The variation of the length is measured after following the procedure of standard. The linear shrinkage is then measured by taking percentage difference of marked length before and after the test procedure. **Figure 3.4** shows the oven used for drying of samples for water absorption and mass loss tests.

ASTM C157M-08 is used for the determination of mass loss in PC and all JWS-FRCs. After following the test procedure, variations and shrinkage in the reference line are marked before being evaluated. Each type of concrete mix specimen is placed in a high-temperature heating oven. The temperature is raised from 20°C to 100°C at the rate of increase of 3°C per minute and maintained at 100°C for one hour. This is done to obtain more realistic data. Then specimens are cooled down with the same rate of decrease in temperature at 3°C to avoid thermal cracking.

FIGURE 3.4: Drying Samples in Oven for Water Absorption and Mass Loss Test

3.4.4 Visual Inspection of Crack Surface

After performing the mechanical testing, the fractured surfaces of broken specimens are examined carefully. In this examination, fiber breakage, pullouts, and bridging effect due to fibers are investigated. For this purpose, microanalysis is done carefully over the broken surfaces of the tested samples. From the fracture surfaces, mixing of all the ingredients can be observed, either it is a good mix or not. Good mixing of ingredients results in achieving the desired property, otherwise, it can lead to degression of the property instead of increasing it. The basic purpose of this investigation is to elaborate the failure mechanism of fibers and the bonding of the fibers with the surrounding matrix.

3.5 Summary

The mix design ratio of 1:2:3 is used for the preparation of PC and all types of JWS-FRCs. For the preparation of PC 0.6 W/C is used whereas 0.7 W/C is used for all types JWS-FRCs specimens. Jute fibers with 25 mm, 50 mm and 75 mm lengths are used along with 12.5 mm and 25 mm long wheat straw fibers. Wheat straw is taken as 4.5% by the mass of cement while the jute fibers are taken as 0.5% by mass of cement. Both fibers are used as hybrid fibers. Total 42 samples are casted in which 28 are cylinder for total 7 combinations and 14 beamlets for total 7 JWS-FRC combinations. ASTM standards are followed for determining slump, dynamic, mechanical and miscellaneous test for PC and JWS-FRCs. The results obtained are discussed in detail in chapter 4.

Chapter 4

Results and Analysis

4.1 Background

4.2 Dynamic Properties

Dynamic properties of JWS-FRCs are investigated to evaluate the effect of hybridization of wheat straw and jute fibers lengths on the properties of concrete specimens. Dynamic properties of plain concrete (PC) samples are obtained by the ASTM standard C215-14.

Due to unavailability of a specific standard to determine the dynamic properties of JWS-FRCs, the same standards are adopted to determine the dynamic properties of JWS-FRCs. The typical graphical response recorded on the accelerometer, while performing the test, has been shown in **Figure 4.1**.

Table 4.1 shows the calculated dynamic properties of the PC and all JWS-FRCs. An average of two obtained values is taken to achieve the average and appropriate results of each JWS-FRC specimens' combination for each corresponding dynamic property. The difference between damping ratio (ζ) of PC and JWS-FRC1, JWS-FRC3 and JWS-FRC4 is 0.39%, 0.21% and 0.019%, respectively.

On the other hand, the damping ratios of JWS-FRC2, JWS-FRC5 and JWS-FRC6 are increased by 24%, 164% and 24% respectively for cylinder specimens.

Table 4.1: Dynamic Properties of PC and JWS-FRCs

Concrete Specimens	**Studied Parameters** RFL (Hz)	RFT (Hz)	RFR (Hz)	ζ (%)	Ed (GPa)	Rd (GPa)	Poisson Ratio (-)
Cylinders							
PC	3302±63	3391±70	3382±36	1.710±0.100	4.07±0.138	4.27±0.073	0.52±0.008
JWS-FRC1	3865±54	3595±44	3461±44	1.315±0.025	5.04±0.137	4.04±0.100	0.38±0.002
JWS-FRC2	4204±42	3617±66	3912±35	2.113±0.250	6.04±0.169	5.23±0.135	0.42±0.001
JWS-FRC3	4184±49	3484±22	3527±22	1.499±0.230	5.99±0.093	4.26±0.008	0.30±0.008
JWS-FRC4	4205±33	3515±53	4283±22	1.691±0.130	5.95±0.093	6.17±0.063	0.44±0.013
JWS-FRC5	4461±22	3887±76	4396±61	4.506±0.924	6.87±0.185	6.67±0.299	0.48±0.009
JWS-FRC6	4303±66	3314±74	4272±40	2.119±0.924	6.3±0.160	6.21±0.083	0.41±0.006
Beamlets							
PC	3107±89	3085±22	3262±22	1.259±0.116	18.88±1.046	24.60±0.97	0.62±0.027
JWS-FRC1	3219±23	3419±44	3329±88	1.810±0.215	18.78±0.127	23.78±1.03	0.58±0.027
JWS-FRC2	3467±39	3603±81	3530±38	2.036±0.623	22.10±0.941	26.85±1.93	0.60±0.022
JWS-FRC3	3351±67	3373±44	3430±62	1.974±0.091	20.54±1.078	25.46±2.09	0.56±0.002
JWS-FRC4	3740±49	3630±40	3569±52	2.462±0.252	25.41±0.407	27.39±1.07	0.54±0.026
JWS-FRC5	3958±36	3936±45	3902±09	3.524±1.143	29.07±0.415	33.42±0.28	0.57±0.010
JWS-FRC6	3651±29	3525±53	3392±25	2.573±0.226	24.23±0.093	24.75±0.12	0.51±0.001

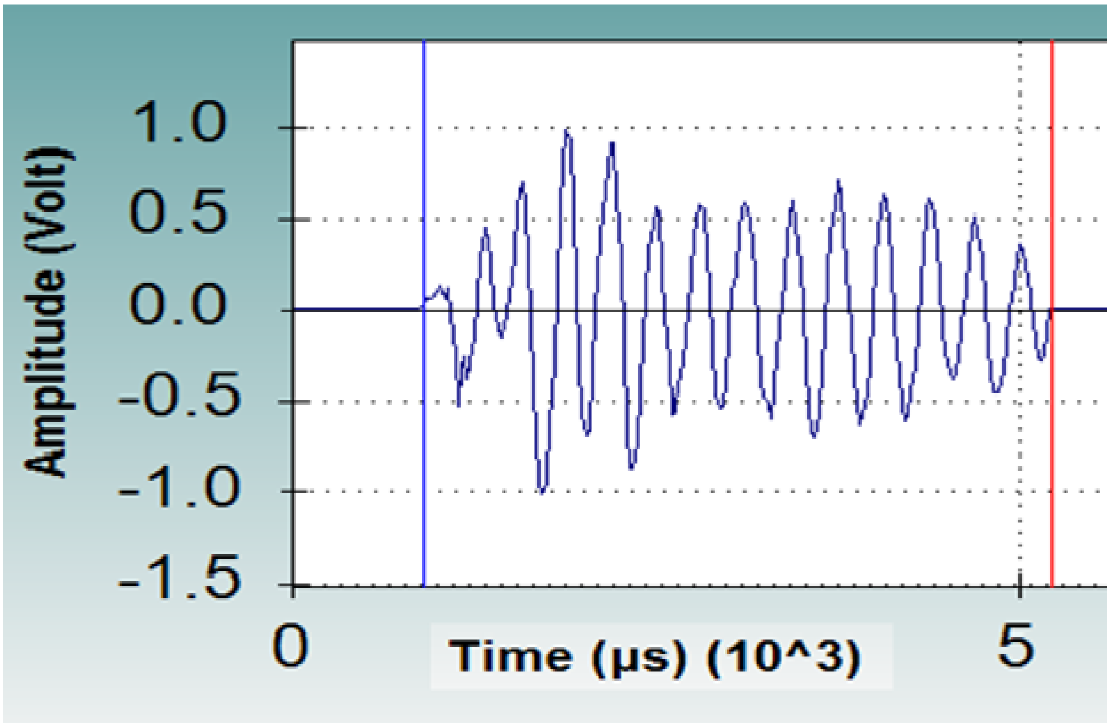


Figure 4.1: Damping Properties of PC and JWS-FRCs

In case of beamlets, the damping ratios of JWS-FRC1, JWS-FRC2, JWS-FRC3, JWS-FRC4, JWS-FRC5 and JWS-FRC6 are increased by 44%, 62%, 57%, 96%, 180% and 104% respectively. It can be noted that the JWS-FRC5 has maximum increase in all combinations of JWS-FRCs. The resistance against dynamic loading is increased in cylinders having fixed 12.5 mm wheat straw lengths by increasing jute fibers lengths up to 50 mm. While the cylinder specimens having 25 mm wheat straw lengths show increment in resistance against dynamic loading by increasing jute fibers lengths. In case of beamlets, the specimens having 25 mm wheat straw lengths show more resistance against dynamic loading as compared to the specimens having 12.5 mm wheat straw length.

4.3 Mechanical Properties

4.3.1 Compressive Properties

The relationship between stress strain graphs of PC, JWS-FRC1, JWS-FRC2, JWS-FRC3, JWS-FRC4, JWS-FRC5 and JWS-FRC6 is described in **Figure 4.2**

b. In this **Figure 4.2 b**, it can be noted that the PC has shown the maximum value of compressive strength (C-S) in comparison with all types of JWS-FRCs. The compressive strength of JWS-FRC1, JWS-FRC2, JWS-FRC3, JWS-FRC4, JWS-FRC5 and JWS-FRC6 are reduced by 62%, 61%, 64%, 59%, 56% and 59%, respectively.

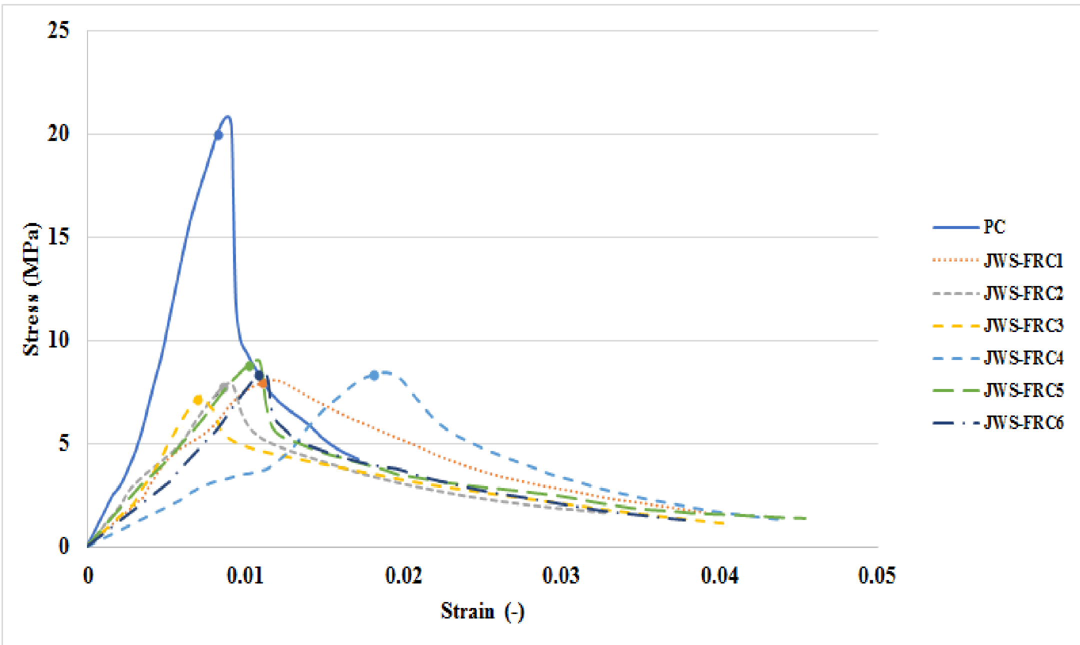
The JWS-FRC5 has shown maximum value of compressive strength among all other types of JWS-FRCs. When jute fiber length is increased in JWS-FRC2 up to 50 mm, the value of compressive strength is increased by 3% as compared with JWS-FRC1 which has jute fibers of 25 mm lengths. After the increment of jute fibers lengths occur up to 75mm, the value of JWS-FRC3 is decreased by 5% as compared with JWS-FRC1. Similar trend was observed in case of JWS-FRC5 because when the jute fiber length increased up to 50 mm the compressive strength value enhanced by 7% as compared to JWS-FRC4 which has 25 mm lengths jute fibers.

The overall C-S values of JWS-FRC4, JWS-FRC5 and JWS-FRC6 are more than that of JWS-FRC1, JWS-FRC2 and JWS-FRC3. It may be due to presence of longer wheat straw fibers i.e., 25 mm which behave as better crack arrestors because JWS-FRC1, JWS-FRC2 and JWS-FRC3 have wheat straw fibers of 12.5 mm lengths. The modulus of elasticity (MOE) of PC and all JWS-FRCs is shown in **Table 4.2**. It can be observed that the MOE of all JWS-FRCs are less than the MOE of PC. The MOE of JWS-FRC3 and JWS-FRC6 are more reduced as compared to other JWS-FRCs. This may be due to presence of 75 mm jute fibers which are longer than the 50 mm optimum jute fibers lengths. **Figure 4.2 a** shows the typical compression failures of PC and JWS-FRC.

Table 4.2 shows the values of compressive pre-crack absorbed energy (CE1), compressive post crack absorbed energy (CE2), compressive total absorbed energy (CTE), and compression toughness index (CTI). All these compressive absorbed energies are calculated by the method described by [99] and [100].

There is reduction of 42%, 59%, 65%, 12%, 30% and 41% in the values of CE1 for JWS-FRC1, JWS-FRC2, JWS-FRC3, JWS-FRC4, JWS-FRC5 and JWS-FRC6 respectively, when compared with PC. On the other hand, the respective CE2 is increased by 88%, 90%, 115%, 103%, 115% and 102% as compared to PC.

a



b

FIGURE 4.2: Compressive Behavior a) Typical Compression Failures of PC and JWS-FRCs, b) Compression Response of PC and JWS-FRCs

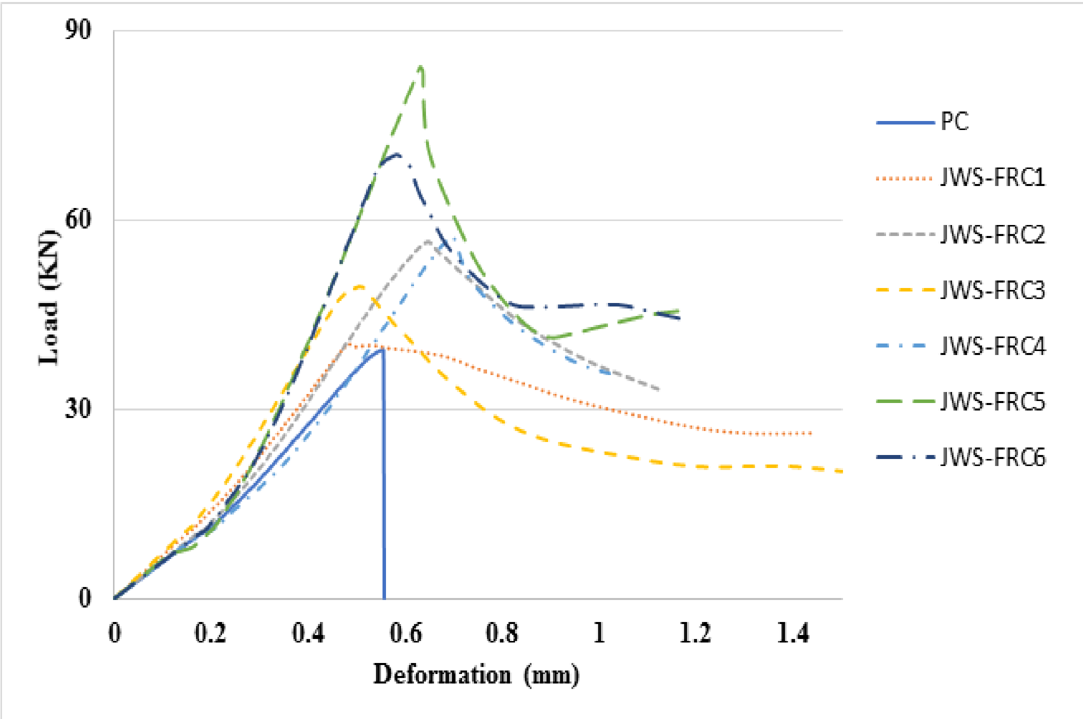
The CTI values for all JWS-FCRs are more than that of PC. This increase is may be due to presence of hybrid agricultural wastes like wheat straw and jute fibers. Instead of spalling like PC, diagonal and shear cracks were appeared on samples of JWS-FRC under compressive loading. The JWS-FRCs with 75 mm jute fibers have maximum values of CTI. So, the 75 mm long jute fibers have positive impact towards CTI.

4.3.2 Splitting Tensile Properties

The load deformation curves for PC, JWS-FRC1, JWS-FRC2, JWS-FRC3, JWS-FRC4, JWS-FRC5 and JWS-FRC6 are given in **Figure 4.3 b**. It may be noted that the JWS-FRC5 carries the maximum load as shown in **Figure 4.3 b**. Due to bridging effect of JF and WS fibers; JWS-FRCS have shown load-carrying capacity. Splitting tensile strength (STS), splitting tensile pre-crack absorbed energy (SE1), splitting tensile post crack absorbed energy (SE2), splitting tensile total absorbed energy (STE) and splitting tensile toughness index (STI) are shown under the section of splitting tensile properties in **Table 4.2**.

The STS is increased by 2%, 44%, 24%, 46%, 115% and 74% as compared with PC. The JWS-FRC5 has maximum value of STS. This may be due to optimum lengths combinations of jute and wheat straw fibers. The overall increase in STS of all JWS-FRCs is due to the bridging effect of fibers. The SE1 of JWS-FRC5 is increased by 69% as compared with that of PC. There is no splitting tensile post crack energy in case of PC because under the peak loading, PC broken apart into two pieces. On the other hand, JWS-FRCs have shown post crack absorbed energies. These energies are due to presence of agricultural wastes JF and WS in concrete. It may also predict that the JWS-FRCs can sustain a little longer against tensile loading as compared with PC because fibers present in concrete act as crack arrestors and resist in crack propagation. The JWS-FRC5 has more pre-crack and post crack energy as compared to that of PC. This is due to the presence of optimum length hybrid fibers in concrete i.e., jute fibers of 50 mm and wheat straw of 25 mm act as crack arrestors and prevent crack propagation. So, JWS-FRC5 has absorbed more energy. The toughness indexes of JWS-FRC1, JWS-FRC2, JWS-FRC3, JWS-FRC4, JWS-FRC5 and JWS-FRC6 are more than that of PC. **Figure 4.3 a** shows the typical splitting tensile failures of PC and JWS-FRC.

a



b

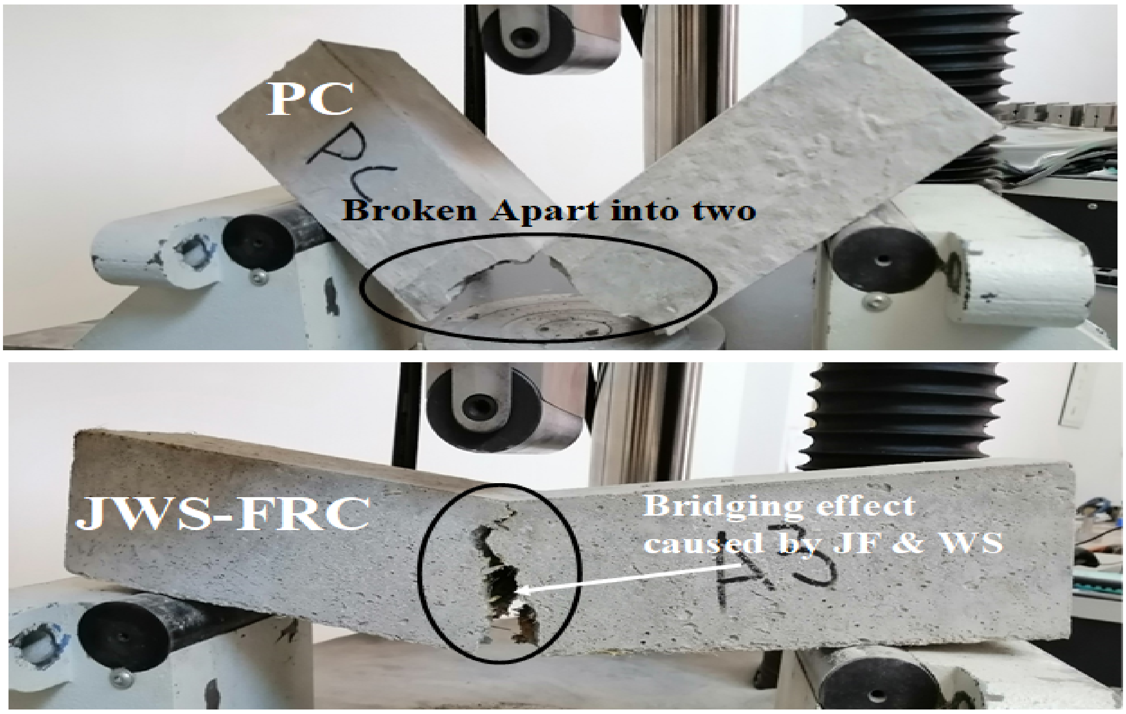
FIGURE 4.3: Splitting Tensile Behavior a) Typical Splitting Tensile Failures of PC and JWS-FRCs, b) Splitting-Tensile Response of PC and JWS-FRCs

The JWS-FRC3 has maximum toughness index because it has maximum pre-crack and post-crack energies. This may be due to presence of longer length jute fibers which arrested crack after tensile loading better than shorter jute fibers.

4.3.3 Flexural Properties

The load deformation curves for PC, JWS-FRC1, JWS-FRC2, JWS-FRC3, JWS-FRC4, JWS-FRC5 and JWS-FRC6 are given in **Figure 4.4 b**. According to ASTM standard C78, a loading rate of 1.03MPa/min is recommended to be applied for testing; but, in this study, a loading rate of 1 kN/sec is applied. It may be noted that the JWS-FRC5 carries the maximum load as shown in **Figure 4.4b** because it resists maximum flexural loading. Due to bridging effect of JF and WS fiber JWS-FRCs have shown load-carrying capacity. Flexural strength (F-S), flexural pre-crack absorbed energy (FE1), flexural post crack absorbed energy (FE2), flexural total absorbed energy (FTE) and flexural toughness index (FTI) are shown under the section of flexural properties in **Table 4.2**.

The F-S is increased by 25%, 48%, 36%, 42%, 108% and 75% as compared with PC. The JWS-FRC5 has maximum value of F-S. This may be due to optimum lengths combinations of jute and wheat straw fibers. The overall increase in F-S of all JWS-FRCs is due to the bridging effect of fibers. The FE1 of JWS-FRC4 is increased by 31% as compared with that of PC. There is no flexural post crack energy in case of PC because under the peak loading, PC broken apart into two pieces. On the other hand, JWS-FRCs have shown post crack absorbed energies. These energies are due to presence of agricultural wastes JF and WS in concrete. It may also predict that the JWS-FRCs can sustain a little longer against flexural loading as compared with PC because fibers present in concrete act as crack arrestors and resist in crack propagation. The toughness indexes of JWS-FRC1, JWS-FRC2, JWS-FRC3, JWS-FRC4, JWS-FRC5 and JWS-FRC6 are more than that of PC. The JWS-FRC4 has maximum toughness index because it has maximum pre-crack and post-crack energies. This may be due to presence of longer length WS which arrested crack after flexural loading better than shorter WS fibers. The loading rate throughout the test is same. The reason behind the nonlinear pre-crack behavior of concrete is the presence of natural fibers of different lengths. As deflection changes the load is also increasing. While in the areas where strong bridging effect and bond of fibers with surrounding matrix is present, sample takes more load and crack propagation is delayed. **Figire 4.4 a** shows the typical flexural failures of PC and JWS-FRC.



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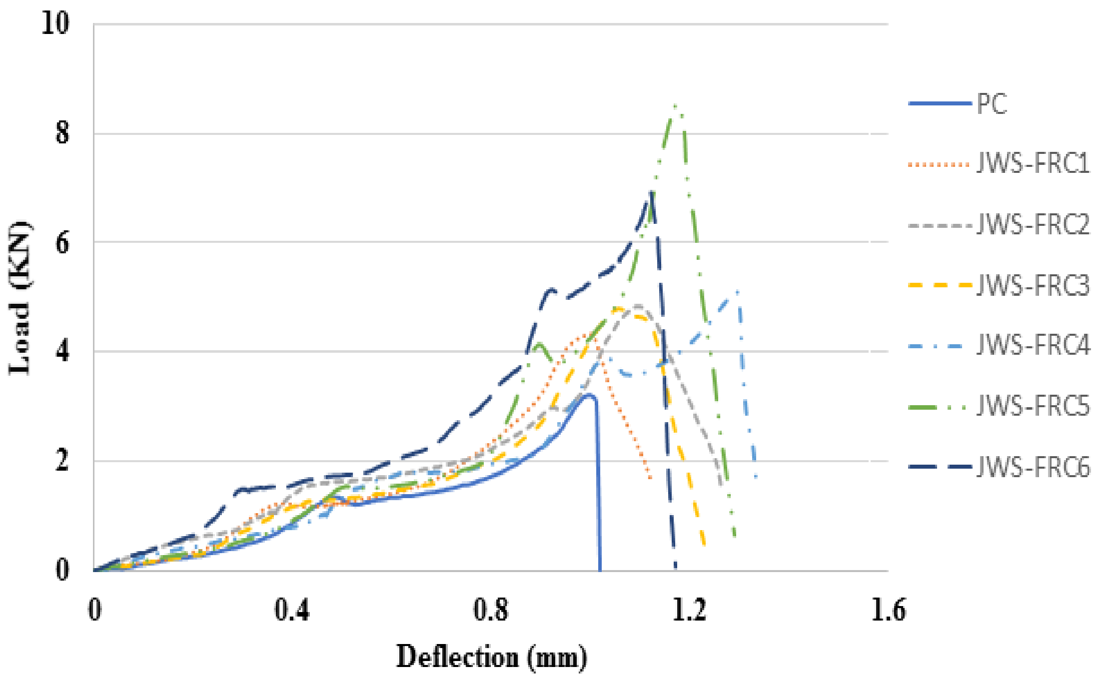

b

Figure 4.4: Flexural Behavior a) Typical Flexural Failures of PC and JWS-FRCs, b) Flexural Response of PC and JWS-FRCs

Table 4.2: Mechanical Properties of PC and JWS-FRCs

Specimens	**Mechanical Properties**																
	Compression Properties						**Splitting-tensile Properties**					**Flexural Properties**					
	MOE (GPa)	C-S (MPa)	CE1	CE2	CTE	CTI	STS (MPa)	SE1	SE2	STE	STI	F-S (MPa)	Δ (mm)	FE1	FE2	FTE	FTI
PC	35	20	0.083	0.059	0.142	1.71	1.2	14	0	14	1	1.2	0.974	3.08	0	3.08	1
	± 1.4	± 0.8	± 0.003	± 0.001	± 0.002	± 0.03	± 0.2	± 1.1		±1.10		± 0.2	±0.52	± 0.12		± 0.12	
JWS-	29.1	7.6	0.048	0.111	0.159	3.29	1.2	12.7	24.65	37.35	2.94	1.5	1.003	3.4	3.44	6.84	2.01
FRC1	± 0.7	± 0.5	± 0.004	± 0.001	± 0.005	± 0.05	± 0.3	± 1.1	± 0.0	± 1.10	± 0.0	± 0.2	±0.42	± 0.13	± 0.0	± 0.13	± 0.0
JWS-	27.7	7.8	0.034	0.112	0.155	3.61	1.7	20.4	31.23	51.63	2.53	1.6	1.102	4.03	5.43	9.46	2.34
FRC2	± 1.2	± 0.2	± 0.002	± 0.001	± 0.001	± 0.05	± 0.1	± 1.27	± 1.02	± 2.29	± 0.04	± 0.1	±0.42	± 0.24	± 0.04	± 0.26	± 0.01
JWS-	25.8	7.2	0.029	0.127	0.156	5.34	1.5	15.4	45.8	61.2	3.97	1.6	1.048	3.56	4.98	8.54	2.39
FRC3	± 1.2	± 0.1	± 0.005	± 0.001	± 0.003	± 0.02	± 0.2	± 1.62	± 1.53	± 3.15	± 0.01	± 0.2	±0.53	± 0.10	± 0.03	± 0.13	± 0.01
JWS-	26	8.2	0.073	0.089	0.162	2.22	1.7	21	32.7	53.7	2.55	1.7	1.292	4.97	7.86	12.8	2.58
FRC4	± 1.2	± 0.2	± 0.003	± 0.001	± 0.002	± 0.05	± 0.2	± 1.69	± 1.05	± 2.74	± 0.02	± 0.4	±0.77	± 0.11	± 0.04	± 0.07	± 0.01
JWS-	26.9	8.8	0.058	0.127	0.185	3.17	2.6	23.7	36.2	59.1	2.52	2.5	1.168	4.7	1.67	6.38	1.35
FRC5	± 0.3	± 0.2	± 0.001	± 0.001	± 0.001	± 0.06	± 0.4	± 0.92	± 2.23	± 3.12	± 0.05	± 0.2	±0.23	± 0.06	± 0.06	± 0.03	± 0.01
JWS-	25.8	8.2	0.049	0.119	0.168	3.45	2.1	20.2	33.8	54	2.67	2.1	1.236	4.95	1.28	6.23	1.25
FRC6	± 0.7	± 0.4	± 0.004	± 0.001	± 0.002	± 0.04	± 0.1	± 1.59	± 0.96	± 2.58	± 0.04	± 0.1	±0.55	± 0.13	± 0.09	± 0.21	± 0.02

4.4 Water Absorption, Mass Loss and Linear Shrinkage

The liquid transportation through the capillary action is given as water absorption and is determined by the mass of absorbed water by the specimen divided by the actual mass of specimen after oven dry (ASTM standard C642-13). The water absorption of PC and all JWS-FRCs is given in **Table 4.3**. It can be noted that JWS-FRC6 has maximum water absorption and PC has minimum water absorption value. The natural fibers like wheat straw and jute fibers have characteristics to absorb water. So, the water absorption of all JWS-FRCs is higher than PC. It also can be noted that by increment of jute fiber and wheat straw fibers lengths the water absorption of JWS-FRC specimens is increased. The JWS-FRC6 has maximum length combination i.e., 25 mm wheat straw and 75 mm jute fiber so it has maximum water absorption which is more than four times the water absorption of PC.

The linear shrinkage of PC and JWS-FRCs is given in **Table 4.3**. There is overall decrease in the values of linear shrinkage of JWS-FRCs as compared to PC. It can be observed that the increment in jute fibers length from JWS-FRC1 to JWS-FRC3 the linear shrinkage is reduced. While from JWS-FRC4 to JWS-FRC6 the increment in jute fiber lengths have more effect towards the reduction of linear shrinkage value. This may be due to presence of longer i.e., 25 mm wheat straw lengths because the earlier described group have 12.5 mm wheat straw lengths which are shorter. It can be presumed that the use of longer jute and wheat straw lengths combination may reduce the vulnerability of concrete towards cracks.

Mass loss of JWS-FRCs is given in **Table 4.3**. It can be observed that the maximum mas loss occurred at the temperature of 100°C. PC has shown minimum mass loss and JWS-FRC6 has shown maximum mass loss. From JWS-FRC1 to JWS-FRC3 as jute fiber length is increased from 25 mm to 75 mm the mass loss is increased. But this increment is less than the increment shown by JWS-FRC4 to JWS-FRC6 because JWS-FRC1 to JWS-FRC3 has WS of 12.5 mm lengths while 25 mm long WS is present in JWS-FRC4 to JWS-FRC6. It may be noted that the presence of longer i.e., 25 mm long WS has positive influence towards mass loss when used with JF of 25 mm, 50 mm and 75 mm. The ML at 50°C is approximately 65% less than the ML at 100°C. This is due to continuous heating of specimens to achieve the temperature of 100°C.

TABLE 4.3: Water Absorption, Mass Loss and Linear Shrinkage of PC and JWS-FRCs

Specimens	**WA** (%)	**Ls** (%)	**ML Temperatures**		
			50°C	**75°C**	**100°C**
PC	1.2	1.359	-0.003	-0.004	-0.005
JWS-FRC1	2.84	1.167	-0.004	-0.005	-0.007
JWS-FRC2	3.24	0.975	-0.013	-0.02	-0.026
JWS-FRC3	3.52	0.846	-0.017	-0.023	-0.03
JWS-FRC4	3.62	0.522	-0.018	-0.024	-0.032
JWS-FRC5	3.69	0.392	-0.026	-0.034	-0.045
JWS-FRC6	4.9	0.196	-0.031	-0.041	-0.054

4.5 Fractured Surface of Tested Specimens

The broken surfaces of JWS-FRCs after the application of loads are given in **Figure 4.5**. The failure patterns and surfaces of PC and JWS-FRCs are quite different. The images of fractured surfaces of JWS-FRCs are present in **Figure 4.5**. The bond between hybrid agricultural waste fibers and the surrounding concrete is studied with these broken surface images. The pullout of wheat straw natural fibers can be observed from the images. A strong bonding is present between the both wheat straw and jute fibers to the concrete with in the specimen.

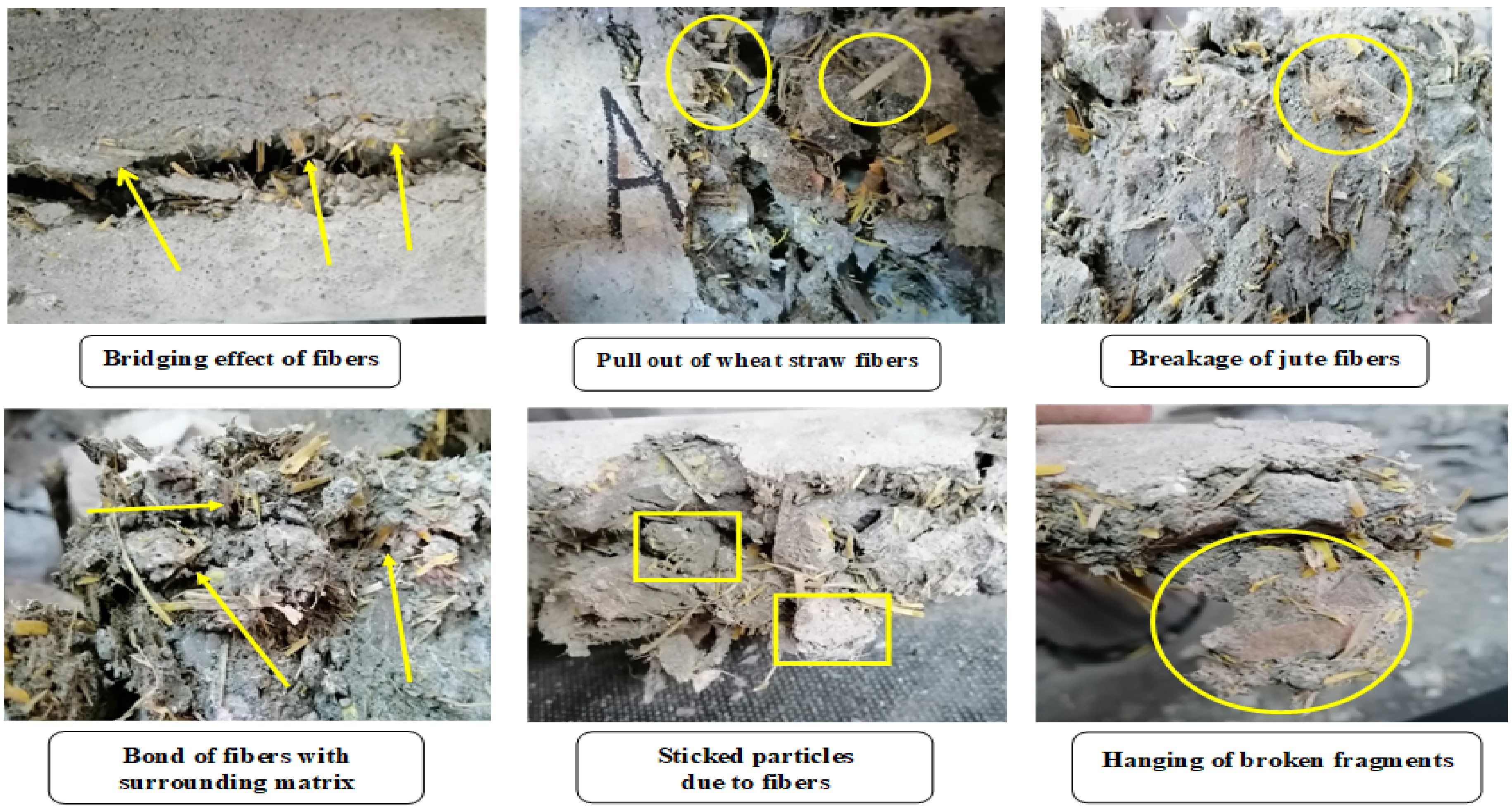

Figure 4.5: Fractured Surfaces of JWS-FRC Tested Specimens

Small sized voids are observed from the images of broken surfaces. A proper and good mixing of fresh concrete for the casting of specimens can be scrutinized from these images. After the application of loads during mechanical testing, the specimens of JWS-FRCs are broken into small pieces. Small fragments of concrete are attached with fibers as shown in **Figure 4.5**. The hanging of major broken particles can also be observed from images. The attachment of small fragments and hanged particles indicates the bridging effect of fibers.

The fibers have tendency to make bond and to hold particles even after the failure of specimens. After the failure of specimens, the pullout of wheat straw fibers is observed instead of fiber breakage. The jute fibers are broken and fiber breakage of jute fibers is shown in images. Even after the initial failure, the samples of JWS-FRC kept resisting against loading due to presence of agricultural wastes hybrid natural fibers which resist the crack propagation and provide bridging effect. It is perceived after performing the experiment that the existence of jute and wheat straw fibers help to resist the production and progression of micro cracks. Shorter length fiber bridge micro cracks while longer length fiber bridge macro cracks as reported by [110].

4.6 Summary

In this chapter, the workability of fresh PC and JWS-FRCs, densities of hard concrete, dynamic properties, mechanical properties, water absorption, mass loss and linear shrinkage properties are calculated with a mix design ratio of 1:2:3 with 0.6 W/C ratio for PC and 0.7 W/C for all JWS-FRCs. Dynamic modulus of rigidity is enhanced by increasing the lengths of jute and wheat straw fibers. The incorporation of hybrid natural fibers with varying lengths leads to decrease the workability of all JWS-FRCs as compared with PC.

The splitting tensile strength, splitting tensile toughness, flexural strength, flexural toughness and tendency to absorb pre-crack and post crack energy has improved with the addition of jute and wheat straw fibers. The compressive toughness is enhanced with compromise in compressive strength. The water absorption of JWS-FRCs is increased by increasing the lengths of jute and wheat straw fibers. Linear shrinkage has shown opposite relation with the increment of lengths of jute and wheat straw fibers. Mass loss is observed more with the increase in fiber lengths. Hybrid agricultural wastes natural fibers have good bonding with the surrounding matrix when the fractured surfaces of specimens subjected to mechanical tests are examined. Fiber pullout and fiber breakage is also observed.

Chapter 5

Guidelines for Practical Implementation

5.1 Background

The specimens subjected to testing provided quantitative results of influence of jute and wheat straw fibers lengths on the properties of jute and wheat straw fiber reinforced concrete. Stress strain, load deflection and load deformation graphs demonstrate the effect of hybrid jute and wheat straw fibers lengths on the mechanical properties of concrete. The obtained data from dynamic testing and mechanical testing is further utilized to find out the optimum lengths' combinations of wheat straw and jute fibers. The comprehensive discussions on practical implementation of this research and recommendation of JWS-FRC in real life are made in this chapter.

5.2 Optimum Combination of Jute and Wheat Straw Fibers Lengths

The maximum and minimum values obtained from both mechanical and dynamic tests are shown in **Table 5.1**. As a result of this study, from the compression members like columns, JWS-FRC5 which have jute fibers of 50 mm length and wheat straw of 25 mm lengths is recommended due to its high compressive strength in all JWS-FRCs. The members in which the tension and flexural forces are the governing forces the JWS-FRC5 is recommended because it has the highest splitting tensile and flexural strengths.

The addition of hybrid natural fibers has positive influence towards the spitting tensile and flexural strength. On the other hand, agricultural waste hybrid natural fibers have negative impact on the compressive strength of concrete. **Figure 5.1** shows the effect of hybrid fiber lengths on the properties of JWS-FRCs. The toughness of all JWS-FRCS is increased as compared to PC. From toughness point of view JWS-FRC3 for both compression and tensile loading is recommended whereas JWS-FRC4 is recommended for flexural loading as it has maximum toughness under the flexural loading.

The effect of addition of varying lengths hybrid fibers have improved the CTI, STI and FTI in JWS-FRCs as compared to PC. Percentage increase or decrease of strengths, absorbed energies and toughness indexes are shown in **Figure 5.1**. It can be noted that the maximum increase in absorbed energies is in JWS-FRC3 and it is under splitting tensile loading.

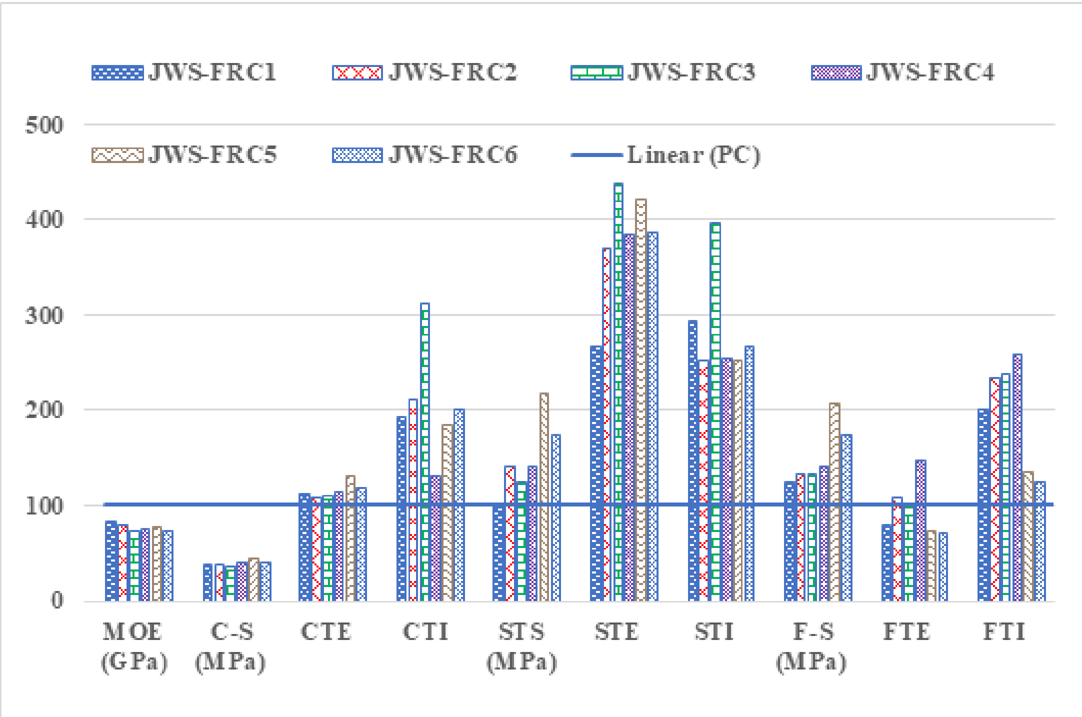

FIGURE 5.1: Effect of Hybrid Fibers of Varying Lengths in JWS-FRCs

5.3 Application of this Research in Real Life

The concrete used in civil engineering structures goes through different types of loadings together like mechanical and dynamic loadings. Due to these loadings' cracks appear on the surface as well as the inner portion of concrete. There are also other reasons of cracking like higher water absorption, more value of linear shrinkage and less strength of concrete in tension phase [101]. The cracks appear on the surface of rigid pavements are due to less flexural strength and differential settlement. These cracks can be controlled by enhancing the flexural strength of concrete. One of other major flaws of concrete is spalling phenomenon. Spalling of concrete is due to exposure of concrete to elevated temperatures.

The spalling can be controlled by enhancing the tensile strength of concrete. For the enhancement of tensile strength to reduce spalling, the hybrid natural fibers can be used in concrete [102]. The poor dynamic properties of concrete lead to failure against impact loadings like blasting, collision of vehicles to the piers of concrete bridges. The resistance against impact loading can be improved by enhancing the dynamic modulus of rigidity and the energy absorption property of the concrete [12].

In this study the effect of hybrid agricultural waste natural fibers with varying lengths is explored when these fibers are used in concrete. The specimens of JWS-FRC5 have shown better performance against compressive loading. So, it can be used in the compression members like columns. These columns are either architectural columns or columns for single story structures where strength capacity is not big requirement (i.e., minimum size is fine).

The properties of JWS-FRC5 have expressed more improved results as compared with other JWS-FRCs. Due to these better properties against splitting tensile and flexural loading, JWS-FRC5 can be used in slabs and beams. The rigid pavements are designed by keeping in mind the flexural strength and modulus of elasticity of the concrete. JWS-FRC5 is suitable for rigid pavements as it has shown better modulus of rupture and modulus of elasticity which are key factors in the stability and durability of the rigid pavements.

TABLE 5.1: Optimum Combinations of Varying Lengths in JWS-FRCs

Concrete	**Compression**				**Splitting Tensile**			**Flexural**			**Dynamic***		
Type	**MOE**	**C-S**	**CTE**	**CTI**	**STS**	**STE**	**STI**	**F-S**	**FTE**	**FTI**	ζ	**Ed**	**Rd**
	(GPa)	**(MPa**	**(MJ/m3)**	**(–)**	**(MPa)**	**(MJ/m3)**	**(–)**	**(MPa)**	**(MJ/m3)**	**(–)**	**(%)**	**(GPa)**	**(GPa)**
PC's Values	35.0±	20.0±	0.173 ±	1.87 ±	1.2±	14.0±	1	1.2±	3.08 ±	1	1.71±	4.07±	4.27±
	1.4	0.8	0.002	0.03	0.2	1.1		0.2	0.12		0.1	1.38	0.07
JWS-FRC	25.8 ±	7.2 ±	0.155 ±	2.22 ±	1.2±	37.35±	2.52 ±	1.6±	6.23±	1.25 ±	1.49±	5.04±	4.04±
with minimum	0.7	0.1	0.001	0.05	0.3	1.1	0.05	0.2	0.21	0.02	0.23	0.13	0.1
values	(JWS-FRC6)	(JWS-FRC3)	(JWS-FRC2)	(JWS-FRC4)	(JWS-FRC1)	(JWS-FRC2)	(JWS-FRC5)	(JWS-FRC3)	(JWS-FRC6)	(JWS-FRC6)	(JWS-FRC3)	(JWS-FRC1)	(JWS-FRC1)
JWS-FRC	29.1 ±	8.8 ±	0.185 ±	4.27 ±	2.6 ±	61.2 ±	3.97 ±	2.5 ±	4.97 ±	2.58 ±	4.50±	6.87±	6.67±
with maximum	0.7	0.2	0.001	0.04	0.4	3.15	0.01	0.2	0.11	0.01	0.92	0.18	0.22
values	(JWS-FRC1)	(JWS-FRC5)	(JWS-FRC5)	(JWS-FRC5)	(JWS-FRC5)	(JWS-FRC3)	(JWS-FRC3)	(JWS-FRC5)	(JWS-FRC4)	(JWS-FRC4)	(JWS-FRC5)	(JWS-FRC5)	(JWS-FRC5)

Recommended													
1. For specific property													
a. From strength point of view	JWS-FRC5				JWS-FRC5			JWS-FRC5			JWS-FRC5		
	26.9	8.8	0.185	3.17	2.6	59.1	2.52	2.5	6.38	1.35	3.52	29	33.4
b. From toughness point of view	JWS-FRC3				JWS-FRC3			JWS-FRC4			(-)		
	25.8	7.2	0.156	5.34	1.5	61.2	3.97	1.7	12.8	2.58			
2. For specific application													
a. JWS-FRC6 for columns/ compression members	25.8	8.2	0.168	3.45	2.1	54	2.67	2.1	6.23	1.25	2.57	24.2	24.7
b. JWS-FRC5 for slabs and beams	26.9	8.8	0.185	3.17	2.6	59.1	2.52	2.5	6.38	1.35	3.52	29	33.4
c. JWS-FRC5 for rigid pavements	26.9	8.8	0.185	3.17	2.6	59.1	2.52	2.5	6.38	1.35	3.52	29	33.4
d. JWS-FRC5 for the structure prone to lateral loading	26.9	8.8	0.185	3.17	2.6	59.1	2.52	2.5	6.38	1.35	3.52	29	33.4

**Data of beamlets specimens is used for comparison of dynamic properties.*

Despite of having good compressive strength, JWS-FRC6 has also shown better energy absorption and toughness among all JWS-FRCs. This is may be due to the presence of longer jute fiber (JF) and smaller wheat straw (WS) fibers i.e., 75 mm JF and 25 mm WS. So, JWS-FRC6 is suitable for columns or for any type of compression member where compressive loading is critical. By using the hybrid fibers as sustainable construction materials, it may provide a step forward towards the sustainable development.

5.4 Summary

The optimum length combinations of jute and wheat straw fibers are determined and recommendations are made as toughness point view and strength point of view. The recommendation regarding use of JWS-FRC in real life are made for different structural elements like columns, beams slabs. The combination having superior appropriate properties is recommended for the application in rigid pavements.

Chapter 6

Conclusions and Recommendations

6.1 Conclusions

The trend of re-using wastes is getting popularity day by day. Burning or dumping of agricultural wastes exerts serious environmental issues and causing damage to eco-system. There is need to utilize these wastes in an effective way to minimize the harmful impacts to environment.

This study explores the behavior of agricultural waste hybrid natural fibers in concrete to utilize these wastes. Different lengths combinations of agricultural wastes i.e., wheat straw and jute fibers have been used in JWS-FRCs. The workability, dynamic properties, mechanical properties water absorption property, mass loss and linear shrinkage property have been considered in this study and following conclusions have been drawn:

- Hybrid agricultural wastes have improved the tendency of resisting dynamic loading; damping ratio and Ed have improved. Rd has improved in all JWS-FRCs except JWS-FRC1 and JWS-FRC3 in cylinders and JWS-FRC1 in beamlets.
- The hybrid agricultural wastes showed influence on the mechanical properties of concrete.

- The different varying length agricultural wastes combinations have shown negative impact towards C-S of concrete The reduction in C-S is due to the use of less dense hybrid fibers. CTI and CTE of all JWS-FRCs have improved as compared with PC.

- The maximum STS and F-S have been observed with 50 mm and 75 mm long JF respectively with fixed 25 mm long WS fibers. The increment of jute fibers lengths from optimum i.e., 50 mm has shown decrease in STS and F-S. The STE and FTE in all JWS-FRCs have improved as compared to PC.

- Due to the bridging effect of hybrid fibers the concrete has avoided the sudden failure and all JWS-FRCs showed post crack energy as compared to PC.

- The increment of JF and WS fibers have shown the direct relationship with water absorption property of concrete. While, the increment in lengths of JF and WS have increased the resistance against linear shrinkage in concrete. JWS-FRCs with longer JF lengths have more mass loss to higher water absorption.
- The bonding of hybrid fibers with surrounding concrete matrix still exists in destructive samples subjected to mechanical testing. WS fibers have pulled out and JF have shown fiber breakage. Bridging effect of fibers is observed in broken samples.
- On the basis of governing properties, JWS-FRC6 is recommended for compressive members. JWS-FRC5 is recommended for beams, slabs, rigid pavements and structure prone to dynamic loading due to having improved splitting tensile, flexural and dynamic properties.

From this research work, the concrete composed with JF of 50 mm and WS of 25 mm lengths by keeping 0.5% and 4.5% fibers content by mass of cement respectively is better. So, JWS-FRC5 is recommended to resist spalling, cracking, flexural and dynamic loading. It also has suitable parameters like modulus of elasticity and modulus of rupture so can be used in rigid pavements. Hence, agricultural wastes can be utilized in a useful way as sustainable construction material.

6.2 Future Works

The agricultural wastes hybrid natural fibers with varying length of jute and wheat straw fibers have potential enhance the dynamic as well as the mechanical properties of concrete. The following recommendations should be taken into count for future working to explore the behavior of JWS-FRCs in further detail:

- Exploring the optimization of fibers lengths against impact loading.
- Behavior should be studied under freeze-thaw conditions.
- Experimental results may be verified by analytical modeling.
- Consideration of carbon footprint may also be taken into account.

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