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Mechanical Properties of Concrete Having Hybrid Natural Fibers with Varying Contents

by

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

CERTIFICATE OF APPROVAL

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Abstract

Concrete has the disadvantages of breaking, cracking, brittleness, and not being environmentally friendly. Although concrete has high compressive strength, it has weak tensile strength. Cracks are the most serious defect in concrete. Despite the environmental characteristics of concrete, it is the main reason to look for some materials that are as sustainable as possible. On the other hand, a large amount of agricultural waste is generated every year, especially in developing countries. Natural fibers are increasingly attracting attention in developing countries as a sustainable building material with clean production due to their environmental characteristics. The use of natural fibers in concrete can improve the tensile and flexural properties of concrete. One fiber can improve the performance to a certain extent, while using two different fibers together can provide the combined effects of both fibers. A mixture of smaller and larger fibers can help fill the cracks and potentially produce better results. Coconut fiber (CF) and sisal fiber (SF) are agricultural wastes that are widely available in developing countries like Pakistan, India, and Bangladesh. These natural fibers can be used as sustainable construction materials and can make the built environment acceptable. The overall objective of this research is to use agricultural waste (instead of burning it) for sustainable construction. The specific objective of this research is to improve the properties of concrete by using agricultural wastes like coconut and sisal as sustainable construction materials.

In this study, natural fibers were added to concrete to improve the properties and performance of concrete for applications in the construction industry. CF and SF fibers are used in concrete as hybrid natural fibers. For this purpose, four cylinders and two beams were cast in normal concrete (PC). Similarly, coconut fiber reinforced concrete (CS-FRC) samples were prepared by adding CS-FRC. Sisal fiber with varying content of the cement mass, and coconut fiber also having varying content of the cement mass. The lengths of CF used for hybridization were 50 mm. The usage range of SF is 50 mm. The water/cement (W/C) ratio is 0.6 and the designed mix ratio is 1:2:3 (cement: sand: aggregate) polymers used in the preparation of PC. Fiber reinforced concrete (FRC) was prepared using

A/C 0.7 with mix design ratio 1:2:3. Slump, dynamic, mechanical and scanning electron microscopy tests were conducted to verify the effects of different content combinations of hybrid natural fibers on concrete properties. The study highlights the possibilities of CS-FRC in terms of its application in structural works such as columns, beams, slabs, as well as pavements, with carrying significant benefits like durability and sustainability. Such practice reduces our dependency on exhaustible resources; through incorporation of renewable fibers, thus creating sustainability in environmentally-sustainable building. Further research is focused on long-term strength, field performance, and feasibility to increase the application of CS-FRC to actual practice.

Keywords: Natural fibers, Agricultural waste,Sustainable construction,Coconut fiber, Hybrid fibers.

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Abbreviations

CCE	Compressive energy absorption from peak load to final load CPE
	Compressive energy absorption up to a peak load
CS	Compressive strength
CTE	Compressive total energy absorption CTI
	Compressive toughness index
CS-FRC	Coconut sisal fiber reinforced concrete
Ec	Elasticity modulus
Edynamic	Dynamic modulus of elasticity
FCE	Flexural energy absorption from peak load to finale load FPE
	Flexural energy absorption up to a peak load
FS	Flexural strength
FTE	Flexural total energy absorption FTI
	Flexural toughness index
HNFRC	Hybrid natural reinforced concrete JF Jute

Symbols

kN	Kilo Newton
L/S	Linear shrinkage
ML	Mass loss
mm	Milli meter
MPa	Mega Pascal

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]. Microcracks caused by the fragility of the concrete reduce the useful life of the structure. This raises durability concerns due to the increased permeability of invasive substances [4]. Because of these properties, concrete is unreliable. Fibers need to be added to concrete to obtain sustainable materials and improve properties and performance. The addition of fibers can improve the toughness and tensile strength of concrete [5]. In recent decades, different natural fibers have been used in concrete to achieve specific desired properties, increase early strength, accelerate setting time, and reduce cement content in concrete. Therefore, high-performance green materials need to meet the characteristics of the economy, safety, sustainability, and environmental friendliness [3]. Fiber-reinforced concrete (FRC) has high toughness, energy absorption, and good tensile strength. Due to these facts, FRCs with short and discrete fibers, of considerable length compared to their diameter, should be investigated to obtain these advantages.

Man-made fibers have adverse effects on the environment and have the reprehensible attribute of causing a certain health risk to human beings. They do not biodegrade easily. Coconut Fiber refers to a by-product of coconut crop, which is regarded as a waste material and sisal being also a by-product of a plant crop is also defined as a natural plant fiber. Both solutions are sustainable to the environment and they do not cause any negative impacts to human health. Advantages of coconut and sisal fibers include local supplies, non-toxicity and cheapness [6]. They can, as well, reduce the cement used in the manufacture of concrete by applying hybrid natural fibers (HNF). Given that the natural fibers can be incorporated in the concrete, it can reduce the crack formation. Alternatively, the tensile strength and energy absorption can be improved by addition of short discrete fibers [7].

Many researchers have reported increased resistance to fatigue, cracking and spalling with a corresponding rise in flexure strength. Thus, it is possible to improve the performance qualities in concrete according to the needs of a particular application. Substitution of hybrid fibre that vary in content in the concrete will reduce macro and micro cracking since the fibre allows a bridging effect in the material. There are different mechanical, dynamic and processes of absorption which can be enhanced by the addition of natural materials in concrete.

1.2 Research Motivation and Problem Statement

In the modern society, concrete is widely used as the major building material. Even with the countless disparities, there is still nothing to compare it with and it has the potential of countering the faults of not having satisfactory tensile strength, non-satisfactory bending strength or the inability to withstand impact loads that occur in the course of explosions or collision with heavy mass objects. The goal of the given research is therefore to contain the effects of the above weaknesses and serve the human race. Destruction of structures made of concrete will also lead to loss of precious lives as well as big economic consequences. As a result, any failures of concrete when facing the different types of loads should be avoided. On the other hand, burning or disposing agricultural waste will result in pollution of the environment. It was discovered that the use of the natural fibers that were short and discrete helped in boosting the expected concrete performance and prevented failures.

Due to the developing nature of the world, construction sector should employ new materials and approaches such as sustainable and high-performance building material. The main aim of this research work is to add agricultural waste into the building materials as a sustainable resource to increase the performance of concrete. It can help correct concrete shortcomings and deter collapse of structures, eventually save lives. This study is based on past works that were utilized in stiffening of pavement showing greater performance [1].

This paper aims at ensuring that the agricultural leftovers are utilized to their best and by making them gain more mechanical and dynamic value to be used in different types of structures.

The study is limited to experimental study due to relative comparison. The present paper can help academic researchers in the development of ideas and mechanisms of effective use of agricultural wastes in concrete. This removes the need to incinerate or take garbage dumping which involves a lot of labour, is expensive and not environment friendly. Hence, the possible one is the following:

As time goes by, the process of urbanization is accelerating, leading to an increase in the use of environmentally unfriendly building materials such as concrete. Agricultural waste such as coconut fiber and sisal fiber can be used in concrete to improve its physical properties. The use of short, discrete natural fibers of varying contents can reduce micro and macro cracks in concrete, thereby increasing the load-bearing capacity and improving tensile strength and impact toughness. Hybridization of natural fibers of different contents such as cocnut and sisal fibers can give better results due to their combined effects. There is no research on the effect of different fiber content of coconut and sisal on the mechanical, dynamic and absorption properties of concrete. The construction industry will never stop, but agricultural waste can be used to improve the condition of houses, protect the environment and obtain eco-friendly materials for sustainable development.

1.2.1 Research Questions

- How much the mechanical behaviour of Sisal and Coconut Fiber Reinforced Concrete (SCFRC) are improved as compare to traditional concrete?
- How much more damping of concrete having HNF can be achieved compared to plain concrete ?
- What is the optimal fiber content of sisal and coconut fibers to achieve the best balance strength and toughness?

1.3 The Research Program Overall Objectives and Specific Aim of MS Research

The overall goal of this research program is to advance toward the development of sustainable concrete suitable for a variety of construction and civil engineering applications. Concrete has many defects that can affect the performance of the structure. Furthermore, the initiative provides a platform to use coconut fiber residues such as instead of burning or dumping them after hybridization with sisal fiber, as coconut has shown good potential for application in concrete.

"*The specific objective of this Master's research work was to investigate the mechanical, dynamic and absorption properties of concrete reinforced with hybrid natural fibres (coconut and sisal) of different contents and compare them with the properties of Plain concrete (PC).*"

1.4 Scope of Work and Study Limitations

For each parameter of CS-FRC, two specimens were taken to study its workability, mechanical properties and dynamic properties. Before studying the mechanical and the dynamic properties were studied first. When the first crack appeared in the specimen, it was considered broken after the load was applied. In this study, various other properties such as shrinkage which is linear, weight loss and by visual inspection of specimens which were broken also studied.

This study specifically focuses on evaluating the mechanical, dynamic and absorption properties of concrete reinforced with a hybrid combination of coconut and sisal fibers of different contents. It does not cover aspects such as durability, impact resistance or performance in extreme conditions of CSF-FRC. Furthermore, the carbon footprint of using these agricultural waste fibers is beyond the scope of this study. This work is based on the findings and suggestions of [8] and therefore does not include a detailed study of the properties of individual fibers. The study used a fixed percentage of fiber content and varied only the fiber content combination of the hybrid.

1.4.1 Rationale Behind the Variable Selection

Fibers are selected because of their availability in the local market and easily preparation in order to other fibers. These properties include strength, flexibility and wear resistance, which makes them competent to specific applications in wide-ranging industries. Construction materials that include such fibers have a big potential of enhancing the performance of concrete. The different kinds of fibers having different compositions that are included help in bridging the micro and macro cracks in the material and hence aid in stopping the spread of the cracks to the material when that material is exposed to any sort of stress [9, 10]. This results in improvements in the entire structural integrity and life of the material. Besides, these fibers are important in enhancing load distribution, enhancing impact resistance and in giving superior fatigue strength. By ensuring that the fibers used in the mixing of the mixture feature the best physical qualities, the professionals will achieve a more durable and a cost effective way of undertaking construction projects. The flexibility of fibers also enables them to be included in all types of construction materials further increasing the design flexibility and usability. The detailed selection of fiber content and the fiber composition is important to obtain desired properties fit to a specific application.

1.5 Brief Methodology

Concrete cracking/fracture process takes place in a multi-scale scene, it happens slowly in the passage of time. Environmental factors generally contribute to this phenomenon e.g. in the case of steel corrosion, this will result in the necessity of continuous repair and replacement of the concrete structures. The factors that affect concrete deterioration are environmental, wear and tear, as well as seismic activity and it is, therefore, necessary to consider both macro and micro fissure development to maximize the load bearing capacity of the material. In this way, the durability of concrete structures would be improved and these structures should be able to resist the force exerted on them with time. Additionally, it is crucial to manage the occurrence of such fractures to guarantee the overall durability and the strength of buildings, minimize the number of repairs and repairing costs. Incorporation of fibers, especially the hybrid fibers, especially fibers with different diameters and moduli could be one of the promising ways of enhancing the mechanical properties of concrete. This plan aids in making reinforcement of concrete more efficiently than the traditional strategies, thereby minimizing the use of steel reinforcement, which is easily corroded. Incorporation of fibers like pine and plastic contributes not only a special solution to the strengthening of concrete but also avoids harmful process of corrosion in concrete and whole effect on environment by slightly lowering the cost of concrete structure. This type of synergetic effects of the hybrid fibers may help to produce a new type of materials which will have a better performance, lower risk to be structurally damaged, and, therefore, make the infrastructure safer and more sustainable. With this new technology, the security of the people and the reduction of environmental risk as well as the expense incurred in the preservation and the rehabilitation of concrete buildings can also be greatly improved. Workability plays an important role in the hardening properties of concrete and the ease with which the concrete can be handled, poured, and transported [11]. Therefore, the feasibility of the new PC and all CS-FRCs was determined by the slump cone test. All specimens were cast in accordance with ASTM standards. After the machinability test, a total of 54 PC and CS-FRC specimens were formed. Each CS-FRC combination is cast from two beams and four cylinders. Among the four cylinders, two were used to test the compressive properties of PC and CS-FRC, and two were used to test the split tensile properties of PC and CS-FRC. The flexural performance of each CS-FRC was explored by subjecting the beam casting specimens to a three-point loading configuration. Servo-hydraulic testing machines are used to perform different types of mechanical tests.

1.6 Research Impact on Industry

This research of coconut and sisal fiber coconut-Fiber and concrete hybridization has the potential to impact significantly on the builder industry. This project solves old problems affecting the industry such as the brittleness and environmental impact of concrete by using agricultural waste as an alternative source of sustainability [12]. The use of natural fibers adds mechanical strength to the concrete giving it an alternative to the environmentally unfriendly tradition building materials. This research can support the construction of more environment-friendly methods, reduce the dependency of the industry on non-renewable resources, and lower the overall environmental footprint of the industry. Besides, it will provide the agricultural sector with an opportunity to recycle rubbish, creating a model of a circular economy that would benefit both building and agriculture

1.6.1 Research Novelty

In the history of Concrete, concrete has brittle behaviour and its deformation capacity is not enough for bearing load by using natural fiber to enhance their properties. This research is has use hybridization of two different natural fiber which coconut and sisal fiber both have varying properties with different contents, these contents were not examined before in the the previous research. The study seeks to comprehend the impact of different fiber combinations on the mechanical, dynamic, and absorption characteristics of concrete [13].

1.6.2 Research Significance and Benefit

The importance of this study is that, it contains a possibility of stabilizing the performance of concrete by incorporating sustainable agricultural wastes. The fusion of CF and SF can increase the protection of concrete against an impacted load, therefore, improving its general mechanical properties. Besides, the use of agricultural waste in concrete production can avert the ecological ramifications of normal concrete and address environmental pollution caused by the wrong disposal of agricultural byproducts [14]. This study provides suggestions on the subject of sustainable construction material, working on the weaknesses inherent with concrete in terms of low tensile and flexure strength as well as increase environmental viability.

1.6.3 Practical Implementation

The practical implication of this research is the use of hybrid CF and SF with a view of producing concrete with better characteristics, in particular, impact resistance and mechanical strength. The paper also looks at the use of the fiber-reinforced concretes (FRCs) in stiff pavement and other structural uses that demand greater performance. This can improve the shortage of viable alternatives in the industry, minimize cost and improve performance by involving agricultural wastes into the construction materials.

1.6.4 National and Global Impact with Emphasis on SDGs Relevance

This study has significant national and international implications in terms of sustainability and waste management. The study is not only in line with the Sustainable Development Goals (SDGs) set out by the United Nations but also a specific goal (goal 12: Responsible Consumption and Production), by eliminating the use of environmentally dangerous materials in favor of agricultural waste used in concrete production. It contributes to the realization of sustainable cities and communities (Goal 11) since it is developing an effective solution to the environmental effect of concrete.

Moreover, such methods, when applied in the world, would reduce environmental degradation caused by the poor disposal of agricultural waste.

1.6.5 Research Challenges

One of the issues experienced in this study is the optimization of combinations of fibers in concrete. The differences in the content of fiber and its effect on the mechanical properties of concrete will have to be tested and studied thoroughly.

Moreover, providing a consistency to the agricultural fiber qualities such as coconut and sisal could be a challenge in a mass scale. Future problems can be encountered in making sure that the fibers hybrid are not likely to effect other concrete aspects negatively such as workability and the curing period.

1.6.6 Ethical and Management Considerations Including Risk Management

An ethical issue that would be brought forth here is that the waste in the agricultural waste of this study would have to be ethically sourced and would not degrade the environment.

Effective resource management, which involves collecting and processing of agricultural fibers, has to be carried out to ensure sustainability. Since there are some possible negative outcomes of utilizing the hybridized fibers in the construction of concrete, which include inconsistency in the material standards and lack of adhering to the rules of the construction, the risks need to be managed. Risk mitigation techniques should be applied in order to avoid structural failures in the real applications.

1.6.7 Research Deliverables, Sales, and Marketing Potential

The present project will generate fiber-reinforced concrete (FRC) with hybrid agricultural fibers, and the results of experimental studies, along with the proposals to use such materials in buildings and constructions.

The prospect of this discovery has significant marketing potential in the term that it can be provided as a sustainable alternative to the traditional concrete and the buildings can be constructed at the lower cost and have an improved performance.

The results of the research could be advertised to the construction companies, paving contractors and other parties interested in using building materials unperturbed by the environment, namely, the ecological and economic benefits of using agricultural waste products in concrete production processes.

1.7 Thesis Outline

The thesis contains six chapters. These are:

Chapter 1. This chapter will include the background of the study, the reason why the study is conducted, the statement of the problem, the general and specific objectives of the study, the scope of work and limitation of the study, a brief methodology and an overview of the thesis statement.

The literature review is contained in chapter 2. It covers background and agricultural wastes and with sustainable materials construction, which is modern trends in using wastes that comes from agricultural as construction materials, different of combination of different fibers, presence of differing contents of fibers that comes from nature in concrete, shortages in concrete and its remedies, conclusion.

Chapter 3. Its contents described in this chapter include experimental framework, basic ingredients of concrete, mix design, casting of specifications and carrying out tests, and summary of Chapter 3.

The chapter 4 shows the outcomes of the testing and following analysis. Here, in the background, threr are dynamic and mechanical properties of the mixtures (Plain concrete and CS - FRCs), different properties, broken surface of the tested samples and a description of Chapter 4 is depicted.

In the Chapter 5 outlines the line of action as far as the practical implementation is concerned and includes the background information, the ideal blend of the coconut and sisal fiber lengths, the use of this research in practice and a concise conclusion of the chapter.

Chapter 6 consists of future recommendations and finding.

References

Chapter 2

Literature Review

2.1 Background

Since ancient times, various fibers have been used to enhance the mechanical strength and performance of composite materials. Natural fibers in particular are attractive for reinforcement because of their eco-friendly nature and low cost. Meanwhile, agricultural wastes are generated in millions of tons every year, and it is necessary to repurpose these wastes for useful applications. Fiber-reinforced concrete (FRC) generally outperforms conventional plain concrete in certain properties, motivating exploration of agricultural waste fibers as sustainable construction materials. Harnessing these fibers – especially in hybrid combinations – in concrete can contribute to improved material performance and represents a positive step toward sustainable development.

2.2 Concrete Flaws And Their Remedial Measures

As warm as concrete is a preferred building material due to its compressive strength, it has a number of defects inherent in it that may influence its effectiveness.

The brittleness of concrete is however among its primary disadvantages since it possesses high compressive strength coupled with very low tensile strength [15]. This process reduces the structural strength of the concrete owing to surface cracks that are common to occur during the hydration process. In the event that such fissures are not fixed, there are very high chances that the building will collapse in a catastrophic way, particularly during the application of loads by outside sources [16]. Corrective measures such as use of natural fibers have been identified to improve the performance of concrete.

2.2.1 Brittleness and Crack Formation in Concrete

Low level tensile strength of concrete is the main cause of the brittleness characteristic, which is one of the greatest downsides of the concrete [17]. Despite being able to resist large lumps of compressive stresses, the concrete tends to fracture easily in tension. The cracks such as this one can develop during the process of hydration when the concrete becomes dry and shrink due to which the construction turns out to be weak [18]. The formation of cracks in concrete leads to serious reduction in tensile strength and the general performance of the concrete which implies that material is most likely to fail under external stress. When such fissures are not taken care of they may extend and eventually cause the structure to collapse [19].

2.2.2 Role of Natural Fibers in Mitigating Cracks

There has been an increment in the amount of natural fibers being mixed with concrete so as to curb the vice of cracking. The fibers serve the role of crack inhibitors therefore sealing any cracks on the structure and giving it an extra reinforcement [20]. It avoids new cracks emerging besides preventing the spread of cracks. This could be done by addition of natural fibers that have different lengths like sisal, jute or hemp because they can close both micro and macro cracks hence creating a high resilience of the concrete. Reinforcing the concrete with the fibers is a way to increase the ability of the material to absorb the energy and the ability to sustain the tensile stresses [16]. Fiber-reinforced concrete is much stronger than regular concrete and can retain its integrity even when the cracks begin developing [21]. The second advantage of the procedure is that it assists in increasing the energy absorption capacity of the concrete as a result of which the concrete becomes appropriate in terms of use where the building needs to be resistant to earthquakes [17].

TABLE 2.1: Results Obtained by Incorporation of coconut fiber in cocnrete Composites

Fiber	**Matrix**	**Fiber Reinforced Composite Properties**	**Values Obtained**	**Application**	**Ref**
Coconut Fiber	Concrete	Compressive Strength	19.0 N/mm^2 (Control) 8.45 N/mm^2 (1.5% Fiber)	Structural elements	[22]
		Tensile Strength	4.0 MPa (1.5% Fiber)	Structural elements	[22]
		Workability (Slump)	130 mm (Control) 20 mm (1.5% Fiber)	Structural elements	[23]
		Impact Resistance	Enhanced with 2% Fiber	Impact-resistant structures	[24]

TABLE 2.2: Results Obtained by Incorporation of sisal fiber in concrete Composites

Fiber	**Matrix**	**Composite Properties**	**Values Obtained**	**Application / Notes**
Sisal fiber	Concrete	Compressive Strength	e.g. control & values for 0.5%, 1.0%, 1.5%, 2.0%	Structural / general concrete
		Split Tensile Strength	values for the same fiber contents	Crack resistance / tensile zones
		Workability (slump)	slump decreases as fiber % increases	Fresh mix behavior
		Density / Water Absorption	density decreases, absorption increases with fiber %	Durability / porosity
		Modulus of Elasticity	values at each fiber %	Elastic response

2.2.3 Reinforcement with Natural Fibers

Concrete has poor tensile strength and therefore needs reinforcement which in most cases can be done using steel bars [17]. This fortification together with the usage of the cement binders has adverse impacts to the environment due to high level of energy being used and the amount of carbon being emitted. Natural fibers, as a substitute reinforcement material, can be applied to address the issues that have emerged [18].

These fibers are friendlier to the environment due to their biodegradability and the fact that less energy is needed when making it than the conventional fibers. Moreover, the use of natural fiber can be used to complement the sustainability of concrete through reduction in the environmental footprint created by the construction materials [25].

Reinforcement of natural fiber in concrete not only enhances the tensile strength of the material it also solves the environmental concerns that has been associated with the traditional reinforcement of concrete using the common methods. Moreover, with the use of fibers, they are now able to control better the fracture, as well as, increases overall structural strength of the concrete that makes the material even more resistant and durable in the long run.

2.3 Hybridization of Different Fibers

The aim of the hybridization of natural fibers is an attempt to attain composite impacts of two or more fibers. Concrete is used to incorporate natural fibres so as to improve its intended properties. The study analysed the use of sisal, flax, and jute fibers concentrating on a length that is 5, 10 mm and 20 mm respectively or using different content of fibers like 1%,2% etc. The results showed that the introduction of these fibers was very remarkable with the increase in flexural characteristics of the concrete. The fibers with 20 mm length are mixed to get maximum flexural strength. Fiber reinforced concrete having fiber length up to 20 mm may have flexural strength increase by 13 percent [26].

2.3.1 Effect of Fiber Length on Flexural Strength

The property enhancement of concrete to different levels is caused by the difference in intensity of strengthening of fiber of different lengths through hybridization. When the length of the fiber given is increased (5 mm- 20 mm), the flexural strength of the concrete improved significantly. Fibers 20 mm length acquired the maximum flexural strength [27]. On the contrary, with a fiber length of 25 mm to 75 mm, the remaining improvement in the flexural strength was quite considerable, as high as 38 percent. Fibers between 25 to 75 mm are preferred with an aim of enhancing the flexural strength of the fiber remodified concrete [28–31].

2.3.2 Optimal Hybridization Ratios and Fiber Blending

The hybridization was done using mixed fibers in a different percentages of 0.3, 0.4 and 0.5. The 0.3% hybrid had the most resistance that indicated that there must be an optimum content of fiber to maximize performance [32]. The paper also stressed on the value of blending fibers of varying measurements to enhance the flexural power of concrete. The flexural strength of blended natural fibers was high in comparison with those of individual types of fibers and this implies that fiber length and ratio are crucial in making impact on overall performance of the composite material [33].

2.3.3 Impact of Natural Fiber Content on Concrete Toughness

Natural fiber reinforced hybrid concrete can be effectively applied to replace traditional concrete (PC). Specifically, macrofibers assist in the healing of the macro fractures and enhance an overall lifting of the concrete hardness [34]. Through their involvement in such forces as frictional sliding, pullout, fracture, and detachment, the presence of such fibers helps in the resistance offered against the crack spreading. These fibers enhance the post-cracking behavior of the concrete considerably since they control energy dissipation and deformation in the post-cracking phase [35]. Fiber hybrid experiments: Addition of natural cellulose fibers Fiber-reinforced concrete experiments which used fiber hybrids (such as jute, coconut, sisal and sugar cane) demonstrated that the proportions of the natural cellulose fiber blend could effectively be altered and increased to improve the compressive as well as tensile strength of the material [36].

2.4 Benefits of Hybrid Fiber Reinforced Concrete

Hybrid fiber-reinforced concrete (HFRC) is a composite in which two or more types of fibers are combined in order to take the advantage of each different type of fiber. This composite technology improves the mechanical properties, strength and the performance of concrete in a variety of uses. Hybrid fibers enhance crack resistance, toughness, impact resistance and general durability of concrete [37]. Also, it expands the capacity of concrete when it comes to energy absorption, which makes it practical in any dynamic loading situation like the case of earthquakes or high traffic. This is achieved through the hybridization so that it enables a control and customization of material properties that can meet the specific demands of construction projects and are thereby preferable in high performance as well as cost-effective [38]. Steel cannot be reduced just because of higher concrete strains, since concrete is weak in tension and codes set minimum steel ratios. The higher strain only shows better ductility and energy absorption, meaning fibers complement steel but cannot replace or reduce its required amount [39].

FIGURE 2.1: Natural fibres bridging crack [40].

2.4.1 Improved Durability and Crack Resistance

The main advantage of hybrid fiber reinforced concrete is that it is more resistant to cracking and is durable. The hybrid fibers increase microcracks control and prevent appearance of large cracks under pressure [41]. Use of fibers of which the types used are steel, polypropylene and natural fibers like sisal helps in countering the cracks that occur in concrete when subjected to loading and curing. The ability to prevent the propagation of cracks is critical where the application has severe environmental factors such as intense temperatures, exposure to chemicals or cyclic loads. Its increased strength reduces the costs of maintenance and makes HFRC a perfect choice to use in infrastructure projects like bridges, tunnel, and highways [42].

2.4.2 Sustainability and Cost-Effectiveness

The benefits of hybrid fiber reinforcement are sustainability because it reduces the impact on the environment brought about by concrete production. The integration of all-natural, renewable and biodegradable fibers lessen the amount of carbon that the material has over the conventional concrete [43]. In addition, we could reduce the amount of cement and steel reinforcement required which is required by hybrid fiber reinforcement and this could help us to use low amounts of energy during the manufacturing process. The reinforcement of fibers in concrete form increases the property of strength and durability that allows the use of less amount of material. The plan has the benefits of environmental gain and cost-saving in projects [44].

2.5 Plants Wastes

Plants wastes (Plants-wastes) are the byproducts or surplus of crops which are abundantly present in developing countries [45]. These wastes need much land to be dumped or disposed. Plant wastes produce about 9% of the total energy production. On the other hand, plants wastes provide around 35% of the total energy consumption in developing countries. World produces about 2.9 billion of crop waste annually and 66% of these crops waste are burnt as source of energy [46–48]. Open burning of these coconut is the wastage of natural resources and causing air pollution; severe threat to highway traffic, impairing human health and safety [49, 50]. Plants wastes include bagasse straw, olive stones, grapes seeds, cotton stalks [27, 51, 52], pine sawdust [53], pecan, coconut shells, sisal, sunflower shells [54, 55], jute, wheat straw, rice straw, rice husk, corncob and cassava rhizome etc [56]. These plants was found that about 59% of the gross residue of rice crop contains rice straw whereas 20% is rice husk [57].

As per the data of united states food and agricultural organization 2017, the world produces about 60.5% of coconut waste and the issue of recycling of this waste is a matter of concern [1]. Worldwide rapeseed production in 2017 was 72.6 million tons and stem or branches of this agricultural waste can be used as construction material [58]. About 200,000 million of waste is generated from date palm. This palm waste is charred and released as plants waste which can be utilized in production of sound absorbing panels [59].

The sisal production process in many countries is highly inefficient, utilizing just 2% of the plant, while 98% is wasted, including damaged leaves, shoots, roots, stems, debarking byproducts and short fibres [2]. Sisal is the plant which used in paper, cloth, footwear, hats, bags, carpets, geotextiles, and dartboards [2]. In the 1960s in the production sisal fiber increased by highest ratio due using environmental friendly fibers [3]. Sisal plants grow in semi-arid to arid climates and have the potential to It is not suitable for other crops and is labeled as a marginal crop. Sisal plant is a renewable resource and contribute significantly to climate change solutions. This is because sisal absorbs more carbon dioxide than it produces over its lifetime. Lifestyle (Food and Agriculture Organization, 2016). Sisal can support up to near 50 °C, and a significant increase in the equilibrium temperature range from 60 − 125 cm, although Heavy rain can cause water stagnation, and too-low temperatures can lead to injuries, often Destruction of trees [4].

Pakistan's coir production is currently low compared to global coir producers such as India, Sri Lanka and Vietnam. Although Pakistan's coconut production has grown significantly due to the expansion of cultivated areas and increased productivity, and is expected to reach 25,000 tons by 2022 , the relevant coconut industry is still in the development stage. Despite the growing global demand for coir fibers (e.g., mats, wool, and horticultural substrates), limited data on coir production suggest that the coir industry in Pakistan is still in its infancy. Stimulating coir production in Pakistan can have a positive impact on its success in the international market. To unlock the potential of Pakistan's coconut industry and make it more competitive in the global market, Pakistan needs more research and investment [5].

2.6 Sustainable Construction Materials

The production of conventional concrete over the last century has imposed adverse effects on the environment. Billions of tons of concrete are manufactured each year, a process that emits substantial carbon dioxide and consumes vast quantities of natural raw materials. Notably, the cement industry alone is responsible for about 7% of global CO_2 emissions [6]. In parallel, enormous amounts of agricultural and industrial wastes are generated in both urban and rural areas, demanding proper disposal or reuse. Recycling these wastes into useful products is seen as a viable solution to the crisis of waste dumping. Indeed, several industrial by-products have already been employed as sustainable construction materials [60, 61].

The use of supplementary cementitious materials like silica fume, fly ash, granulated blast furnace slag, and palm oil fuel ash in concrete are examples of such practices. These by-products have been added to concrete mixes to reduce Portland cement content and improve durability, thereby turning waste into a resource. Such materials can be utilized in various concrete structural elements without compromising performance. In addition to industrial wastes, natural fibers derived from agricultural by-products have been increasingly investigated as sustainable reinforcement in concrete. For example, coconut fiber has been used as an eco-friendly additive in concrete for structural applications under freeze–thaw conditions [7]. In one study, coconut fiber–reinforced concrete exhibited reduced damage from freeze–thaw cycling, allowing the design of building structure with reduced thickness but equivalent performance to conventional concrete pavements [62]. Sisal fiber is another plants material with promising properties for cement composites, such as high energy absorption and toughness indices, strong reinforcing ability, and high water absorption capacity [12]. Table 2.1 in the original thesis compiles several studies on sisal fiber–reinforced concrete, highlighting its potential as a sustainable construction material.

Some researchers have explored adding coconut fiber to concrete mixes [13, 14]. For example, a bio-based concrete using coconut fibers has been developed for thermal insulation purposes; the resulting composite exhibits excellent hygroscopic properties (moisture resistance), ensuring comfortable hygrothermal conditions inside buildings. Another study used coconut fiber in cement-based mortar to create a more sustainable mortar. Under impact compression loading, the coconut fiber specimens did not disintegrate; instead, they exhibited only discrete cracks, and their overall mechanical properties were improved without any adverse changes in thermal properties. These results suggest that the incorporation of natural fibers, such as jute and coconut fibers, can improve the toughness and durability of concrete while maintaining or even improving functional properties, contributing to more sustainable construction practices [63].

Sisal fiber are used as sustainable building materials and are used to produce environmentally friendly, ultra-high performance concrete. Sisal fibers delay setting time by limiting the hydration process and also reduce shrinkage [11]. Natural fibers from coconut, sisal, jute and sugarcane can be used as sustainable building materials and can improve the tensile and compressive properties of concrete [45].

Plants that goes to waste such as bagasse and coffee husks can be used to partially replace crushed stone in the manufacture of concrete blocks. The husk of coffee and bagasse can improves the thermal, physical and mechanical properties of the material. Compared to coffee husks, bagasse has superior properties and can be used as a sustainable building material. With the addition of 5% bagasse, the concrete blocks showed greater compressive strength and all the properties required for commercial use [46]. Agricultural waste and by-products can be used for useful purposes in concrete and can also improve the desired properties of concrete or mortar by selecting the right natural fibers as a sustainable building material.

2.7 Latest Trends in Use of plants Wastes as Construction Materials

In today's era, sustainable development is a vital issue. Every step towards achieving the Sustainable Development Goals is important. As the world strives to implement sustainable solutions, the focus is on reducing waste, which directly contributes to global warming. Today, reuse and recycling have become top of mind concerns, catching the attention of people seeking solutions to environmental issues [47, 48]. In recent years, there has been great interest in using natural fibers/agricultural waste in cementitious composites to produce sustainable and environmentally friendly building materials. In addition, natural fibers have great potential for reinforcing concrete and eliminating common defects. Natural fibers from agricultural waste can be used in brittle cementitious composites to improve their strength and energy absorption [17]. Many researchers have used natural fibers as alternative materials in various fields. Agricultural waste/natural fibers used in cementitious composites include bamboo, banana, waka, palm, jute, hibiscus, hellebore leaves, sisal, coconut shell, date palm, mallow, pineapple leaves, hemp, ramie, wheat straw, tiger tail orchid leaves, kenaf, etc [27, 50, 51].

Natural fibers are cheap and available in large quantities in many countries. To improve the performance of cement-based composites, natural fibers from agricultural waste can be used as a renewable and low-cost building material. Besides being low-cost, high-quality, and readily available, natural fibers are also easy to handle compared to man-made fibers. According to [52], hybridization of two natural fibers can provide better results. They can also promote sustainable development due to their low cost and other desirable properties for use in cementitious composites [53]. An experimental study was conducted on the use of date palm agricultural waste as sound absorbing building material. 25 mm, 35 mm, 45 mm and 55 mm samples were produced. The results show that the sample with a thickness of 55 mm has the greatest sound absorption effect [54].

Natural fibers have good properties and can be used in concrete. Table 2.3 shows the properties of some natural fibers. It can be seen from Table 2.3 that the performance characteristics of JF and WS are better than those of other natural fibers. The dynamic and mechanical properties of coconut shell fiber reinforced concrete were determined in [55]. The optimum content is 5%, the optimum length is 5 cm. The compressive strength of coconut shell fiber reinforced concrete was significantly improved by 910%. Bamboo fiber is used in asphalt pavements to improve road performance and increase crack resistance. Bamboo fiber improves fatigue strength and dynamic modulus [56].

TABLE 2.3: Properties of Natural Fibers

Sr.	**Fibers**	**Properties**	**Ref**
1	Coconut fiber	High toughness index, high damping ratio, economical, good flexural strength.	[55]
2	Sisal fiber	High tensile strength, good abrasion resistance, high durability, biodegradable, renewable.	[58], [59]
3	Wheat Straw	High energy absorption, high toughness index, strong, high water absorption capacity, easily available.	[57]
4	Jute fiber	Lighter than steel, higher breaking strength, easily available, high energy absorption.	[16]
5	Flax fiber	High tensile strength, elongation property up to 2.7-3.2%, biodegradable, cost effective.	[64]

Research has found that hemp stone can improve the energy efficiency of buildings. It can reduce the impact on the environment [65]. Agricultural waste can be used as Mixed with other composite materials to make insulating materials [66].

TABLE 2.4: Composition of coconut and sisal Natural Fibers

Fiber	**Component**	**Percentage (or Range)**	**Reference**
Coconut	Cellulose	27–45%	[33]
fiber (coir)	Hemicellulose	∼15–20%	[33]

Table 2.4 (continued from previous page)

Fiber	**Component**	**Percentage (or Range)**	**Reference**
	Lignin	40–50%	[33]
	Moisture	8.9% (air-dry)	[34]
	Ash	9.70%	[34]
	Carbon (C)	49.4% (wt%)	[35]
	Oxygen (O)	44.4% (wt%)	[35]
Sisal fiber	Cellulose	68.10%	[36]
	Hemicellulose	11.90%	[36]
	Lignin	7.20%	[36]
	Moisture	4.90%	[36]
	Ash	2.50%	[36]
	Carbon (C)	35.10%	[67]
	Oxygen (O)	47.10%	[67]
	Calcium (Ca)	1.30%	[67]

The mixture of coconut fiber and sisal fiber increased the compressive strength by 11.6% and 22.2%, respectively. According to the research results, these natural fibers can be used as environmentally friendly building materials for flooring and paving [68].

2.8 Summary

In summary, the literature shows that the use of agricultural waste in concrete can significantly improve the properties and performance of the material. The natural fibers obtained from these composites act as permanent reinforcements and improve the mechanical strength and dynamic behavior of concrete. It turns out that isolating the two different fibers can provide greater benefits to the joints than using either fiber alone and can take advantage of the unique strengths of each fiber. Obviously, improving the mechanical and dynamic properties of concrete, especially its toughness and strength properties, is crucial to preventing crack propagation and extending the service life of the structure. Agricultural waste, which would otherwise be burned or dumped, causing environmental problems, can now be used as a useful material for concrete. The reviewed literature confirms that many common concrete defects (e.g., low tensile strength and brittleness) can be reduced by adding agricultural waste fibers. It has been shown that hybrid reinforcement of natural fibers, such as a mixture of coconut and sisal, can improve the tensile and flexural strength of concrete. In addition, the use of fibers of different lengths can bridge microcracks and macrocracks, effectively preventing crack propagation and improving the overall performance of concrete. Therefore, hybrid reinforcements with natural fibers of different lengths become a promising strategy to develop more durable, ductile, and durable concrete materials.

Chapter 3

Experimental Scheme

3.1 Background

The wastes that comes from plants are very common in those region which can not use it. Due to easily handling, availability, also environment friendly and having low cost of these natural fibers can be use in concrete. In this study, coconut fibers and sisal were used as reinforcements in concrete. Since the previous chapter, many researchers have used natural fibers in concrete to improve the desired properties. Meanwhile, hybridization of coconut and sisal fibers with different contents combinations has not been explored. For this purpose, slump cone test, mechanical test, dynamic behavior of concrete and scaning electron microscopy were considered. These tests were conducted to verify the effect of different combinations of sisal and coconut fiber different contents used in concrete. In addition, the fracture surfaces of the fractured specimens were also analyzed. Raw materials, coconut fiber processing, PC and CS-FRC joining methods, casting procedures, and testing methods are discussed in detail in this chapter.

3.2 Raw Materials

For the preparation of concrete the ordinary Portland cement (OPC) with crush having size of maximum 20 mm and locally available good quality sand are used at the time of plain concrete and FRC.

The fibers are purchased from local market in the raw condition then coconut fiber was not straight which was difficult in cutting, both fibers cut into 50mm length and put them in the water for 24 hours to absorb the water. The properties of coconut and sisal fibers are given in Table 3.1.

TABLE 3.1: Properties of coconut and sisal Natural Fibers [69]

Parameters	**Coconut**	**Sisal**
Length (mm)	18	18
Diameter (mm)	0.1–0.5	0.1–0.3
Density (g/cm3)	0.67–10.00	0.75–10.70
Tensile strength (MPa)	108.26–251.90	227.80–1002.30
Modulus of elasticity (GPa)	2.50–4.50	10.94–26.70

FIGURE 3.1: Images of Coconut Fibers (Raw, Treated, Cut Lengths Used) and Sisal

Figure 3.1 shows the coconut and sisal fibers; on treatment process of coconut fibers is also present in this image. At the time preparation of FRC, sisal and coconut fibers are used. The the varying contents of 2%, 1.5%, 1.75%, 0.5% and 0.25% of coconut fibers are used in the preparation of the FRC. Whereas, the same percentage of coconut fiber used for sisal fibers combined with coconut in FRC. Proportion of sisal is kept varying with coconut fibers in all CS-FRCs as recommended by [18]. normal water is used at the time of preparing the all PC specimens and all CS-FRCs. There is two different water-cement ratios are used for manufacturing different types of specimens. 0.55 water-cement ratio is used for making PC and 0.65 water-cement ratio is used at the of casting all CS-FRCs as reported by [70]. For the CS-FRC the water-cement ratio increased because of the fiber water absorption of coconut and sisal which is reported in the previous literature [70, 71]. The W/C for PC is 0.6 to 0.7 as reported by [19]. Due to high w/c ratio the bleeding occur in concrete and may cause the segregation reported [72].

3.3 Mix Design, Mixing Procedure, Casting of Specimens and Fresh Properties

For the preparation of concrete, a mix design ratio of 1:2:3 (cement: sand: aggregate) is employed. Fixed proportions of 50 mm Sisal and 50 mm coconut fibre with fix length are incorporated into the mixture for the production of coconut and sisal fibre reinforced concrete (CS-FRC). All materials are positioned in the drum mixer for the preparation of the PC mix. Water is introduced into the mixing machine 30 to 45 seconds after the initiation of rotation. The mixture machine is operated for five minutes. The slump cone test is conducted following the manufacture of Portland cement.

Table 3.2: Concrete Mix Design

Labeling of Samples	**Coconut(%)**	**Sisal(%)**	**Cement**	**Sand**	**Aggregate**
PC	0	0	1	2	3
C-FRC	2	0	1	2	3

Table 3.2 (continued from previous page)

Labelling of Samples	Coconut(%)	Sisal(%)	Cement	Sand	Aggregate
C-FRC 1	1.5	0.5	1	2	3
C-FRC 2	0.5	1.5	1	2	3
C-FRC 3	1.75	0.25	1	2	3
C-FRC 4	0.25	1.75	1	2	3
S-FRC	0	2	1	2	3

Note: water cement ratio is kept same for PC and CS-FRC i.e,0.60 and 0.70 *By cement mass. The cement sand, aggregates ratios and percentage fiber content are taken from the recommendations of the previous researcher [72]

In the production of cs-FRC, materials are arranged in layers to provide optimal mixing of hybrid fibres within the concrete. Three to four layers are utilised to create an optimal mixture of the CS-FRC. A third set of layers comprising aggregates, sand, sisal, coconut fibre, and cement is introduced into the mixing machine. Subsequently, the second and third layers of aggregate, sand, coconut, sisal, and cement are applied using the same methodology. The mixing apparatus is activated to commence rotation. Two-thirds of the water is added at the commencement of the machine's operation. Following three minutes of continuous spinning of the mixer machine, one-third of the remaining water is added, and the mixer continues to rotate for an additional two minutes, after which a slump cone test is conducted to assess the workability of the fresh CS-FRC. The same methodology was applied to the other categories of CS-FRCs containing a predetermined quantity of coconut and sisal fibres. The slump cone test is performed to assess the workability or consistency of the produced concrete mix. The slump test for the PC and CS-FRCs is conducted for every mixture prior to the pouring into moulds. The slump cone test, as perform on the basis ASTM standard C143/C143M-15a, slump test conducted to assess the workability of fresh concrete. The slump cone has a bottom diameter of 200 mm (8 in), a top diameter of 100 mm (4 in), and a height of 300 mm (12 in) for conducting the test. The cone mould must be non-absorbent. The tamping rod is hemispherical at both ends, with a diameter of 16 mm (5/8 in) and having maximum length of 600 mm (25 in). The cone contains three uniform volumetric layers of concrete. Following the placement of the initial 1/3-layer, compaction is achieved by randomly dropping a tamping rod onto the surface of the layer a total of 25 times from a height of 25 mm (1 in). Additionally, there are two or more layers of the cone are filled and compacted using a tamping rod. The excess concrete was eliminated using the tamping rod, followed by smoothing through screeding and rolling the rod over the surface. The slump cone is subsequently lifted vertically upward. The cone is positioned inverted adjacent to the concrete of the slump cone mould. The tamping rod is positioned over the inverted slump cone, allowing for measurement of the reach over the slump concrete using a ruler. The slump value is measured with precision, as illustrated in Figure 3.2a.

TABLE 3.3: Test and specimens to be prepare

Sr.	**Test**	**ASTM Code**	**Dimensions**	**Sample Cast**	**Shape**
1	Slump Test	ASTM C143	Fresh Concrete	No Casting	Slump Cone
2	Compression Test	ASTM C39	100mm (Diameter) × 200mm (Height)	2 per mix (Total Mix = 7 x 2, Total Cylinders = 14)	Cylinder
3	Split Tensile Test	ASTM C496-96	100mm (Diameter) × 200mm (Length)	2 per mix (Total Mix = 7 x 2, Total Cylinders = 14)	Cylinder
4	Flexural Test	ASTM C78 - C1609	450mm × 100mm × 100mm	2 per mix (Total Mix = 7 x 2, Total = 14)	Beam
5	SEM	ASTM E1508	-	2 specimens	Beam & Cylinder
6	Dynamic Behavior	ASTM C215	-	42 specimens	Cylinder & Beam

*These sample will use for Dynamic behaviour and mechanical tests.

Currently, no standardised test exists to assess the workability of fresh CS-FRC. Thus, the identical procedure and test standard are employed for assessing the workability of all CS-FRCs. Figure 3.2b illustrates the relationship between the observed slump values and the determined hard densities.

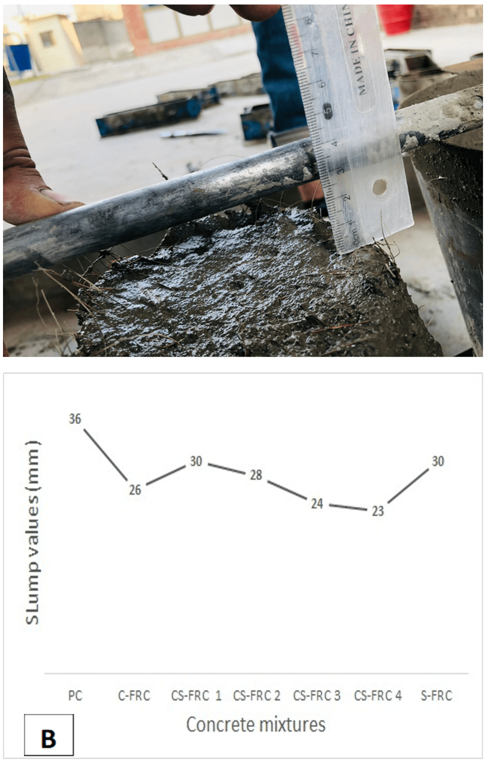

FIGURE 3.2: a) Measuring Value of Slump of CS-FRC, B) Slump values of different combination of CS-FRC

TABLE 3.4: Labelling of Specimens, their Density and Slump of Fresh Concrete

Labelling of Specimens	**C:S:A***	**Addition of % of Fibers by mass of Cement**		**W/c**	**Slump of fresh Concrete (mm)**	**Density of hard Concrete (kg/m^3)**
		Coconut fiber	**Sisal Fiber**			
PC	1:02:03	0	0	0.6	36	2339
C-FRC	1:02:03	2	0	0.7	26	2175
CS-FRC 1	1:02:03	1.5	0.5	0.7	30	2169
CS-FRC 2	1:02:03	0.5	1.5	0.7	28	2158
CS-FRC 3	1:02:03	1.75	0.25	0.7	24	2199
CS-FRC 4	1:02:03	0.25	1.75	0.7	23	2187
S-FRC	1:02:03	0	2	0.7	30	2178

* The ratios of cement, sand, and aggregates, as well as the percentage of fibre content, are derived from the recommendations of prior research [73].

The PC exhibits the highest density and slump value. Maintaining a varying content of coconut and sisal fiber where the length is fixed for both fiber, the results in a decrease in both slump and density values. Maintaining a constant water-to-cement ratio of both fiber while varying contents at 2%, 1.5%, and 0.75 results in a decrease in both slump and density of CS-FRCs in comparison to PC. The different combination of CS-FRCs is showed in the graph with red colour while the combination on the bottom and slump values are on vertical line.

The coconut fibres, contents of 2%, 1.5%, 1.75%, 0.5%, and 0.25%, are in the table. An average of two specimens is utilised for density measurement in each mix design. The volume of the beamlets is quantified in cubic meters by calculating the internal volume of the moulds utilised for their casting. Upon reaching the final setting time of the concrete, the moulds are removed, and the mass of each specimen is recorded in kilograms using a weighing balance. The minimum measurable increment of the weighing balance utilised for mass determination is 5 grammes. Densities are determined by calculating the ratio of weight (kg) to volume (m^3). Table 3.4 presents the determined values of densities and slumps. Currently, there are no established tests available to assess the workability and density of fresh CS-FRCs. Therefore, identical procedures and testing standards are employed to assess the workability and densities of all CS-FRCs.

3.4 Testing Methodology

This component of the testing methodology includes the slump test, dynamic test and mechanical test, assessment to evaluate various properties of concrete based on the a for mentioned tests. All tests are conducted in accordance with ASTM standards or as referenced by prior researchers. The mean of two samples is calculated for each test. Figures 3.3a and 3.3b illustrate the configurations for dynamic and mechanical testing. An accelerometer and a hammer are utilised in order to monitor longitudinal, lateral, and rotational frequencies in order to ascertain the dynamic properties of plain concrete, coconut, and sisal fibre reinforced concrete.

This is done in order to determine the dynamic qualities of these materials. There are three distinct forms of test setups that are utilised in order to ascertain each respective type of resonance frequencies that were described earlier. In the longitudinal frequency setup, the hammer is struck to the other cross-sectional side of the specimen, and the accelerometer is attached to one of the cross-sectional sides of the specimen (either the beamlet or the cylinder).

For the purpose of determining the transverse frequencies, the accelerometer is positioned along the length of the specimen at a distance of 25 centimetres from the edge of the cross-sectional area. Following this, a stroke of the hammer is applied parallel to the accelerometer on the opposite edge of the specimen.

When using the third type of test setup, the accelerometer is attached in the same manner as it is arranged in the longitudinal arrangement. This allows for the determination of the tortional frequencies. When this occurs, however, the length of the specimen that is perpendicular to the accelerometer is used to determine the stroke of the hammer.

In order to investigate the mechanical properties of PC and various types of CS-FRCs, tests such as compression, split tensile, and flexural testing are carried out. The cylinder specimens are positioned vertically between the test machine in order to execute the compression test. This allows the test machine to function as a prototype of a compression member or a column.

For the purpose of conducting a splitting tensile test, cylindrical specimens are positioned in positions between the testing plates. The purpose of this setup is to allow for the observation of the splitting tensile characteristics.

When attempting to establish an accurate value for any results obtained from these tests, the average of the values of two specimens is taken into consideration.

Toughness is the ability of bearing load on concrete element. By doing so, the average of the data acquired from the dynamic and mechanical characteristics is taken into consideration in order to achieve precision and to check for deviations in the results.

Figure 3.3: Tests setups; a) mechanical properties, b) dynamic properties

3.4.1 Dynamic Testing

The dynamic test carried out prior to destructive mechanical analysis was full and is conducted per the ASTM C215 standard to determine the frequency response of concrete under different loads. Frequency responses of concrete samples to impacts of impact hammers were measured, including lateral responses, transverse responses and rotational responses under the trigger of accelerometers. In the lateral frequency response, the accelerometer was mounted on the one side of the cylinder and the other pair hit with a hammer. In the transverse frequency response, they have positioned the accelerometer on the top of the cylinder as the hammer hit the same side. The rotational frequency response entailed hitting the other side of the accelerometer at 90-degree angle. The method was done in a similar manner to both cylindrical and the beam specimens to ascertain uniformity in the results. The frequency data, which was attached to the accelerometer was sent to a computer system and processed using RTG software. In the case of transverse frequency response, the accelerometer was set at 25 cm edge of the cylinder, and the hammer was hit at the middle of the cylinder length. In this configuration, the dynamic properties of the concrete could be measured accurately at various loads. The measurements made by these tests provide useful information on the behavior of the material under dynamic loads, such as vibrations and rotational stresses, in order to determine the material applicability as structural material exposed to such loads. For the response frequency, the cylinder top showing face the accelerometer attached the space was same length as like response frequency transverse. The hammer strike perpendicular to the accelerometer on the opposite edge of the cylinder length. For the case of beamlets, for response frequency transverse at the time of determination, accelerometer at the same margin at one side of length was attach as like cylinders on length of beamlets from edge. Hit the hammer at the center of length to the same side where the accelerometer is attached. For response frequency transverse, the accelerometer is fixed at the upper corner of the rectangle (side of the beam). The impact is applied to the other lower corner of the same side of the rectangle so that the line joining the hammer point and the accelerometer forms the diagonal of the rectangle. From these observed frequencies, the damping coefficient, dynamic elastic modulus, dynamic stiffness modulus and Poisson's ratio are calculated. These calculated properties help in understanding the behavior and resistance of PC and all types of CS-FRC under dynamic loading. These properties are essential for the design of structures subjected to dynamic loading and earthquakes.

3.4.2 Mechanical Testing

3.4.2.1 Compressive Test

The compressive strength of PC and all CS-FRCs was determined using a servo-hydraulic testing machine (STM). The tests were carried out on PC and CS-FRC cylinders according to ASTM C39. The following parameters were measured: compressive strength , energy before crack and energy after crack, total absorbed energy in compression and compression toughness index for PC and CS-FRC. To distribute the load evenly throughout the cylinder, it was covered with plaster. The energy absorption can be calculated by using area under curve.

3.4.2.2 Splitting Tensile Test

ASTM C496M-02 is used for the split tensile crack test. The tests were conducted using the same STM apparatus. The tests were conducted on PC and CS-FRC cylinders. The tensile crack test does not require the cylinder to be closed.

The load-strain curve, crack tensile strength (ST-S), pre-crack energy absorption in tensile crack (SE-1), post-crack energy absorption in tensile crack (SE-2), total tensile crack energy absorption (ST-E), and tensile crack toughness index (ST-I) are calculated from this test. The energy absorption can be calculated by using area under curve.

3.4.2.3 Flexure Test

The bending tests were conducted according to ASTM C78 standard. A three-point loading mechanism was used. The tests were performed on PC and CS-FRC beams.

The parameters studied included load-deflection curve, flexural strength (F-S), flexural energy absorption before cracking (FE-1), flexural energy absorption after cracking (FE-2), total flexural energy absorption (FT-E) and flexural toughness index (FT-I). The energy absorption can be calculated by using area under curve.

3.5 Scanning Electron Microscopy

Scanning electron microscopy (SEM) analysis of the fibers was performed to collect information related to failure analysis of inorganic materials, chemical composition, quality assessment, and external texture and structure of the fibers. Figure

3.3a shows the SEM image of sisal with diameters between 5μm and 7μm. In contrast, Figure 3.3b shows the microstructure of coconut fiber, which is composed of nanofibers with diameters between 20μm and 200μm.

Figures 3.2a and 3.2b show SEM images of the tubular edges of coconut fiber and sisal fiber filaments that swelled due to sufficient water absorption.

The SEM analysis in Figure 3.2a shows the inner and outer layers of wheat straw. The coarse texture of wheat straw facilitates the frictional interaction between the concrete and the fibers, thereby resisting tensile forces, as shown by the outer friction surface of the wheat.

The inner layer of wheat straw is less porous and less absorbent than the coconut fibers. Figure 3.3b shows impurities on the surface of the coconut fibers and the presence of nanoporous carbon, which is characterized by its rough surface and fiber edges. The rough surface of natural fibers creates a frictional effect that resists the forces pulling them out of the matrix.

3.6 Procedure for Empirical Modelling

Experimental testing determines the empirical relation between experimental measurement of Linear Shrinkage and Splitting Tensile Absorb Energy. To start with specimens of concrete are manufactured and their Linear Shrinkage measured as the difference between initial and final length after drying. Linear shrinkage is calculated as percentage of the dimensional change. The Splitting Tensile Absorb Energy is determined by a diametrical compression trial whereby, the specimen is loaded up to failure and the absorbed energy is calculated by integrating the area under the load displacement curve. Several specimens are tested and data is collected, and regression analysis can be used to ascertain relationship between Linear Shrinkage and absorbed energy which is usually linear in form. This relationship helps understand the influence of shrinkage manipulations on the ability of the material to absorb energy under tensile stress and give a clue on the performance of the material under real work conditions.

3.7 Summary

PC and all types of CS-FRC specimens were prepared with a design mix ratio of 1:2:3. The water-cement ratio of PC was 0.6, while that of all types of CS-FRC specimens was 0.7. sisal fibers of lengths 50 mm fixed were used in combination with coconut fibers of lengths of 50 mm, and the content of fiber is varying for coconut fibers which is 2%,1.5%, 1.75%, 1%, and 0.25% of the cement mass, while sisal fibers accounted for the same content of the cement mass. Both fibers acted as mixing fibers. A total of 42 specimens, including 28 cylinders (from 7 combinations) and 14 beams (from 7 combinations of CS-FRC), were cast. Slump, dynamic, mechanical, and other tests of PC and CS-FRC were determined following ASTM standards. A comprehensive analysis of the results obtained is presented in Chapter 4.

Chapter 4

Results and Analysis

4.1 Background

The mix design ratio of 1:2:3 is used for casting specimens of both PC and HNFRCs. The w/c of 0.7 is used for all specimen type. For preparation of HNFRCs (C-FRC, CS-FRC-1, CS-FRC-2,CS-FRC-3, CS-FRC4 and CS-FRC), fiber is added 2% by the mass of cement, according to their ratio. Fibers are used with same length length of 50mm for coconut and sisal fiber, respectively.

4.2 Dynamic Properties

This work is intended to assess the influence of different ratios of the compound of coconut and sisal fibers on the dynamic characteristics of the samples of the Concrete Composite with Sisal and Coconut Fibers (CS-FRC). To be able to evaluate these effects, standardized procedures were used in order to determine the dynamic properties of CS-FRC. Dynamic properties of plain concrete (PC) specimens were firstly identified based on ASTM C215-14, which is a commonly accepted norm that defines the testing conditions of a dynamic property of concrete materials. Nonetheless, there being no particular standard that could be used to test the dynamic properties of CS-FRC, the same principle of the ASTM C215-14 standard was used to test the same. An accelerometer was also used to assess the dynamic properties of CS-FRC whereby a real-time connection on the reaction of the concrete test samples said to be providing is a real-time judgment. As shown in Figure 4.1, an average graphical response by the accelerometer was expected, wherein the vibrations and movements of the specimens, under forces of dynamic nature, will be captured. The data that was extracted by the help of accelerometer was examined and Table 4.1 explained the operational dynamic properties of both plain concrete (PC) and the different CS-FRC mixes. CS-FRCs were subjected to various fiber content combinations and the outcome was documented to help in the evaluation analysis. The mean of the two values in each CS-FRC specimen combination was then found in order to have a uniform result to help in calculating the dynamic characteristics. The one important dynamic aspect is known as damping ratio (ζ). It is the parameter that will help determine the ability of the material to dissipate energy under dynamic loading. Damping ratio is especially special in the study about how a material receives and dissipates vibrational energy. In the study findings, significant differences can be noticed with regard to damping ratios of plain concrete (PC) and the different CS-FRC mixtures. Specifically, values of damping ratios of CS-FRC1, CS-FRC3 and CS-FRC4 showed minute variations of 0.38 percent, 0.22 percent and 0.02 percent respectively with plain concrete. These differences indicate that incorporation of fibers in these mixtures did not have significant influence on their energy dissipation characteristic. Conversely, the damping ratios of cylinder specimens of CS-FRC2, CS- FRC5, and CS-FRC6 were remarkably higher by 25%, 165%, and 25% respectively than plain concrete. Such big rises show that there is increased energy dissipation capacity with the inclusion of coconut and sisal fibers in these mixtures, and they are thus able to resist dynamic force more readily. The great increase demonstrated by CS-FRC5, in which the damping ratio increases by 165 percent, is notably striking and reflects a possibility that a specific fiber content combination can significantly enhance the dynamic behavior of the concrete. The given findings make their contribution to the comprehension of the way in which fiber-reinforced concrete can be designed in order to maximize its dynamic properties with respect to its application, i.e., it can be applied in the buildings that are exposed to dynamic loads or in the regions with seismic activity. Investigation of the exact effect of varying fiber ratio would be useful in optimization of the material to be used in a real life application.

Table 4.1: PC and CS-FRCs Dynamic Properties

Concrete specimens	**Studied Parameters**						
	RFL	**RFT**	**RFR**	ζ	**Ed**	**Rd**	**Poisson Ratio**
	(Hz)	(Hz)	(Hz)	(%)	(GPa)	(GPa)	(-)
Cylinders							
PC	3303 ± 64	3393 ± 73	3384 ± 37	1.711 ± 0.110	4.08 ± 0.139	4.28 ± 0.074	0.53 ± 0.009
C-FRC	3866 ± 55	3596 ± 48	3462 ± 45	1.315 ± 0.026	5.05 ± 0.138	4.05 ± 0.101	0.40 ± 0.003
CS-FRC1	4205 ± 42	3619 ± 68	3913 ± 37	2.114 ± 0.251	6.06 ± 0.170	5.25 ± 0.136	0.44 ± 0.003
CS-FRC2	4183 ± 47	3486 ± 24	3528 ± 24	1.498 ± 0.231	6.00 ± 0.094	4.27 ± 0.009	0.31 ± 0.009
CS-FRC3	4205 ± 33	3518 ± 55	4284 ± 23	1.692 ± 0.131	5.96 ± 0.094	6.18 ± 0.064	0.46 ± 0.014
CS-FRC4	4460 ± 23	3889 ± 78	4397 ± 63	4.507 ± 0.925	6.88 ± 0.186	6.69 ± 0.300	0.47 ± 0.008
S-FRC	4304 ± 65	3316 ± 75	4274 ± 42	2.118 ± 0.925	6.32 ± 0.161	6.22 ± 0.084	0.42 ± 0.007
Beamlets							
PC	3108 ± 88	3087 ± 24	3264 ± 23	1.258 ± 0.117	18.89 ± 1.047	24.62 ± 0.98	0.624 ± 0.028
C-FRC	3218 ± 25	3421 ± 46	3330 ± 89	1.811 ± 0.216	18.79 ± 0.128	23.79 ± 1.04	0.59 ± 0.028
CS-FRC1	3468 ± 38	3604 ± 83	3535 ± 40	2.037 ± 0.624	22.14 ± 0.943	26.88 ± 1.95	0.64 ± 0.024
CS-FRC2	3352 ± 68	3374 ± 46	3434 ± 64	1.975 ± 0.092	20.55 ± 1.079	25.49 ± 2.08	0.58 ± 0.003
CS-FRC3	3741 ± 50	3632 ± 42	3570 ± 53	2.463 ± 0.253	25.43 ± 0.408	27.40 ± 1.09	0.56 ± 0.028
CS-FRC4	3959 ± 37	3938 ± 47	3904 ± 10	3.525 ± 1.144	29.08 ± 0.416	33.44 ± 0.29	0.59 ± 0.011
S-FRC	3652 ± 30	3528 ± 55	3394 ± 26	2.574 ± 0.227	24.25 ± 0.092	24.76 ± 0.15	0.52 ± 0.003

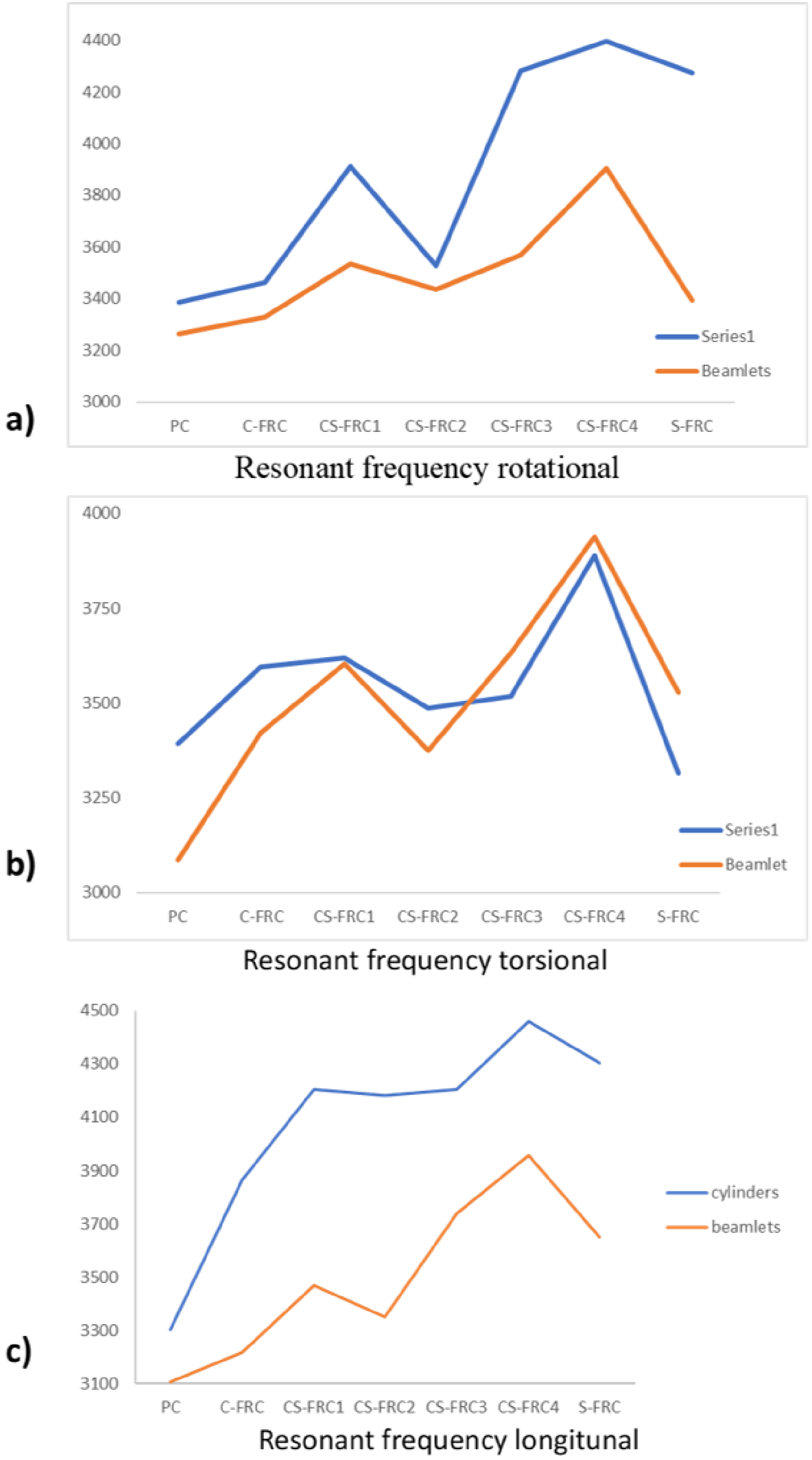

FIGURE 4.1: a),b),c),Damping Properties of PC and CS-FRCs

This work has determined the dynamic behaviour of different mixes of the fiber reinforced concrete (FRC) such as C-FRC (Coconut Fiber Reinforced Concrete), CS-FRC (Coconut and Sisal Fiber Reinforced Concrete) and S-FRC (Sisal Fiber Reinforced Concrete), in terms of damping ratio, which is an indicator of the ability of concrete mixes to consume energy under dynamic loading. Testing was done on beamlet and cylindrical specimen with certain differences in the length of the coconut fibers and proportion of sisal fibers. The findings revealed that the damping ratios of the concrete mixes with fibers were much improved compared to the plain concrete mixes that implies that the addition of these fibers has been effective in improving the dynamic properties of concrete. In case of the beamlet specimens, representing thin beam-like elements of concrete, damping ratios of C-FRC, CS-FRC1, CS-FRC2, CS-FRC3, CS-FRC4 and S-FRC increased significantly by 45, 63, 58, 97, 181 and 103 percentages respectively compared to plain concrete. CS-FRC4 showed the maximum rise in the damping ratio among all the mixes, and the improvement experienced was an amazing 181%. The large increment in damping ratio of CS-FRC4 shows that it has a better dynamic behavior implying that the given combination of coconut and sisal fibres is extremely effective to boost the energy dissipating capacity of concrete. The fact that CS -FRC4 has a high damping ratio demonstrates that it can be used in applications involving dynamic loading and vibration control; e.g. structure exposed to seismic forces or vibrations in machines.

When it came to cylindrical specimens, the research showed that the behavior to dynamic loading was enhanced by increasing the sisal fiber content and it was more conspicuous when the length of the coconut fibre was kept to 50 mm. Namely, the dynamic resistance improved more with the addition of sisal fibers up to 1% to the cylinders that contained 1% of coconut fiber content. This trend shows that there can be a balanced blend of coconut and sisal fiber which can effectively enhance dynamic force resistance capability of the concrete. Likewise, cylinders filled with 1% coconut fibers also showed an increase in dynamic resistance as they were filled with more sisal fibers thereby strengthening the argument that a conjugated blend of these two fibers offer superior results. In the case of the beamlet specimens, which had coconut fibers of 50 mm in length, it was realised that the resistance to dynamic loading was considerably more compared to those that had coconut fibers of 1.5 percent. This fact indicates that the coconut fiber length is a very important parameter to indicate the dynamic behavior of the concrete. The addition of dynamic loading resistance by the coconut fibers with length 50 mm in the beamlets shows that at particular length there might be an optimum effect of the coconut fibers on the dynamic loading strength of the concrete. This better performance with shorter fibers indicates, as well, that there may be a maximum fibre length associated with the greatest dynamic properties of the material, and that too much filament content or length would not necessarily provide better performance.

In summary, the findings of this research prescribe the significance of the two - the fiber content and the fiber length in dictating the dynamic features of fiber-concrete reinforced. Out of all the combinations they were tested upon, CS-FRC4 showed the highest improvement upon the damping ratio, which denotes that it has greater dynamic performance. Also, the study established that addition of sisal and coconut fibers in concrete has the potential of enhancing the concrete efficiency in dynamic loading, although this would depend on the actual volume and length of the fibers. Such results can be used to influence the fabrication of fiber-reinforced concrete mixes to suit a project where higher dynamic performance is desired e.g. inducing earthquake-resistant structures, or infrastructure subjected to high vibration, caused by heavy machinery. The test of the optimum fiber content and length might give further ideas on the performance of the material and possibilities of its use in civil engineering.

4.3 Mechanical Properties

4.3.1 Compressive Properties

In the figure 4.2b illustrates the correlation between the stress-strain graphs of PC, C-FRC, CS-FRC1, CS-FRC2, CS-FRC3, CS-FRC4, and S-FRC. In the figure 4.2b illustrates that the PC exhibits the highest compressive strength (C-S) due to the highest cement, relative to all variants of CS-FRCs which is less than Pcs samples.

The compressive strengths of C-FRC, CS-FRC1, CS-FRC2, CS-FRC3, CS-FRC4, and S-FRC are diminished by 63%, 62%, 65%, 60%, 57%, and 60%, respectively. CS-FRC3 was found to have the highest compressive strength compared to all other CS-FRC varieties.

In CS-FRC2, the compressive strength values increased by 4% when the sisal fiber content increased to 1.75%. In comparison, the sisal fiber content of CS-FRC1 was 0.5%. When the coconut fiber content decreased to a maximum of 0.25%, the compressive strength values of CS-FRC4 decreased by 5% compared to CS-FRC1.

When the sisal fiber content decreased to 1.75%, the compressive strength values increased by 7% compared to CS-FRC4, which had a sisal fiber length of 1.75%. This was also found in S-FRC with a similar pattern.

If we compare the C-S values of CS-FRC3, CS-FRC4, and CS-FRC with those of CS-FRC1, CS-FRC2, and C-FRC, we see that there are large differences. Since the straw fibers of CS-FRC1, CS-FRC2, and CS-FRC3 are more tha 1% content, this could be due to the presence of more more coconut fiber (1% and more), which act as stronger crack arresters. According to Table 4.1, the modulus of elasticity (MOE) of PC and all CS-FRCs are shown separately.

It can be seen that the MOE of each CS-FRC is lower than that of PC. In addition, the MOE of CS-FRC4 and S-FRC is significantly lower compared to the other CS-FRCs. This could be because the sisal fiber contents is less than coconut fiber content, which is more than the ideal sisal fiber content. Both PC and CS-FRC are prone to compaction problems, as shown in Figure 4.2a. Table 4.1 lists the values of pre-cracking compression energy absorption (EC1), post-cracking compression energy absorption (EC2), total compression energy absorption (ECT) and compression toughness index (ITC). All these compression energy absorption values were calculated using the methods described in references [74] and [75].

The reduction of CE values is about 43%, 60%, 66%, 13%, 31% and 42% for different combination of the sample which is C-FRC,CS-FRC1,CS-FRC2,CS-FRC3,CS-FRC4, and S-FRC as above sequence as compared to PC. With compared to pc the CE2 values are increased by 89%,91%,116%,104%,116% and about 103%.

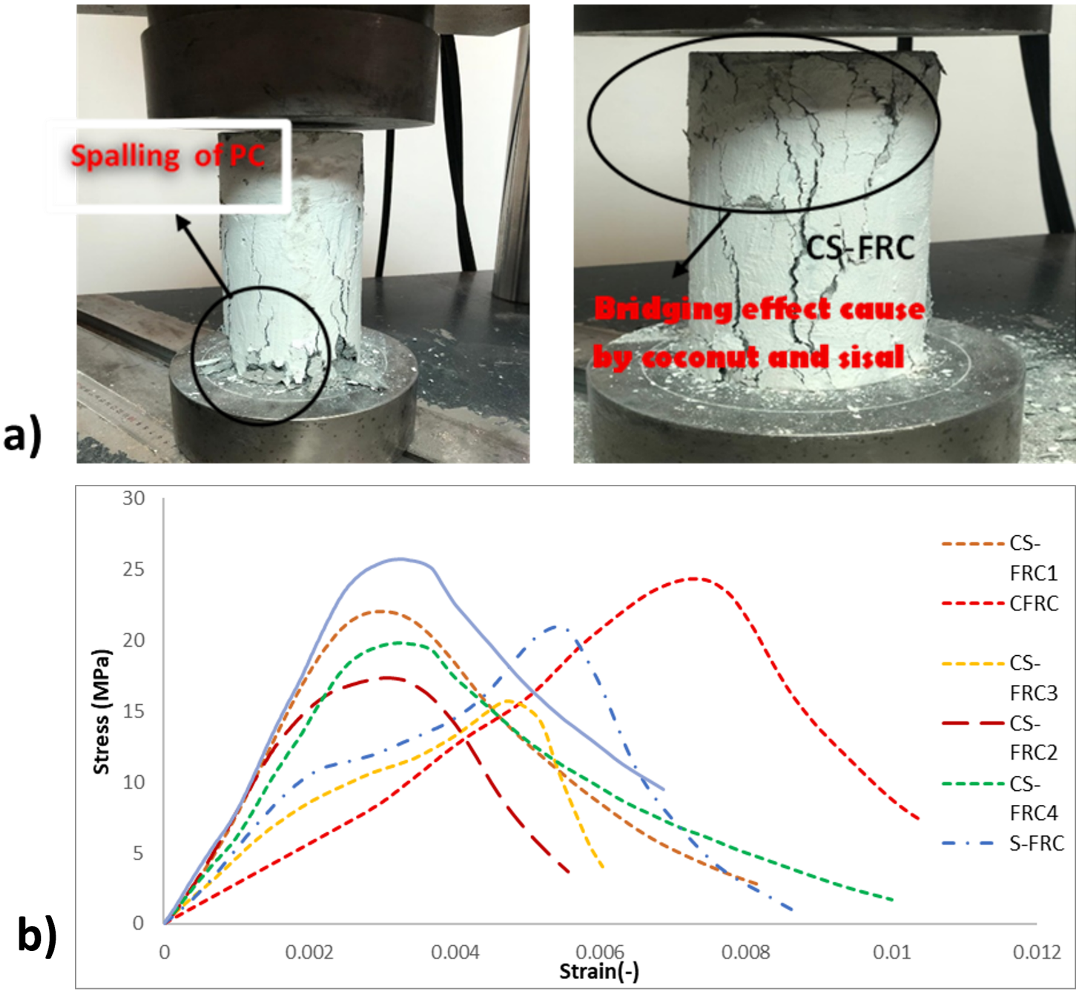

FIGURE 4.2: Compressive Behavior a) Typical Compression Failures of PC and CS-FRCs, b) Compression Response of PC and CS-FRCs

By comparing the stress strain of different fiber-reinforced concrete (FRC) mixtures, coconut and sisal mixing with concrete to plain concrete (Pc), this graph shows how is different when compared to plain concrete. The strain value is shown on the x-axis, whereas the stress value is given on the y-axis in the megapascals (MPa) units. On the graph, it is evident that coconut and sisal fiber combinations that have different stress responses, as compared to the ordinary concrete. Owing to brittle quality, plain concrete, as represented by the yellow line, experiences a rapid decrease in stress once it has attained the high, which is further tracked by the rapid rise in stress until it hits the peak. The various colored lines on the other hand represent the fiber-reinforced concretes which have varying stress-strain curves. Some of the combinations, including CS-FRC1 and CS-FRC2, show slower growth of stress and the reduction after the ultimate stress is not as sharp and it shows that these combinations are characterized with better ductility and energy absorption capacity.

As shown in the graph, some combinations of the fibers, e.g. CS-FRC1 (orange dashed line) and CS-FRC2 (dark red line), stress abilities surpass plain concrete. This goes ahead to show that, the reinforcement of these fibers into the material increase its ability to carry load before the material fails. In addition, CS-FRC3 and CS-FRC4 (demonstrated by the lines with color green and blue correspondently) produce diverse stress level and distinguish themselves in behavior related to strain, which makes it evident that these two samples have different performance altogether with respect to the fiber content and the type of fiber which was used. By reference to what is stated in this graph, one can form an idea of the prospective benefits of incorporating natural fibers, including coconut and sisal, into concrete so that it could get better mechanical properties. Such properties are tensile strength, energy absorption, and toughness.

Table 4.2: Compressive strength properties of PC and CS-FRCs

Specimen Parameter	**CS (MPa)**	ε_o **(-)**	**CPE (MJ/m^3)**	**CCE (MJ/m^3)**	**CTE (MJ/m^3)**	**CTI (-)**
PC	26±2.31	0.004±0.001	0.084±0.004	0.06±0.002	0.14±0.09	1.71±0.73
C-FRC	24±1.61	0.017±0.003	0.049±0.004	0.111±0.002	0.16±0.17	3.26±0.94
CS-FRC1	20±2.34	0.0123±0.002	0.035±0.003	0.112±0.002	0.14±0.21	4.2±1.03
CS-FRC2	17.2±2.11	0.012±0.001	0.028±0.006	0.127±0.002	0.15±0.18	5.54±0.89
CS-FRC3	15.6±3.35	0.010±0.003	0.072±0.004	0.090±0.002	0.16±0.16	2.25±1.25
CS-FRC4	19.5±1.2	0.008±0.001	0.059±0.002	0.128±0.002	0.187±0.19	3.17±0.65
S-FRC	18.9±2.08	0.0057±0.56	0.050±0.005	0.119±0.002	0.169±0.23	3.38±0.87

All CS-FRCs had higher CTI values than PC. The presence of mixed agricultural residues such as coconut and sisal fibers could be the direct cause of the increased CTI values. CS-FRC specimens formed diagonal cracks and shear cracks when subjected to compressive loads, while PC specimens fragmented. The highest CTI value was obtained for CS-FRC containing 1% sisal fibers. Therefore, 1% sisal fibers have a beneficial effect on CTI.

4.3.2 Splitting Tensile Properties

Figure 4.3b shows the load-strain curves for the following materials: PC, C-FRC, CS-FRC1, CS-FRC2, CS-FRC3, CS-FRC4, and S-FRC. Based on the data shown in Figure 4.3b, CS-FRC3 has the highest load capacity. The load capacity of CS-FRCs was shown to be the result of the bridging effect of the coconut and sisal fibers. Table 4.1 contains a section on split tensile properties, which includes parameters such as split tensile strength (S-T-S), pre-crack absorbed energy in split tensile (SE-1), post-crack absorbed energy in split tensile (SE-2), total absorbed energy in split tensile (S-T-E), and split tensile toughness index (S-T-I). These parameters are listed in this section.

Compared to PC, S-T-S was improved by 3%, 45%, 25%, 47%, 116% and 75%, respectively. CS-FRC4 showed the highest S-T-S value. This can be attributed to the optimum fiber length combination of sisal and coconut. The overall improvement in S-T-S in all CS-FRCs can be attributed to the bridging effect provided by the fibers. SE-1 of CS-FRC4 was improved by 70% compared to PC. For PC, there was no post-cracking tensile energy as the material broke into two parts at the peak load. On the other hand, CSWS-FRC showed the ability to absorb post-cracking tensile energy. The presence of agricultural residues coconut and sisal in concrete helped in absorbing this energy. CS-FRC may show a higher ability to withstand tensile loads for a long time compared to PC. This is attributed to the fibers embedded in the concrete, which acted as a crack protector and prevented crack propagation. CS-FRC4 concrete showed higher pre and post-fracture energy as compared to conventional concrete. Due to the presence of hybrid fibers of optimum content in the concrete i.e. 2% of sisal fibers and coconut fibers combine, a crack limiter was formed which successfully stopped the propagation of cracks. Conventional concrete absorbed more energy than before. There was significant difference between the hardness index of conventional concrete and that of conventional concrete (C-FRC, CS-FRC1, CS-FRC2, CS-FRC2, CS-FRC4 and CS-FRC). Figure 4.3 illustrates the single crack tensile failure found in conventional concrete and conventional concrete.

Concrete cylinder specimen after evaluation of tensile strength through cracking test. The characteristic vertical crack is caused by tensile stress applied along the vertical axis. The natural fibers within the crack effectively connect the failure planes, improve tensile strength and ductility, and prevent sudden brittle failure.

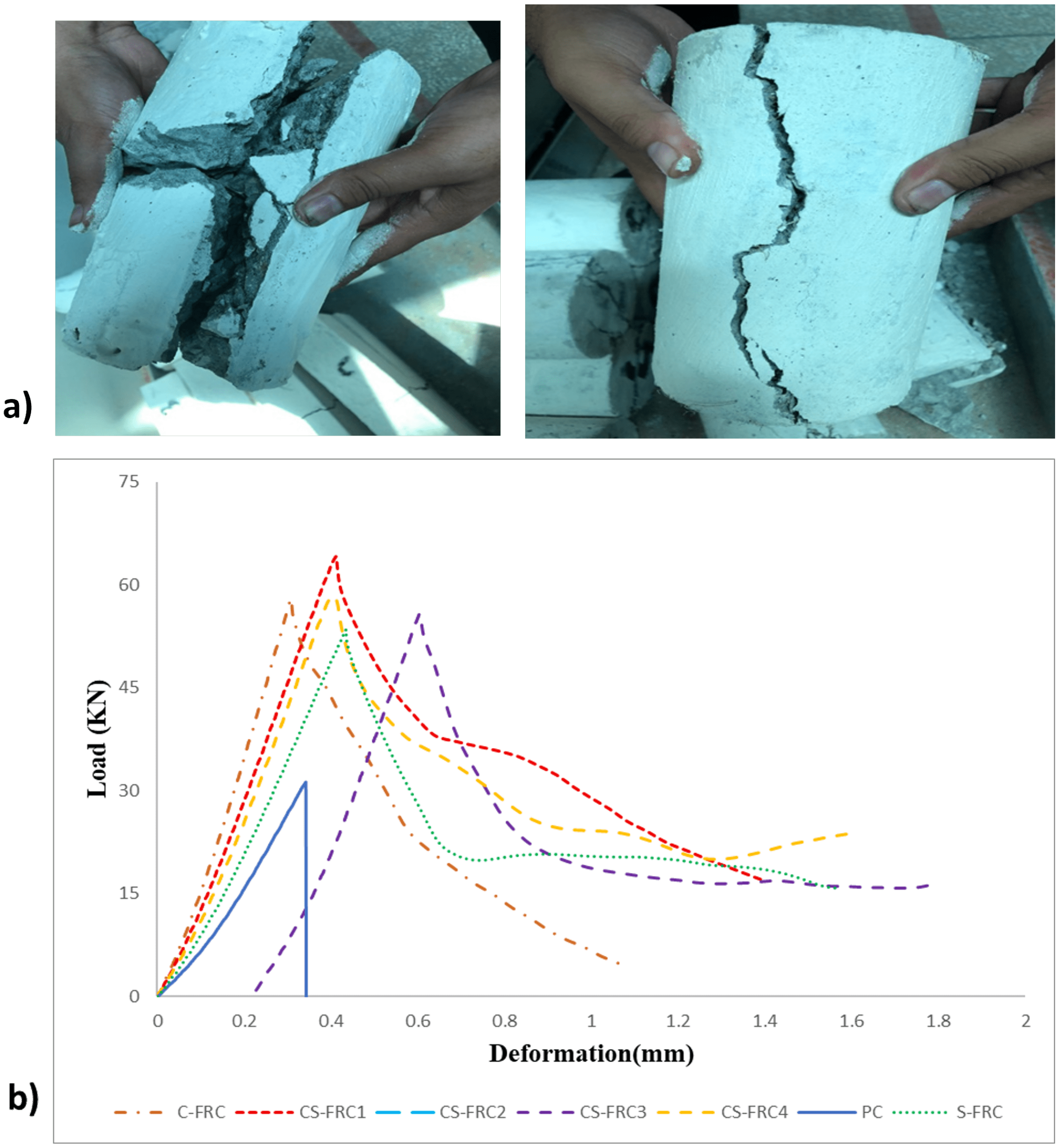

FIGURE 4.3: CSplitting Tensile Behavior a) Typical Splitting Tensile Failures of PC and CS-FRCs, b) Splitting-Tensile Response of PC and CS-FRCs

TABLE 4.3: Splitting tensile strength comparison of PC and CS-FRCs

Specimen	**SS**	**SPE**	**SCE**	**STE**	**STI**
Parameters	(MPa)	(kN·mm)	(kN·mm)	(kN·mm)	(-)
PC	1.18 ± 0.88	47 ± 5.0	–	47 ± 5.0	1.00 ± 0.73
C-FRC	2.27 ± 1.02	58.47 ± 3.0	14 ± 2.0	72.47 ± 2.5	1.23 ± 0.86

Table 4.3 continued from previous page

Specimen **Parameters**	**SS** (MPa)	**SPE** (kN·mm)	**SCE** (kN·mm)	**STE** (kN·mm)	**STI** (-)
CS-FRC1	2.22 ± 0.94	64.3 ± 5.0	12.26 ± 1.7	76.56 ± 4.0	1.19 ± 0.58
CS-FRC2	2 ± 0.73	63.7 ± 6.0	10.19 ± 1.5	73.89 ± 5.5	1.15 ± 0.67
CS-FRC3	2.1 ± 1.02	54.37 ± 4.0	9.64 ± 2.0	83.01 ± 3.0	1.52 ± 0.49
CS-FRC4	1.7 ± 0.4	48.2 ± 3.0	10.35 ± 3.0	58.55 ± 2.5	1.21 ± 0.37
S-FRC	2.3 ± 0.84	53.5 ± 5.0	10.09 ± 3.4	63.59 ± 4.0	1.18 ± 0.69

4.3.3 Flexural Properties

The load-strain curves of PC, C-FRC, CS-FRC1, CS-FRC2, CS-FRC3, CS-FRC4, and S-FRC are shown in Figure 4.4b. According to the ASTM C78 standard, the recommended loading rate for testing is 1.06 MPa/min, but the loading rate used in this study is 1.02 kN/s. Considering that CS-FRC2 can withstand the maximum bending stress, it has the highest load-bearing capacity, as shown in Figure 4.4b. CS-FRC has the highest load-bearing capacity due to the bridging effect played by both coconut fibers and sisal fibers. Flexural strength (FS), bending energy absorption before crack (FE-1), bending energy absorption after crack (FE-2), total bending energy absorption (F-T-E), and flexural toughness index (F-T-I) are all included in the area dedicated to addressing flexural properties in Table 4.1. From the PC perspective, the FS increased by 26%, 49%, 37%, 43%, 109%, and 76%, respectively. The maximum FS value was shown by the CS-FRC unit. This may be caused by the optimum combination of coconut and sisal fiber content. Therefore, the bridging effect of fibers is responsible for the overall increase in FS observed in all the CS-FRCs. The FE-1 of CS-FRC3 increased by more than 32% compared to PC. There is no post-crack flexural energy in PC as it splits into two pieces when subjected to peak load.

In contrast, CS-FRCs have been shown to absorb energy after crack formation. The presence of agricultural waste coconut and sisal in the concrete is the source of energy generation. CS-FRC is expected to have a higher flexural load capacity than PC since the fibers embedded in the concrete act as crack retainers, thus preventing crack propagation. The hardness index of C-FRC, CS-FRC1, CS-FRC2, CS-FRC3, CS-FRC4 and S-FRC is higher than that of PC. CS-FRC2 has the highest toughness index due to its higher pre- and post-crack energies. This can be attributed to the presence of longer coconut fibers, which effectively attenuate crack propagation under bending loads compared to less percentage of coconut fibers. The loading rate was kept constant throughout the test.

The nonlinear behavior of the pre-cracked concrete is attributed to the presence of natural fibers of different lengths. When deflection occurs, the load increases simultaneously. In areas where a strong bridging effect is exhibited and the fibers have strong adhesion to the surrounding matrix, the specimens are able to withstand higher loads, thereby delaying fracture propagation. Figure 4.4a shows typical bending failures of PC and CS-FRC.

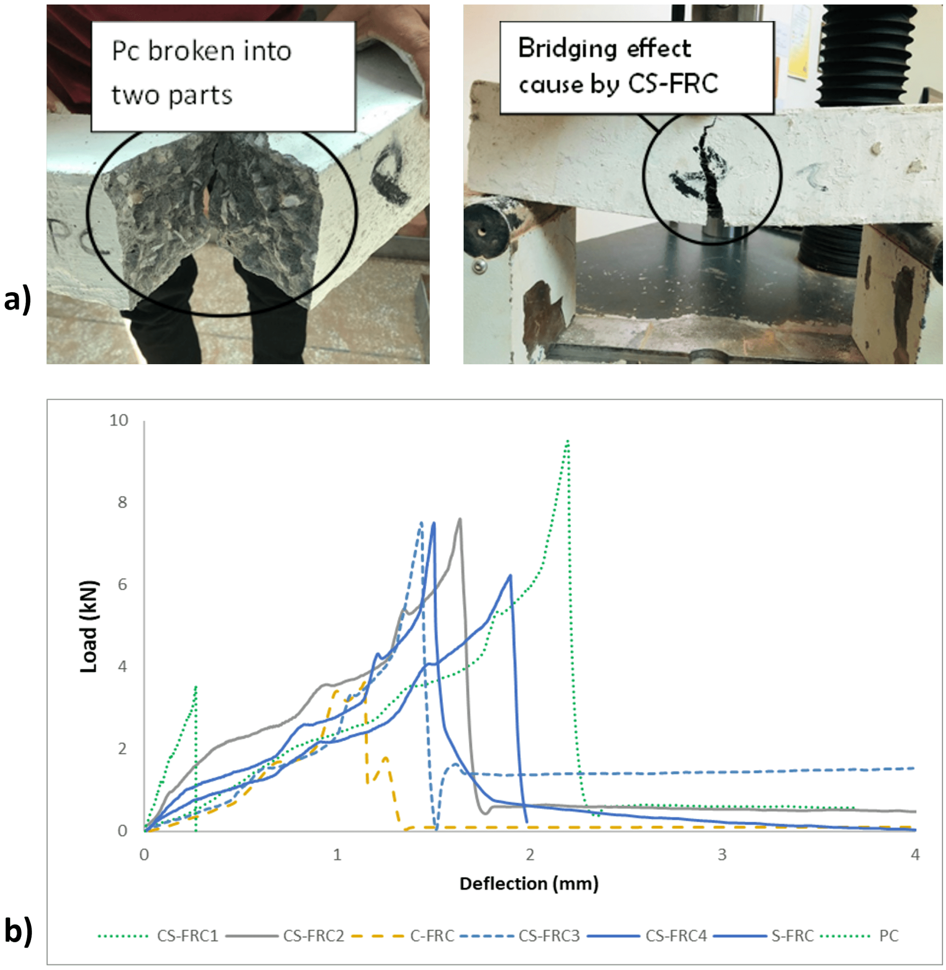

Figure 4.4: Flexural Behaviour a) Typical Flexural Failures of PC and CS-FRCs, b) Flexural Response of PC and CS-FRCs

Since the x-axis - deflection (mm) versus the y-axis - applied load (kN) represents the model output the graph can be used to illustrate how certain categories of fiber-reinforced concrete (FRC) and plain concrete (PC) behave under the effect of changing loads. The different fibers reinforced concrete (FRC) components used, which are called as, CS-FRC1, CS-FRC2, CS-FRC3, and CS-FRC4 (coconut-sisal combination of fibers), S-FRC (sisal fiber), C-FRC (control fiber), and PC (plain concrete), are represented in various lines and colors. The first part of the graph shows that the samples of fiber-reinforced concrete, especially CS-FRC1 to CS-FRC4 exhibit more evident increase in loading capacity than plain concrete. It means that fiber reinforcement in material will enhance its load carrying capabilities, especially the lower levels of deflections.

Table 4.4: Flexural strength values of PC and CS-FRCs

Specimen	**MoR (MPa)**	Δ_o **(mm)**	**FPE (kN·mm)**	**FCE (kN·mm)**	**FTE (kN·mm)**	**FTI (-)**
PC	2.2 ± 0.96	0.75 ± 0.53	3.4 ± 1.55	–	3.4 ± 1.55	1.0 ± 0.05
C-FRC	3.6 ± 1.06	1.4 ± 0.69	1.3 ± 0.72	3.5 ± 1.24	4.8 ± 2.09	3.69 ± 0.37
CS-FRC1	3.4 ± 0.93	1.3 ± 0.9	0.8 ± 0.43	3.6 ± 1.59	4.4 ± 1.84	5.5 ± 0.72
CS-FRC2	3.4 ± 1.25	1.2 ± 0.8	1.5 ± 0.87	2.6 ± 1.04	4.1 ± 2.12	2.7 ± 0.65
CS-FRC3	3.0 ± 1.07	1.0 ± 1.04	0.4 ± 0.72	1.6 ± 0.98	2.0 ± 0.89	5.0 ± 0.62
CS-FRC4	2.2 ± 1.06	0.8 ± 1.02	1.0 ± 0.12	1.7 ± 0.95	2.6 ± 0.65	2.6 ± 0.70
S-FRC	2.2 ± 1.01	0.8 ± 1.01	1.0 ± 0.39	1.7 ± 0.92	2.6 ± 0.66	2.6 ± 0.70

Due to the rising deflection, the load-bearing capacity of each and every sample finally stops growing to the full. The outstanding aspect is the fact that fiber-reinforced samples have better performance as they can sustain higher peak loads compared to ordinary concrete. FRC samples, especially those that have coconut-sisal fibers exhibit greater progressive decline in loads following the peak deflection compared to the plain concrete that shows abrupt decline in loads following the peak deflection. This implies that fiber reinforcement enhances and improves post-peak behavior by increasing ductility as well as decreasing brittle failure in addition to enhancing post-peak behavior. Overall, this graph represents how the use of fiber reinforcing, especially a combination of coconut and sisal, can be used to maximize the load bearing capacity of concrete as it is already undergoing a stress.

4.4 SEM Analysis

The data of scanning electron microscopic (SEM) analysis carried out on the specimen of CSFRC shows the existence of the considerable dimensions of the air-void. In addition, Ettringite structure can be seen under magnification of high power which is the needle-like crystals. Moreover, it can also be clearly seen that not only sisal fiber but also coconut fiber is in the fractured parts of the CSFRC specimens. The circumferential debonding is represented as shown in figure 4.5 around the embedded fibers. The fact that there were two different fibers used yield a measurable amount of air-voids, and the fact that the pull-out force rise directly with the length of the sisal fiber is measured. Figure 4.5b is extracted with the same sample and draws the resistance of the fibers to pull-out loads and the bond of fibers with the concrete matrix adhesively. The non-uniform and roughed up surface texture value of the fibers points out at their ability to withstand debonding and pull out. There is also an indication of matrix bulging around the fibers and also the fibers appear to be in a twisted instead of being in the form of a fragment which could be attributed to the elasticity of the fibers. The fact that the intact fibers left in the concrete following rigorous loading lead to the bridging effect and the resistance of pull-out augers well with the increased mechanical behavior of CSFRC.

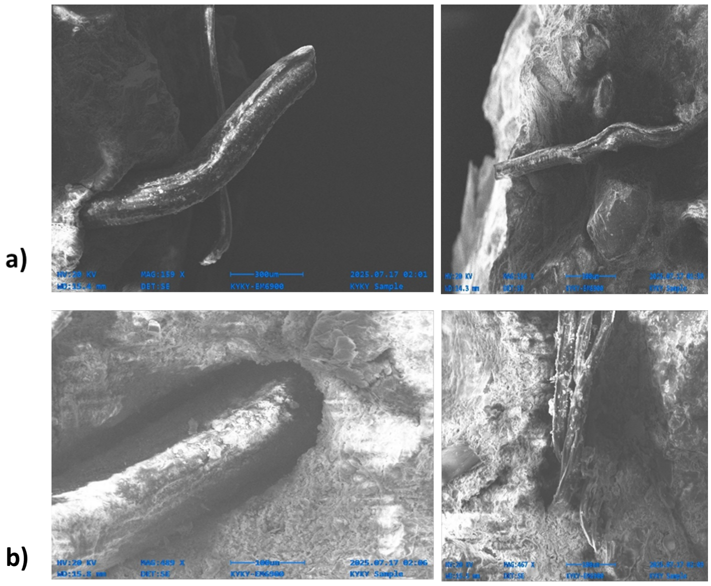

Figure 4.5: Fibers reinforced concrete exploration through SEM; a)Coconut fiber, b) Sisal fiber

4.5 Summary

The chapter at hand queries the workability traits of freshly blended plain concrete (PC) and sisal coconut-fiber strengthened concrete (CS-FRC) and the densities of hardened concrete, dynamic characteristics, and mechanical performance, scaning electron microscopy behaviour that belong to a 1:2:3-concrete mix design and a water-to-cement (W/C) ratio equating to 0.6 in PC and for CS-FRCs w/c was 0.7. The addition of hybrid natural fibers, consisting of different content distributions, was proved to improve only dynamic modulus of stiffness and simultaneously deteriorated the working performance of all CS-FRCs as compared to PC. Due to the addition of sisal and coconut fiber reinforcement to fiber-reinforced concrete (CS-FRC), an improvement in splitting tensile strength, splitting tensile toughness, flexural strength, flexural toughness, and energy-absorbing capacity before cracking as well as after cracking have been generated. Compressive toughness also increases and the compressive strength suffers. The higher the content of coconut and sisal fibers are, the higher their absorption of water. Linear shrinkage has an inverse proportionality to longer fibers. The more fibers also associate with large mass losses. Analysis by scanning electron microscopy as shown in Figure 4.2 of fractured specimens of the mechanical tests seems to suggest good fiber-matrix bonding and the tendencies of braided out and breakage of the fibers in the hybrid agricultural wastes natural fibers.

Chapter 5

Practical Implementation Guidelines

5.1 Background

The given study addresses the impact of sisal and coconut fibers on the properties of concrete reinforced. Verifiable variables indicate that the content of these fibers dictate the mechanical performances. The focus is put on the hybrid sisal-coconut system and the mechanical properties which were determined through stress-strain, load-deflection, and load-deformation graphs. The results of mechanical testing and dynamic testing are utilized to get ideal combinations of coconut and sisal content. The findings are also drawn to the real life construction practices, and the findings are used in recommendations regarding the coconut-sisal Fiber Reinforced Concrete (CS-FRC) system.

5.2 Development of Empirical Relation

The parameters which can be employed to test the performance of a structure are its mechanical property, dynamic property, water absorption property and mass loss property and liner shrinkage property. These properties of concrete are affected by numerous factors such as the properties of this material and the content used. These factors have an effect of the performance of the structure that results into cracking and impairment. Linear shrinkage is one of the most important parameters that lead to the cracking in the concrete pavements. Moreover, splitting tensile property of concrete and the amount of energy which is absorbed by the specimens are associated with the crack which is experienced in concrete. On the scope of energy absorption tensile strength fracture before yielding, empirical relationship is derived between LS and the phenomenon. It can potentially be used as a performance indicator especially where there is an inclusion of natural fibers in concrete.

$$\mathrm{CS} = -3.65 \cdot \mathrm{CSFC} + 15 \tag{5.1}$$

$$\mathrm{SS} = 0.71 \cdot \mathrm{CSFC} + 1.40 \tag{5.2}$$

$$\mathrm{FS} = 0.20 \cdot \mathrm{CSFC} + 0.75 \tag{5.3}$$

SS splitting tensile strength, CSFC = Coconut-sisal fiber content in percentage and FS = flexural strength. The best fit curves are gained in the basis of the experimentally determined values in the given study to gain the empirical equations of CS, SS, and FS. Such an approach to the development of empirical equations has been reported by different authors [76].

After equations have been formulated, a review on the differences between empirical and experimental values has been made. A comparison of the experimental and the empirical values of the compressive strength, the splitting-tensile strength, and the flexure strength are shown in table 5.3. When the empirical values are compared to experimental values, it can be analysed that, all the properties have less than 10 percent deviation in results as compared to the experimental value.

Table 5.1 shows the relationship between experimental values that were determined in the tests and the numerical values calculated in line with the developed empirical equations.

We do not have any value higher or less than 10 percent of the experimental value. The accuracy of formed equations is determined by this phenomenon.

Table 5.1: Comparison of Empirical and Experimental CS, SS, and FS

Specimen	**Experimental**			**Empirical**		
	CS (MPa)	**SS (MPa)**	**FS (MPa)**	**CS (MPa)**	**SS (MPa)**	**FS (MPa)**
PC	22.8	2.2378	1.19	23.0	1.18	2.2
C-FRC	22.3	3.0117	1.47	22.0	2.27	3.6
CS-FRC1	20.2	2.9762	1.43	20.0	2.22	3.4
CS-FRC2	16.9	2.8200	1.43	17.2	2.00	3.4
CS-FRC3	15.0	2.8910	1.35	15.6	2.10	3.0
CS-FRC4	19.0	2.6070	1.19	19.5	1.70	2.2
S-FRC	17.8	3.0330	1.19	18.9	2.30	2.2

The table shows the mechanical characteristics of several concrete sample such as plain concrete (PC) and numerous types of fiber-reinforced concrete (FRC) namely C-FRC and CS-FRC1-CS-FRC4. The document gives the values of compressive strength (CS), splitting tensile strength (SS), flexural strength (FS) of each of the specimens, determined under two different conditions. According to the findings of the research, both synthetic as well as steel fiber reinforcement results in a significant increase in splitting tensile strength and flexural strength compared to plain concrete.

C-FRC and CS-FRC usually have higher tensile and flexural strengths than PC and S-FRC also shows improvements especially in tensile strength. The second data block, which is covering all the specimens, shows marginal decreasing in compressive strength, with uneven effects on splitting tensile and flexural strengths.

These variances are the effects produced on the material under different testing conditions or curing techniques. Reinforcing with the fibers prevents cracking and bending, making such materials stronger than the traditional concrete.

5.3 Optimum Combination of Coconut and Sisal Fibers Content

In the current study, the results obtained with the help of the static (mechanical) and dynamic (impact) testing method are presented as the greatest and the least values of characteristics.

Table 5.2 shows these values and allows determining appropriate composite grades in particular structural applications. According to the principle of compressive performance, CS-FRC1 composite with 1.5% content of coconut fibers and 0.5% content of sisal is most appropriate to act as a compression member, as it had the best compressive strength among the CS-FRCs. On the other hand, CS-FRC1 composite is most preferred where tension or flexural forces prevail, due to the supremacy of the composite in the split tension or flexural strengths.

The replacement of natural derived fibers (NDFs) by so-called hybrid natural derived fibers (hybrid NDFs) improves the tensile strength as well as flexure strength of fiber-reinforced concrete (FRC) specimen, but at the same time reduces the compressive strength. Those results show that there is a significant interaction of the content of fibers and properties of CS-FRC systems.

The average tensile and compressive strain energies of each CS-FRC specimen are found to be much greater than that of plain concrete (PC) and, under compression and tension conditions, CS-FRC2 specimen is most preferential and the grades of CS-FRC1 specimen is the most preferential grade to be used under flexural conditions as it has the highest overall toughness under varying loading conditions.

Augmentation of Compressive toughness index, Split toughness index, and Flexural toughness index values of CS-FRCs compared with PC through the introduction of hybrid fibers with controlled variable content has been indicated in fig:5.1. An almost tenfold increase of the absorbed energy was identified in the case of CS-FRC3 in splitting tensile loads featuring the combination of the highest Compressive toughness index and the lowest Split toughness index.

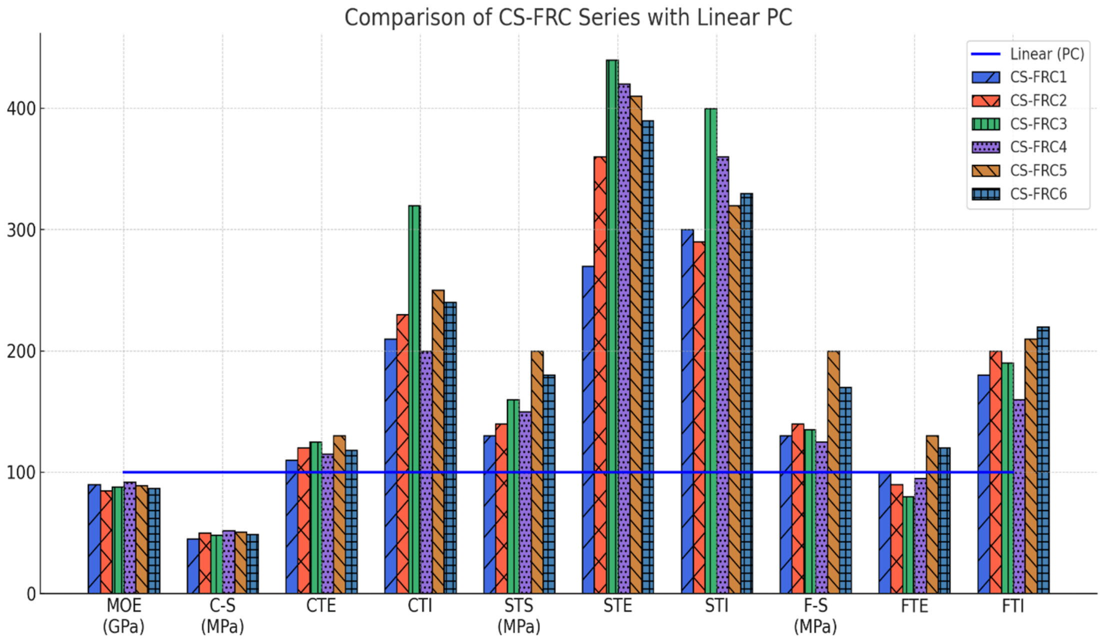

FIGURE 5.1: Effect of Hybrid Fibers of Varying Lengths in CS-FRCs

5.4 Application of this Research in Real Life

The concrete used in civil engineering constructions has to face a combination of the dynamic and mechanical loadings. These mixed loads lead to crack development that continues at the surface of material, as well as, interior microstructure which worsen the durability and long term behavior. Some of the causes of cracking are the high water absorption rates, higher linear shrinkage as well as lower concrete tensile strength after curing the concrete [77].

Formation of cracks at the surface of rigid pavements is often explained by reduced flexural strength, alongside with the factors of a differential settlement. These defects can be mitigated by increasing flexural strength of the concrete. The other important issue here is spalling of concrete surfaces which arises due to high temperatures.

Spalling which can be cited as one of the corrosive factors that impairs the integrity of structures made of concrete material can be inhibited by limiting its mode of actions by improving the tensile strength of concrete. Utilization of hybrid natural fibers in the concrete mixtures proved to be effective in the increase of tensile strength and consequently, the reduction of spalling [78].

Lack of stability against dynamic loads, especially blasting and vehicle impact with concrete bridge abutments is very often the factor that leads to structural breakdown.

These failures could be mitigated by strength of the concrete through increased dynamic modulus of stiffness and requirement of the energy absorption capacity of the concrete [13].

The given research investigates the influence of hybrid agricultural wastes auxiliary natural fibers of varying content on the concrete performance. The CS-FRC5 specimens have high compressive resistance.

The given research investigates the influence of hybrid agricultural wastes auxiliary natural fibers of varying content on the concrete performance. The CS-FRC5 specimens have high compressive resistance.It is such improved features that make it suitable to compression members such as architectural columns including those carrying single-story buildings where incompressibility is not much of a factor and strength capacity does not require a wide cross-section.

In comparative analyses, it is apparent that the performance outcomes of CS-FRC2 are significantly higher in relation to the earlier versions of CS-FRCs. Specifically, the ability of the material to share tensile and flexural loads at very efficient rates makes it quite compatible with usage in slabs and beams amid construction works.

In comparative analyses, it is apparent that the performance outcomes of CS-FRC2 are significantly higher in relation to the earlier versions of CS-FRCs. Specifically, the ability of the material to share tensile and flexural loads at very efficient rates makes it quite compatible with usage in slabs and beams amid construction works. Such a stiff pavement design is influenced by flexural strength and modulus of elasticity of CS-FRC2. Based on this, pavements made using this material are characterized by better modulus of rupture and modulus of elasticity two parameters that are major factors in rigidity and long-lastingness.

Table 5.2: Optimum Combinations of Varying Lengths in CS-FRCs

Concrete types	Compression				Split Tensile			Flexural			Dynamics		
	MOE (Gpa)	C-S (Mpa)	CTE (MJ/m3)	CTI (-)	STS (Mpa)	STE (MJ/m3)	STI (–)	F-S (Mpa)	FTE (MJ/m3)	FTI (–)	ζ %	Ed (GPa)	Rd (Gpa)
PC's Values	35.1±1.5	23.00±2.31	0.174 ±0.003	1.18±0.88	1.2±0.2	14.0±1.1	1	1.2±0.3	3.08 ±0.13	1	1.71 ± 0.2	4.07 ± 1.39	4.27±0.07
CS-FRC with min values	25.9 ± 0.8 S-FRC FRC	15.6 ± 3.3 CS-FRC3	0.156 ± 0.002 CS-FRC2	1.7 ± 0.4 S-FRC	1.3± 0.4 CS-FRC1	37.36± 1.2 CS-FRC2	2.53 ± 0.06 CS-FRC5	1.7± 0.3 CS-FRC3	6.24± 0.22 CS-FRC4	1.26 ± 0.03 CS-FRC4	1.48± 0.24 CS-FRC3	5.05± 0.14 CS-FRC1	4.05± 0.2 CS-FRC1
CS-FRC with max values	29.2 ± 0.8 C-FRC	22 ± 1.61 CS-FRC4	0.186 ± 0.005 CS-FRC4	2.3± 0.84 CS-FRC4	2.7 ± 0.5 CS-FRC4	61.2 ± 3.16 CS-FRC2	3.98 ± 0.02 CS-FRC2	2.6 ± 0.3 S-FRC	4.98 ± 0.12 CS-FRC3	2.59 ± 0.02 CS-FRC3	4.51± 0.93 CS-FRC4	6.88± 0.19 CS-FRC4	6.68± 0.23 CS-FRC4

Table 5.3: Recommendation

Recommended													
1. For specific property													
a. From strength point of view	CS-FRC2				CS-FRC2			CS-FRC2			CS-FRC2		
	27.9 8.9		0.186	3.18	2.7 59.2		2.53	2.6 6.39		1.36	3.53 30		33.5
b. From toughness point of view	CS-FRC1				CS-FRC1			CS-FRC3			(-)		
	25.9	7.3	0.157	5.35	1.6	61.3	3.98	1.8	12.9	2.59			
2. For specific application													
a. CS-FRC1 for column/compression members	25.9	8.3	0.178	3.46	2.2	55	2.65	2.2	6.24	1.26	2.58	24.3	24.8
b. CS-FRC4 for slabs and beams	26.8	8.9	0.187	3.18	2.7	59.2	2.53	2.6	6.39	1.36	3.53	29.2	33.5
c. CS-FRC4 for rigid pavments	26.8	8.9	0.187	3.18	2.7	59.2	2.53	2.6	6.39	1.36	3.53	29.2	33.5
d. CS-FRC4 for the structure prone to lateral load	26.8	8.9	0.187	3.18	2.7	59.2	2.53	2.6	6.39	1.36	3.53	29.2	33.5

CS-FRC1 is much stronger in compressive strength, possesses better energy absorption and much more tough than all other CS-FRCs. Perhaps, this outcome can be attributed to the more coconut fibers (CF) with 1.5% and lesser sisal (SF) fibers with 0.5%. In this regard, CS-FRC1 could be used successfully in compression members (columns). Use of hybrid fiber as building material is a prospective research technique in the context of sustainable development.

5.5 Summary

The current study aims to conduct a practical comparison between the optimal combinations of fiber content of coconut and sisal fiber that will be adopted simultaneously in fibre-reinforced concrete (CS-FRC). It is also established through extensive testing that optimal value of toughness and strength will be realized when the content of the concrete in fibers is set at 1.5% and the sisal fiber content set at 0.5% parameters. The results are subsequently used to isolate that which represents the best ratio of the fiber content i.e.: coconut:sisal = 1.5:0.5, 1.75:0.25, 0.25:1.75, 2:0, 0:2 which in each case will provide different benefits in the way of performance measures. The suggestions especially focus on the usage of CS-FRC in the structural components such as column, beams, and slab. In such applications the better balance between ductility and strength will be attained by a combination of more coconut fibers with less content of sisal fibers or more sisal fibers and less coconut fibers. More precisely, one of the reasons, as to why CS-FRC is highly recommended to use in hard pavements, is that this construction had excellent load-carrying capacity and structural resilience to fatigue effects.

Chapter 6

Conclusion and Recommendations

This research discusses the effectiveness of natural hybrid fibers i.e. Coconut and sisal fibers to the mechanical and dynamic properties of concrete and is aimed at enhancing the concrete to exhibit better strength, durability, and sustainability. The result of the experimentation found these fibers to significantly improve the structural performance of concrete under both the cases of static stresses and dynamic stresses. Studies show that the mixture of coconut and sisal fibers produces maximum tensile strength, flexural strength, and energy absorption capacities compared to plain concrete (PC) and other concrete fiber reinforced types. It has been noted that the hybrid CS-FRC system, especially with 1.5 percent of coconut fibers and 0.5 percent of sisal fibers, is the best option with respect to compressive strength but also presents the best toughness, adaptability, and resistance to cracks. This perfect combination of fibers is used to solve common issues of cracking and spalling in concrete that are crucial in ensuring that there will not be any flaws when it comes to the durability of construction materials. Moreover, the piece of work has successfully come up with empirical links amongst fiber content and critical mechanical characteristics, namely, compressive strength, splitting tensile strength, and flexural strength, which can be used in designing as well as predicting the performance of CS-FRC in more realistic scenarios. The results have major implications on the construction industry where there is an increasing need of low cost and sustainability of material use. The study outlines the reasonable applications of CS-FRC on various structural components, including columns, beams, slabs and pavements.

The high tensile and flexural strength of CS-FRC make it especially suitable in such applications that require additional tensile and flexural strength such as bridge, pavements, and structures that are required to bear loads.

The research highlights the effectiveness of hybrid natural fibers as a practical approach to reinforcing concrete behavior and grain sustainability in constructions.

a) The study has been successful in demonstrating better mechanical and dynamic properties of concrete with addition of hybrid coconut and sisal fibers and thus significant enhances are noticed in tensile strength, flexural strength and energy absorption.

b) The ideal mixture of 1.5% coconut fiber and 0.5% sisal fiber (CS-FRC1) exhibited superior performance in compressive strength, while also enhancing toughness and crack resistance relative to conventional concrete.

c) Empirical relationships obtained from experimental data demonstrate a high level of accuracy, with deviations of less than 10% between practical and theoretical values, so confirming the reliability of the generated equations for forecasting concrete performance.

d) CS-FRC, especially in variants like CS-FRC1 and CS-FRC4, demonstrates significant potential for use in compression members (columns), slabs, beams, and pavements, rendering it appropriate for diverse building requirements.

e) The study emphasizes the capability of hybrid natural fibers, like coconut and sisal, to enhance concrete performance and promote sustainable construction practices by diminishing dependence on non-renewable materials.

6.1 Suggestions and Prospective Research

This research presents various recommendations for the implementation of CS-FRC and offers proposals for future research.

For Targeted Property Enhancements

a) Strength Augmentation:

   CS-FRC2 This fiber combination, characterized by an equitable ratio of coconut and sisal fibers, is advised for applications where compressive strength is critical. It provides a comprehensive improvement to the total strength of concrete, especially advantageous in structural applications subjected to compressive force.

For Particular Applications

a) Compression Elements (Columns):

   CS-FRC1 Structural columns and other compression elements in edifices or bridges would significantly benefit from CS-FRC1 owing to its exceptional compressive strength and energy absorption capabilities. CS-FRC1's enhanced durability and crack resistance render it an optimal selection for essential load-bearing structural elements.

b) Slabs and Beams:

   CS-FRC4 is advised for slabs and beams, especially in rigid pavement systems, owing to its superior flexural strength and toughness. This renders it very appropriate for components exposed to bending stresses, where conventional concrete may succumb to failure under cyclic loading.

c) Stiff Pavements:

   CS-FRC4 has exceptional performance in rigid pavements, attributed to its greater modulus of elasticity and enhanced flexural strength, which augment endurance and resistance to cracking under dynamic loading. CS-FRC4 provides superior long-term performance relative to conventional concrete, particularly on streets and highways exposed to substantial traffic.

d) Structures Vulnerable to Lateral Forces:

CS-FRC4 is an ideal selection for constructions subjected to lateral forces, including bridge abutments and retaining walls. Its substantial energy absorption capacity mitigates structural failure under impact or lateral pressures, hence enhancing the overall safety and durability of these buildings.

6.2 Future Work

a) Long-Term Durability Assessment: This study has elucidated the short-term mechanical performance of CS-FRC; nevertheless, subsequent research should concentrate on the material's long-term durability. Evaluating the performance of CS-FRC under many environmental conditions, such as moisture exposure, temperature variations, and chemical exposure, will yield a more thorough comprehension of its appropriateness for various climates and areas.

b) Extensive Field Evaluations: A rational subsequent action would be to do extensive field tests on buildings constructed from CS-FRC to assess its performance in practical applications. Utilizing this material in large-scale construction projects, including bridge decks, highways, and buildings, would yield significant data regarding its practical performance and guide future design standards.

c) Enhancement of Fiber Composition: Although the present study determined ideal fiber combinations for CS-FRC, subsequent research should investigate the potential for further refinement of fiber content for particular applications. Exploring the utilization of alternative natural fibers or the amalgamation of several fiber types may improve the efficacy of CS-FRC, providing more sustainable and economical solutions for building.

d) Economic Feasibility Analysis: A vital consideration in the adoption of any new material within the building sector is its cost-effectiveness. Subsequent research ought to evaluate the economic viability of employing CS-FRC on a broader scale, taking into account variables such as material expenses, labor, and the comprehensive life-cycle cost of structures constructed with this material. A comprehensive cost-benefit analysis would ascertain the feasibility of CS-FRC for extensive implementation in construction projects.

e) The influence of fiber durability on concrete performance: Given that fibers significantly enhance concrete performance, it is essential to investigate their durability and behavior over time under various loading circumstances. Future research should concentrate on evaluating the deterioration of fibers during the structure's lifespan and its effects on the long-term performance of CS-FRC.

f) Establishment of Standards and rules: As CS-FRC becomes increasingly prevalent in construction, the formulation of defined rules for its implementation across many contexts is essential. Future endeavors may concentrate on formulating building regulations and standards that integrate CS-FRC, offering explicit directives for engineers and construction professionals to utilize this material safely and efficiently in their projects. The study conclusively supports the incorporation of hybrid coconut and sisal fibers in concrete. The material has favorable mechanical properties and presents considerable promise for enhancing the sustainability and durability of concrete buildings. Future study should concentrate on enhancing the material's performance in practical applications, further perfecting its composition, and investigating its long-term sustainability in construction endeavors.

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