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Effect of Pine Needles and Glass Fibers on Concrete Performance

by

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Dedicated to my brother Umair Sajid Khan, a key motivator, who gave me the strength to achieve my goals.

CERTIFICATE OF APPROVAL

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Abstract

Concrete has limitations that make it unsuitable for challenging engineering applications. Incorporating fibers into concrete has come up with improved mechanical properties of concrete. Synthetic fibers have some reported flaws in terms of their high cost and negative impact on the environment. In order to overcome the shortcomings of synthetic fibers, research is being conducted to explore the use of natural fibers as a potential solution for enhancing concrete strength, reducing manufacturing costs, and mitigating environmental impacts. Moreover, the combination of natural and synthetic fibers through hybridization has the potential to enhance the performance of concrete by combining the benefits of both materials. However, additional research is required to fully understand the properties and potential benefits of utilizing multiple fibers in order to create more sustainable and efficient materials. Thus, the aim of this study is to investigate the synergistic impact of natural and synthetic fibers in hybrid fiber reinforced concrete. Initially, the study considers the primary factors affecting the performance of natural fibers (i.e., pine needles), particularly their hydrophilic nature, which is mitigated through alkali treatment. Subsequently, the study investigates the optimal volume of fiber content by varying the proportions of natural fibers, synthetic fibers (i.e., glass fibers), and a combination of short (i.e., 10 mm) and long (i.e., 25 mm) fibers. Pine needle and glass fiber percentages are maintained within the range of 0.25% - 2%. The subsequent analysis focuses on presenting the impact of hybridization on the mechanical and dynamic properties of concrete that incorporates a combination of both pine needle and glass fibers. The optimization is carried out while taking into account the strengths and energy absorption capacities under compressive and flexural loadings. Additionally, the structural response of hybrid fiber reinforced concrete beams subjected to flexural loading is also investigated for reducing the required steel area while enhancing the nominal moment capacity of beams resulting from hybrid fibers addition for the optimal mix design. According to the results, mix design having 1.5% Pine needles and 0.5% Glass fibers is optimized having 150% enhanced energy absorption capacity and 131% more compressive toughness index than PC with minimal decrease in compressive strength. Furthermore, flexural energy is enhanced upto 36% and flexural toughness index has shown 38% increment as compared to PC. Results obtained for reduction of steel against enhanced moment capacity is varying without any predictable trends but there are notions that indicate prominent reduction in steel. Considering the hypothesis made in this study, experimental validation is recommended. This type of hybrid fibers can contribute towards the development of sustainable building material in terms of cost and environment.

Keywords : Natural Fibers, Hybrid Fiber Reinforced Concrete, Sustainability , Moment capacity

Contents

List of Figures

List of Tables

Abbreviations

ACI	American Concrete Institute
As	Area of Steel
CBE	Compressive Energy Before Crack
CC	Conventional Concrete
CPE	Compressive Energy After Crack
CS	Compressive Strength
CT	Total Compressive Energy
CTI	Compressive Toughness Index
FBE	Flexural Energy Before Crack
FRC	Fiber Reinforced Concrete
FPE	Flexural Energy After Crack
FTE	Flexural Total Energy
FTI	Flexural Toughness Index
GF	Glass Fiber
HF	Hybrid Fibers
HFC	Hybrid Fiber Reinforced Concrete
MOR	Modulus of Rupture of plain concrete
$\mathbf{MOR}_{fiber}$	Modulus of Rupture of Fibers
NFC	Natural Fiber Reinforced Concrete
PC	Plain Concrete
PF	Pine fiber
SFC	Synthetic Fiber Reinforced Concrete
PF	Pine fiber
TS	Tensile Strength
TI	Toughness Index

Chapter 1

Introduction

1.1 Background

Concrete is one of the most easily available building material on a global scale in recent years. It is the most favorable construction material due to its numerous advantageous properties including its affordability, availability, ability to harden at room temperature, ability to be shaped to be consumed and recycled. Contrarily, without addition of reinforced steel, concrete has limited capacity to resist crack formation and cracks spread particularly when put under tensile and flexural loading. Concrete is brittle and has number of unfavourable characteristics, such as poor fracture resistance and high density [1]. Two significant parameters used to describe the mechanical characteristics of concrete are its compressive strength and tensile strength. For some specific applications, such as structures near earthquake excitation, airfield runways, pavement slabs and so on, structural design also needs to include tensile strength in addition to compressive strength. Although it has a high compressive strength, it cannot be widely used due to its poor toughness, low tensile strength and susceptibility to cracking. A major cause of deterioration in concrete structures is the rusting or corrosion of the steel reinforcements embedded in the concrete. Reinforced concrete buildings are frequently subjected to tensile loading, that causes plain concrete to crack at loads that are significantly lower than those that would cause traditional steel reinforcement to yield [2]. Once a crack has developed, it can weaken the concrete structure's overall stiffness and strength as well as allow water and aggressive substances like chlorides to penetrate the concrete more quickly and deeply. The accelerated corrosion caused by these factors reduces the lifespan of reinforced concrete structures [3]. Researchers have been pushed to develop a suitable solution because of this demand. The addition of fibers in concrete is the most effective remedial measure to overcome the flaws of concrete. Materials including industrial footings, canal linings, roads, bridge decks, pathways, precast buildings and water storage tanks all benefit from enhanced properties of concrete [4]. Typically, fibres are employed to enhance the mechanical characteristics of concrete and transforms the material's brittle fracturing mechanism into more desirable ductile mechanism and behavior. Concrete can be strengthened and made more ductile by adding fibres. (ACI Committee 544, 2002) [5]. With the addition of dispersed fibers to the concrete mixture, brittle failure of concrete in tension can be prevented or delayed. Conventional concrete (CC) is typically robust in compression but weak in tension. Steel bars are added to compensate the tensile stresses. To overcome the material's drawbacks of brittleness and weak resistance to crack propagation, concrete can be reinforced with short, randomly placed fibers. The construction industry is currently looking for new high strength materials that have benefits such as renew ability, minimal environmental impact and affordability. Therefore, there is an inclination of researchers towards natural fiber reinforced concrete (NFC) materials because natural fibers have more advantages over synthetic fibers such as their lower cost and lower environmental impact. Eco-friendliness of natural fibers which is correlated with lower energy usage in their manufacturing process, is an important consideration for employing them as reinforcement materials. NFCs have few limitations including their hydrophilic nature due to which they have relatively poor mechanical qualities. They have weak matrix-fiber interface adhesion, a high combustibility, and the ability to absorb a lot of moisture, which restricts their application in fiber reinforced concrete [6]. Hybridization approach have received attention recently as a means of resolving this problem that combines two or more fibers into a matrix. This hybrid reinforcement can take many different forms, from weaving fibres to combining short fibres in a matrix that are randomly oriented. The main aim of this study is to increase the overall capacity of concrete by reinforcing more than one fibers [1]. On the other side, the interlacing of fibre bundles may increase the damage tolerance and strength of composites [7]. Additionally, by blending natural and synthetic fibres, environmental impact of waste materials can be balanced while also improving mechanical performance and resistance to moisture absorption [8]. There is often only one type of fibre used in fiber-reinforced concrete that is put into use. Concrete failure is a recognised slow, multi-scale phenomenon. Concrete has small, pre-existing cracks on the scale of microns. These cracks expand as a load is applied, eventually combining to form macrocracks [9]. A macrocrack spreads steadily until it reaches conditions that make it unstable, at which point a rapid fracture occurs. Single fiber reinforcement can only compensate at limited level because of multiscale nature of concrete fracture. Therefore, different types of fibres may be blended for the best outcome. For an optimal response, it is beneficial to combine different types of fibers. For example, one type of fiber can be tougher and stiffer, providing adequate initial crack strength and ultimate strength, while the second type of fiber can be flexible, improving toughness and strain capacity in the post-crack zone. Additionally, a different combination may use one type of fiber that is smaller to bridge microcracks and so restrict their growth, thus increasing the tensile strength of the composite and a second fibre that is larger to stop the spread of macrocracks, significantly increasing the composite's fracture toughness. Several studies have been conducted on glass fibres as an alternative to steel fibres due to the latter's costliness and susceptibility to thermal expansion and corrosion [10]. Due to the limited knowledge regarding glass fibres in concrete, this study will explore the physical characteristics of glass fibres and the potential benefits of using them in concrete mixes [11]. It is hoped that a successful outcome will encourage future researchers to further investigate the use of glass fibres in practical applications. Glass fibers are reported in many researches where it is used as a single fiber while in most of the cases in hybrid fibers but along with synthetic fibers. Research on GF-reinforced concrete suggests that incorporating glass fibres into concrete mixes may improve the concrete's resistance to shrinkage, increase their FS and CS and boost their hardness and other related properties.Khan and Ali [12] investigated the application of glass and nylon fibres in bridges to lessen micro cracking at initial stages. The addition of the fibres reduced CS and energy absorption before cracking compared to the control sample, but it increased toughness and flexural and splitting tensile stress. Glass fibre is used in concrete to stop the spreading of small cracks. Additionally, it makes the concrete more resilient. They are fire and weather resistant. The weight and tensile strength of GF reinforced concrete are superior than those of conventional concrete. This inspired further research to determine whether it could be used as a structural material [12]. Among all the natural fibers, few researches have been done on Pine fibers while it is reported to have comparable properties as compared to other natural fibers. Moreover, MOR and ductility of the considered mix designs are improved with the addition of PF, as the maximum values of MOR, and TI were increased by 46.1% and 129% respectively, in comparison to the control specimen [13].

1.2 Research Motivation and Problem Statement

The building industry is continuously progressing, necessitating concrete with improved mechanical and dynamic properties. Conventional concrete is susceptible to cracking, leading to reinforced steel corrosion, and has inadequate energy absorption, resulting in structure failure. To tackle these concerns, researchers are investigating the integration of hybrid fibers, comprising both natural and synthetic fibers. This thesis aims to address the following problem statement: *"Brittleness, poor crack resistance and low tensile strength are the drawbacks of concrete that restrict its employment in a variety of challenging engineering applications because cracks impair their durability and period of service life. Concrete not only uses a lot of energy but also emits lots of greenhouse gases. Fibers can address these issues but natural fibers and synthetic fibers when used as a single fiber, have negative impact as well. To cater limitations of natural and synthetic fibers, hybrid fibers can be used to enhance mechanical properties while minimizing negative impacts."*

1.2.1 Research Questions

- What would be the combined effect of glass fiber and pine needles on the compressive strength of concrete?
- Can hybrid fiber enhance the toughness of concrete?

- How the varying percentages of natural and synthetic fibers will affect the pre and post cracking behaviour of concrete ?
- Is it possible to reduce the substantial amount of steel by the addition of hybrid fibers ?

1.3 Overall Objective and Specific Aim of Research Work

This research aims to develop a sustainable building material that is eco-friendly, cost-effective, and meets the required properties for construction. Hybrid fibers are being investigated to enhance the mechanical properties of material [14].

The specific aim of this MS thesis is to study the combined effect of pine needles and glass fiber on the performance (mechanical properties, dynamic properties and micro-structure analysis) of concrete and to investigate the structural capacity of hybrid fiber reinforced concrete beams.

1.4 Scope of Work and Study Limitations

The mechanical and dynamic properties of hybrid fibers are investigated by keeping constant percentage of fiber content i.e. 2% by volume of wet concrete with addition of 2% super plasticizer in mix designs having fibers while SP is not added in control batch. Whereas different combinations by varying percentages of natural and synthetic fibers are made to check the behaviour of HFC. Natural fiber treatment is done by 2% NaOH, as it gives maximum performance as evident from literature [15]. Different percentages of Glass fibers and Pine needles i.e., 0.5%,1 %, 1.5%, 2% are used. Ratios of fibers are kept in range of 0.5%-2% for hybridization of synthetic and natural fibers. Total of 36 specimens are cast having six batches of mix designs. Each batch consists of three cylinders and three beams. Micro-structure analysis is also performed including SEM and EDX analysis. Secondly, hybrid fiber reinforced concrete is explored for structural applications by gathering results from previous available literature for area of steel calculations. Accordingly, the optimization for mix design of hybrid fibers i.e., content by volume is done.

This study is limited only to mechanical and dynamic (non-destructive testing only) properties of hybrid fiber reinforced concrete. Glass fibers of length 25mm and Pine needle of length 10mm are kept under consideration during the whole study. Durability of hybrid fiber reinforced concrete is not included in scope.

1.4.1 Rationale Behind Variable

Pine needles and Glass Fibers can be used as reinforcing materials in hybrid fiber reinforced concrete (HFC) because they can improve the strength and overall performance including mechanical properties of the concrete. Pine needles are natural, biodegradable, and environmental friendly material that can be used as a substitute for synthetic fibers in HFC. They are strong, lightweight, and have good tensile strength, making them effective to be used as a reinforcement in concrete [16]. Additionally, pine needles are sustainable resource and their use can help reduce the environmental impact of concrete production. Glass fibers are also commonly used as reinforcing fibers in HFC and they are known for their high strength, low density, and good corrosion resistance. Glass fibers are also very durable and can last for the entire service life of the concrete structure [17]. In comparison of other synthetic fibers including steel and carbon, GF produces less pollution and also cost effective [16], [17].

1.5 Brief Methodology

1.6 Research Significance

Concrete cracking and fracture are gradual, multi-scale process. Significance of this idea lies in the development of more effective material for building and renovating structures as concrete needs to be repaired that is caused due to corrosion

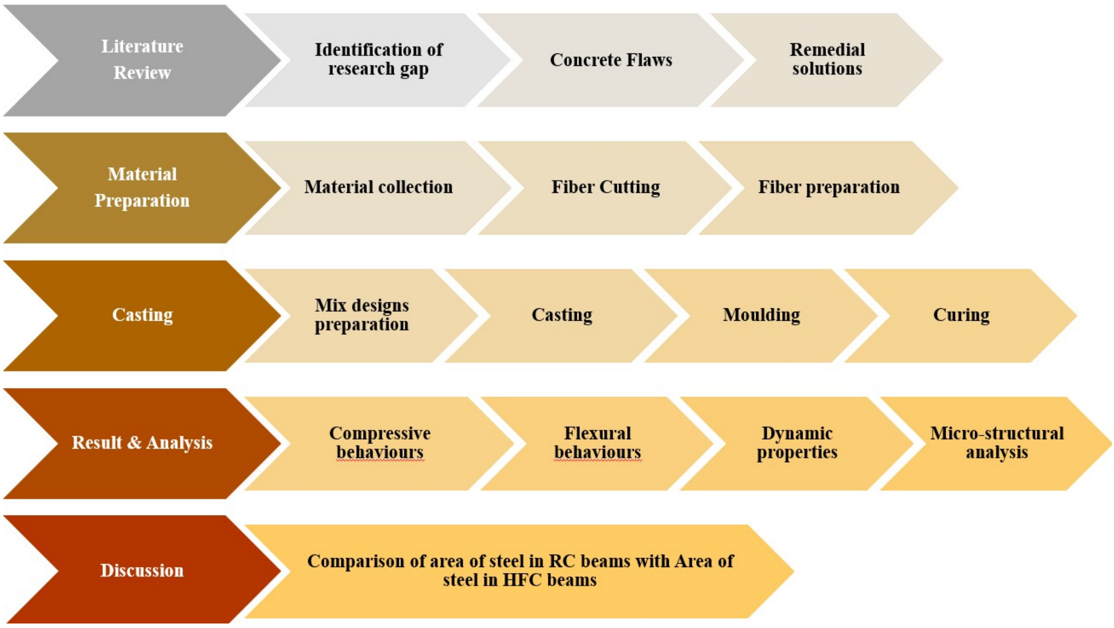

FIGURE 1.1: Brief Methodology

of steel and replaced due to environmental factors, wear and tear, and seismic activity. To optimise its load-bearing capacity, crack growth must be inhibited at both the macro and micro levels. Fibers of different diameters and moduli must be mixed in a way that maximises the effectiveness of the reinforcement, yet there is limited documentation on these composite materials. Steel reinforcement should be minimised to avoid problems with corrosion which can lead to structural damage and early deterioration in reinforced concrete construction. Fibers can increase a beam's flexural strength and reduce the amount of steel needed compared to plain reinforced concrete. The research significance of this thesis is to use pine and glass fibers to improve the mechanical properties of concrete, and to incorporate the synergistic effects of hybrid fibers into concrete to create an alternative material with reduced steel requirement. This would improve infrastructure and increase public safety by reducing the risks posed by damaged structures, eliminating negative environmental effects, and reducing cost.

1.7 Novelty of Research

The use of pine needle and glass fibers as hybrid fibers in fiber reinforced concrete (HFC) is a relatively new area of research and there is still much to learn about the performance and behavior of this type of HFC. There are very limited number of researches that investigates the mechanical properties of Pine needle fibers. As such, the use of pine and glass fibers as hybrid fibers in HFC represents a novel contribution to the field, as it has the potential to improve the structural capacity of the concrete. In this research, the structural capacity of HFC containing pine and glass fibers is investigated with a focus on understanding the consequences of different fiber contents and volume fractions on the mechanical properties of the concrete. Overall, the novelty of this research lies in its focus on the use of pine and glass fibers in HFC. By providing new insights into the performance of hybrid HFC, this research has the potential to contribute significantly to the field.

1.8 Thesis Outline

This thesis is organized into six chapters in order to explore the experimental research on material characterization.

Chapter 1 provides an introduction, research motivation, problem statement, overall objective, specific aim, research methodology and thesis outline.

Chapter 2 offers a literature review on the flaws of concrete at the structural level, governing parameters in performance consideration, and remedial measures of these flaws. In addition, the incorporation of hybrid fibers in discrete form in concrete for enhancing the structural performance is discussed.

Chapter 3 comprises the experimental procedure. Background, materials used, optimization procedure of mix design, the procedure of casting and parameters to be considered for optimized mix design are explained.

Chapter 4. Results and Analysis of mechanical properties and microstructural analysis including SEM and EDX are discussed in this chapter.

Chapter 5. This chapter discusses the optimization of mix design and structural capacity of hybrid fiber reinforced concrete in terms of enhanced moment capacity and reduced area of steel against that moment.

Chapter 6 This chapter includes the conclusion and future recommendations.

Chapter 2

Literature Review

2.1 Background

In engineering, concrete is often used in its natural state in engineering applications due to its cost-effectiveness, malleability, and excellent strength and its better compressive behaviour. However, the drawbacks of conventional concrete, such as its lower tensile strength, prone to cracking, and zero ductility, have been the main factors in the choice of other alternative materials.For many years, researchers have conducted extensive research in an effort to reduce the need for steel reinforcement while also improving the performance of plain concrete (PC). Fiber-reinforced concrete (FC) materials have been shown to have a significant effect on the performance of the composite and the results of this work have been promising. Both macro and micro cracks can be effectively stopped with fiber-reinforced concrete (FC). The majority of FC now in use only uses one kind of fiber. This suggests that a specific fiber has a finite range of strain or fracture opening and can only provide reinforcement at one level. Therefore, multiple fibers can be blended to create HRC. Effects of different HF combinations on the fresh properties and hardened properties of concrete, such as CS, were quantified. However, the primary purpose of this study is to examine the mechanical characteristics of hybrid fiber-reinforced concrete and to detect any synergistic effects between fibers as per previous literature there is some synergistic effect exists between fibers [18]. Due to the potential synergistic benefits of various fiber combinations, hybrid fiber technology can provide mechanical performance that is more evenly balanced than single HFC. The hybrid fibers can improve the performance of the matrix at various levels and scales. Regarding the tensile strength, the HFC has showed a beneficial hybrid effect and a favourable combination performance. This research is designed to examine the hybrid effect of synthetic fiber (glass) and natural fiber (pine needle) in terms of structural capacity of hybrid fibers in terms of steel reduction. Section 1 studies the mechanical properties of the hybrid effect of glass and pine needle in terms of section 2 further investigates the optimised mix design for hybrid fibers in terms of enhanced structural Capacity to reduce steel reinforcement dependency.

2.2 Problem Identification

2.2.1 Flaws in Concrete

2.2.1.1 Brittleness of Concrete

Concrete has some flaws, including brittleness, low post-cracking capacity, and low tensile strength. Cement-based materials have major flaws, including low tensile strength and weak fracture toughness, which limit structural designs and reduce structures' long-term durability. Regarding this, advantages of fiber addition in enhancing the impact resistance, alter brittle behavior of concrete, and energy absorption capacity are well established [19].

2.2.1.2 Internal Micro-Cracking

Concrete is a key component utilized in nearly all sorts of structures around the globe. The internal stress concentration zone is a spectral drawback of concrete constructions, for example, and it occurs in heterogeneous structures built of concrete. As a result, certain internal micro-cracks appear in freshly hardened concrete [2]. By serving as stress-transfer bridges, fibers prevent cracks from forming, and once cracks do form, they are prevented from spreading by providing improved fracture toughness and flexibility at the crack tip. However, the science of fiber reinforcement of concrete is still in its infancy, and theories are continually developing to determine the qualities of the ideal fiber system. Concrete is a material with a very low strain capacity and a quasi-brittle structure. Concrete reinforcement with a combination of short, randomly placed fibers can only address the issue of brittleness and inadequate crack-propagation resistance.

2.2.1.3 Steel Corrosion

One of the main reasons concrete constructions degrade is the corrosion of the steel reinforcements in the concrete [20]. The mechanical loading conditions that plain concrete is frequently subjected to in reinforced concrete constructions cause it to crack at load levels significantly lower than those that would cause traditional steel reinforcement to yield. Once a crack appears in concrete, it weakens the material and increases its susceptibility to water and chemical penetration, which can lead to corrosion and reduced service life of reinforced structures [21]. To mitigate corrosion damage in susceptible environments, protective measures should be taken.

2.3 Possible Remedial Solution

2.4 Fiber Reinforced Concrete

Since (FC) was first used in modern architecture more than 60 years ago [22], However, the idea of adding fibers (such straws and horsehair) to brittle materials to strengthen them was discovered more than thousand years ago [23]. The construction industry today uses a variety of fiber reinforced concrete kinds for diverse applications [24]. Reducing the brittleness of concrete is one goal of utilising fibers. Fibers have the ability to delay the onset of cracking, altering the brittle behaviour and offer strength and toughness [22]. The material (steel, mineral, or synthetic fibers), shape, aspect ratio (fiber length divided by fiber diameter), and mechanical qualities can all be used to describe the fiber reinforcement [12]. There are many distinct geometrical shapes and lengths, ranging from varied diameters of straight fibers to diverse deformed fibers like hooked-end, corrugated, and twisted fibers. The volume fraction or percentage (vol%) is the standard way to express the fiber content. For the same volume fraction, smaller fiber geometry will produce more fibers than larger geometry. Longer fibers can help improve durability and strength by limiting the propagation of macroscopic cracks, while smaller fibers can be more densely arranged in the cement matrix, aiding in controlling the formation of microcracks [16]. Generally, HFC uses a fiber volume fraction ranging from 0.25 to 2 vol%. Over the last decade, the use of hybrid fiber-reinforced concrete (HFC) for rehabilitation and retrofitting has become increasingly popular [25].As implied by the name, HFC comprises fibers that are spread randomly throughout the concrete, enhances the material's tensile characteristics, aids in crack resistance, and increases its ductility [26].Concrete performance has been significantly improved with the incorporation of various types of fibers including both natural and artificial fibers [27].

2.4.1 Synthetic Fibers

2.4.1.1 Behavior of Synthetic Fiber Reinforced Concrete

In last few decades, there has been an inclination of researchers to work out the potential of utilizing fibers in place of CC to reinforced concrete structures [28]. Concrete is commonly robust in compression, but its tensile capacity is relatively low [29]. To compensate this, steel reinforcements are usually used in CC, which is also referred to as Reinforced Concrete. Fibers have been incorporated into concrete to improve its flexural strength, resulting in Fiber-Reinforced Concrete (FRC) [30]. Hydraulic cement concrete reinforced with fibers is known as High-Performance Fiber-Reinforced Concrete [31]. Fiber reinforcement with glass fibers is particularly advantageous due to their low specific weight, water absorption, and high elastic modulus, tensile strength, and weight [31]. The use of fibers for reinforcement not only reduce the overall construction costs by replacing traditional and energy-intensive techniques such as steel reinforcing bars [32]. This leads to decreased labor costs, lower maintenance costs, shortened construction time, and a lower cost of construction. Additionally, due to the much lower volume of fibers

Table 2.1: Mechanical Properties of Synthetic Fibers

Reference	**Fibre**	**Fibre Reinforced Concrete Properties**	**Obtained Values**
Ghani [34]	Polypropylene	Shrinkage Crack Resistance	-
Gupta[35]	Polyester	Tensile Strain	48-60 MPa
	Polypropylene	Compressive Strength	4.4-5.0 MPa
Blunt et al.[36]	Polymer	Flexural Strength	0.15-0.21%
		Abrasion Loss	43-54.9 MPa
		Compressive Strength Frost Resistance	12.8-28% Strength Loss (300 cycles)
		Compressive Strength	33.3-39 MPa
		Flexural Strength	18.9-20.2 MPa
Kumar et al. [30]	Polypropylene	Compressive Strength	56.3-59 MPa
		Split-tensile Strength	4.2-5.1 MPa
		Flexural Strength	8.9 MPa
Yang et al. [16]	Amorphous Metallic	Compressive Strength	23.7 MPa
		Flexural Strength	4.2 MPa

required compared to traditional reinforcement, there is also a reduction in energy consumption [33].

2.4.1.2 Glass Fiber Reinforced Concrete

In 1931, GF were initially utilized as a reinforcement material in concrete [37]. They are made by combining around 200–240 individual threads together after pulling molten glass through sphere-shaped pores [38]. Glass-producing industries generate huge amounts of glass fiber as waste. Adding fibers to concrete can both improve its strength and provide a way to dispose of industrial waste. Waste generated by the construction and aerospace industries can be eliminated

Table 2.2: Fresh & Mechanical Properties of Glass Fiber Reinforced Concrete

Ref.	**GF**	**Slump(mm)**	**CS (MPa)**		**FS(Mpa)**	
Kizilkanat et al.,[41]	0%	18		63	5	
	0.25%	12		62	6.5	
	0.50%	8		62	6.5	
	0.75%	11		67	6	
	1.00%	8		64	6.3	
Asokan et al.,[42]	-		WC	OC		
	0%	-	61.45	54.8	-	
	5%		70.25	66.17		
	15%		65.21	59.77		
Kumar et al.,[30]			14 days	28 days	14 days	28 days
	0%	-	31.36	39.85	2.94	3.02
	0.5%		26.88	34.07	2.89	3.76
	1.00%		36.88	41.63	5.42	6.63
	1.50%		30.37	36.00	6.35	6.48
	GF SF					
	70% 30%				234.12	217.38
	60% 40%				208.45	205.15

by incorporating these fibers into concrete. Approximately 55,000 tonnes of GF waste is produced in the UK on annual basis, with that figure anticipated to rise [30]. Table 2.2 displays the physical characteristics of glass fibers. Glass is available in variety of colors, physical properites and compositions. Glass fibers are increasingly being used as a reinforcement material in composites due to their excellent strength, thermal properties, endurance, and interfacial adhesion to the matrix [17], [39]. GFC (glass fiber-reinforced concrete) offers less density, better toughness, reduced cost and minimal water absorption, making it a popular choice for numerous applications [40]. GFC is used to manufacture prefabricated façade panels for different structures, museums, and galleries due to its capacity to resist temperature changes, corrosion and solar radiation. Furthermore, it is also lighter in weight and has a better tensile strength than concrete [40]. To further explore its potential as a structural material, Khan and Ali [40] studied the use of glass and nylon fibers in decks. Their research showed that by adding fibers, compressive strength and energy absorption is reduced before cracking compared to the control sample, but increased toughness and flexural strength, which helped in delaying the onset of microcracking. Increasing the concrete's cracking resistance with fiber reinforcement is an effective option to prevent frequent rehabilitation of structure.

2.4.1.3 Typical Role of Glass Fiber on Design Capacity

As per literature, there is a prominent improvement in mechanical properties reported by the addition of glass fibers to the natural fibers. Glass fibers not only improves the mechanical properties but also enhacnes the strucrtural capacity of concrete. The tensile and flexural strength of bamboo fiber improved when up to 20% by mass of glass fiber was added [43], [44]. The best performance was noted with composites that contained 30% curaua and 70% glass fibers when they were combined with polyester resin [45]. Flexural and shear properties of jute fabrics were significantly enhanced by the addition of glass fibers [19]. In a different study, unidirectional glass and flax fiber composites outperformed glass fibers in terms of shear strength, and glass fibers can improve tensile properties [46]. Glass fiber hybridization has been reported to improve the performance on tensile and flexural properties of sisal fiber polypropylene composites with polypropylene grafted with maleic anhydride as a additive [47]. The combination of glass fiber with abaca and jute fiber demonstrated improved flexural and the mechanical properties of composites and are significantly influenced by the orientation of the fibers [48]. The hybrid sisal-jute with glass ply composite can be used in place of glass fiber reinforced polymer composites [49]. Hence, from literature it is clear that glass fibers can be used to enhance the design capacity of cross-sections to some extent. In recent researches they are proven to reduce the slab thickness to approximately 10mm and also reduced the thickness of pavement slab as well.

2.4.2 Natural Fiber Reinforced Concrete

2.4.2.1 Behavior of Natural Fiber Reinforced Concrete

Concrete is the material that is used the most globally in the construction sector. But due the drawbacks of having low tension, poor resistance to crack opening, and low fracture strain capacity restricted its use in some applications. In order to make up for plain concrete's brittleness, fiber-reinforced concrete is sometimes viewed as an option (improved the tensile strength). Fiber has been used to strengthen porous matrices. Numerous investigations found that adding fibers to concrete significantly improves the concrete's characteristics. The American Concrete Institute (ACI) [50] claims that long fibers are less effective than thin fibers at reducing the breadth of plastic shrinkage fractures.Natural fiber reinforced cement composites have been found to be an intriguing choice for economical construction in developing and under developing countries. Due to their sustainability and biodegradability, natural fibers have emerged as one of the most widely used reinforcing materials. Natural and non-toxic, beneficial to the environment characteristics that are especially useful for producing bio composites [51]. On the other side, natural fibers also assist in lowering CO2 emissions into the environment [52].Globally accessible natural fibers are also more affordable, more rigid than synthetic fibers, more recyclable than synthetic fibers [53]. Bio composites made of natural fibers have mostly replaced synthetic polymers in due to their many advantages, which include their biodegradability, widespread availability, light weight, lesser cost, and ease of fabrication [54]. Researchers have suggested a variety of natural fiber composites for use in various technological applications [55]. NFCs are known for their high specific mechanical qualities, low weight, low cost, renew ability, and biodegradability. Natural fiber reinforced composites are also thought to be environmentally benign and carbon neutral [56]. Numerous non-structural automotive applications, including door panels, oil filter liners,instrument panels, and oil air filters,use natural fiber reinforced composites [57]. The use of NFCs in structural applications, such as exterior underfloor panelling and seatbacks, is now being researched. However, there are drawbacks to natural fiber reinforced composites, including hydrophilic, poor heat stability, low mechanical characteristics, and weak fiber/matrix interfacial interaction. Natural fibers have a high moisture sensitivity, which makes them more likely to absorb moisture from the air, resulting in low fiber/matrix interfacial bonding and low mechanical properties [58]. This may have slowed down the use of natural fibers as reinforcement in composites for both structural and non-structural applications. Natural fibers derived from plants can be added to concrete to boost its tensile, compressive, and toughness properties. Additionally, it affects the resistant properties and cracking behaviour of the concrete. Additionally, it increases strain capacity, impact resistance, and fatigue strength.This can be explained in one statement by the following: Flexural strength of fibers improves because of the bridging effect of fiber. Table 2.3 depicts the properties of natural fiber reinforced concrete.

2.4.2.2 Surface Treatment of Natural Fibers

The results showed that the coconut shell fiber that was treated had a surface that was both cleaner and more textured compared to the untreated coconut shell fiber. The composite samples also saw improvements in their tensile and fatigue parameters of 17.8% and 16.7%, respectively. Coconut fiber was treated chemically and then immersed in boiling water [37]. The tensile strength and fiber-concrete bond of the fiber rose after soaking in boiling water by 34%, 55%, and 184%, respectively, while the BS and TS were decreased by 25% and 23%, respectively, by the chemical pre-treatment. After the NaoH treatment on the mechanical characteristics and structure of fiber was investigated. The tensile strength of the fiber rose by 37% after 2 hours of treatment with a 5% NaOH solution. When coconut shell fiber was chemically modified using a 1% NaOH solution, Li et al [59] observed that it not only increased the composite's short-term flexural strength and toughness, but also increased the index of long-term toughness. Table 2.4 depicts the results after alkali treatment of natural fiber concrete. This research have demonstrated that pretreatment can improve the characteristics of plant fibers and their composites.

2.4.2.3 Pine Fiber Reinforced Concrete

The use of pine needles as a fiber reinforcement in concrete has only been the subject of a small number of research. Pine needle reinforced concrete was the subject of research by Daxiang et al. in cold climates [60]. The mechanical characteristics of standard concrete with pine needle additions were studied by Mashri et al. [61]. The mechanical characteristics of cementitious mortar enhanced with pine needle fiber were studied by Abdin and Khitap [62]. 50 mm long fibers were inserted with 1% by weight had the highest compressive strength values. Long and Wang investigated how different treatments for pine needles affected the mechanical characteristics of concrete [13]. Hence among all natural fibers, PF has comparable properties as compared to other fibers so it can be used.

2.5 Hybrid Fiber Reinforced Concrete

Numerous studies have been conducted in concrete engineering since the early 1960s to develop HFCC technology, and as a result, a wide range of practical applications have been developed. Hybridization incorporates two or more reinforcing materials to utilise the varied properties of those incorporated fibers while preserving their unique qualities in the new develop material. Mechanical strength of NF can be improved by using the blend of two fibers. If synthetic fibers are used in combination of natural fibers, drawbacks of natural fibers can be incorporated.

Table 2.3: Properties of Natural Fiber Reinforced Concrete

Natural Fibers	**References**	**Properties**	**Values (MPa)**
Jute	Kundu et.al[63]	a.Compressive strength	27.5
		b.Flexural strength	4.9
		a.Flexural strength	4.3
Hemp	Polytanovic[64]	a.Compressive strength	23.9
		b.Flexural strength	5.7
Wheat Straw	Mansur et.al[65]	a.Compressive strength	31-32.1
		a.Compressive strength	31.7
		c.Fracture energy	122.5
Sisal	Ramakrishna[58]	a.Compressive strength	21-26
		b.Flexural strength	5.8
Coir	Gowripal et.al[26]	a.Compressive strength	2.95
		b.Flexural strength	1.07

The use of hybridization fibers (HF) resulted in improved mechanical properties and a decrease in durability parameters. It shows that concrete's hybridization. The use of hybridization fibers (HF) resulted in improved mechanical properties and a decrease in durability parameters. It shows that concrete's hybridization fiber (HF) is useful for structural applications. Numerous studies in hybrid fiber reinforced concrete (HFC) claim that adding fibers significantly improves HFC's performance, particularly in terms of tensile properties, crack resistance, ductility, and toughness [66]. Consequently, a variety of fiber types are frequently used in engineering. The essential fiber properties, such as fiber type, fiber elastic modulus, volume fraction primarily determine how well HFC performs.

Table 2.4: Alkali Treatment of Natural Fiber Concrete

Hybrid composite	**Chemical Pretreatment**	**Effects of Pre-treatment**
Glass / Sisal[67]	5% NaOH Sol.	FS increased from 26.4 to 35.3 MPa on alkali treatment.
Kenaf / Glass[34]	6% NaOH solution	Glass and Kenf yielded maximum properties of TS, and IS of 39.3 MPa, and 140.3 J/m, respectively
Glass / Kenaf[68]	Silane coupling for glass fibers and 6% alkali for kenaf fibers	Chemical pretreatment improved the IS,FS, and FM by 40%, 13%, and 15%, respectively
Glass / kenaf[69]	6% NaOH solution	NaOH treatment increased the IS by 127%. Treatment of kenaf fiber causes reduction in FM of composite samples.
Kenaf / Glass[70]	2, 6, and 10% NaOH solution	Alkali treatment influences physical properties.
Carbon / Jute[71]	5% NaOH for 3 h	Alkali treated samples showed higher FS of 380 compared to 200 MPa.

Many results have shown the positive hybrid effect between two different fibers greatly enhanced the mechanical characteristics and energy absorption capacity and rupture modulus while only slight improve the compressive strength. According to Yap et al.,[72], combining steel and polypropylene fibers with oil palm shell concrete increased its residual strength. In a different study, Banthia et al.,[73] used steel and NF and came to the conclusion that while natural fibers do not naturally impart toughness, they do improve HRC performance when mixed with steel fibers. Steel and polypropylene fibers were combined to create an HRC by

Ganesan et.al [74], which was successful in boosting the binding stress of rebars inside the concrete. Additionally, steel, polypropylene, and polyethylene fibers were hybridised by Kheni et al.,[75] and integrated inside a beam-column joint. In comparison to ordinary concrete, the hybrid concrete performed better in reducing the steel congestion on the joints.Xu et al., [76] examined the effect of mixing steel and PF in concrete, discovering that the addition of the two fibers caused a rise in tensile performance. In another experiment, Zhou et al., [24] investigated the combination of steel and polyvinyl alcohol fibers, uncovering a successful hybridization with considerable engineering potential for the resulting material. The impact of metallic (steel) and nonmetallic (polyester and polypropylene) fibers on HRC was examined by Koniki et al., in 2019. According to Tey, by adding synthetic fibers to the concrete mix design improved the toughness of the HRC. their remarkable chemical stability and hydrophobicity [77]. The effects of basalt fibers, polypropylene fibers, and hybrid fibers with varying volume fractions on the compressive, tensile, and flexural strengths as well as the stress-strain curve of HFC were investigated. It was discovered that hybrid-fiber concrete improved overall performance, while single-fiber concrete only increased the flexural and splitting tensile strengths [38]. Additionally, the performance of several aspects of concrete can be improved by cooperation with diverse fiber qualities. The assessments described above principally concentrate on two types of fiber in concrete without steel fibers, whose qualities are superior to those of concrete made with single-type fibers. It has to be further investigated whether concrete with numerous fibers will produce better hybrid effects. In order to optimize the mechanical properties of the HRC, it is essential to assess the volume fraction of the two different types of fibers it contains.

2.5.1 Mechanism of Hybrid Fibers

Other than altering the fiber's composition and characteristics, other efforts have been done to create fresh and enhanced FC systems. Hybrid fiber reinforcing systems are one such effort. The interaction of several fiber kinds has been researched. Rossi et al.,[23] suggested that fibers are beneficial at two different levels: at the material level, if a high number of small diameter fibers is used, strength and ductility of concrete can be increased; at the structural level, by using a low amount of long fibers, it is possible to increase the bearing capacity and ductility of the structure. The concept of multi-scale theory states that many thin, short metal fibers can help to bridge microcracks during the initial loading stage, and a smaller proportion of longer metal fibers can bridge macrocracks that happen during the propagation stage. Microfibers may prevent the development of macrocracks, According to one of the researcher's theory [78] , improving the strength and toughness of composite materials. However, there aren't many investigations on the toughening mechanisms of HFCs. There is often only one type of fiber used in fiber-reinforced concrete that is put into use. Concrete failure is a recognised slow, multi-scale phenomenon. Concrete has small, pre-existing fissures on the scale of microns. These cracks spread out and finally come together to produce macrocracks when a load is applied. A macrocrack spreads steadily until it reaches conditions that make it unstable, at which point a rapid fracture occurs. A specific fiber can only offer reinforcement at one level and within a certain range of strains due to the progressive and multi-scale nature of concrete fracture. Therefore, multiple fiber kinds may be blended for the best response. One type of fiber in hybrids is more robust, stiffer, and offers sufficient initial fracture strength,while the second type of fiber in hybrids is somewhat flexible and contributes to enhanced toughness and strain capacity in the post-crack zone, the first type of fiber in hybrids is stronger and stiffer and provides acceptable initial crack strength and ultimate strength. Another combination uses a smaller-sized fiber to bridge microcracks and so regulate their growth, increasing the composite's tensile strength, and a larger-sized fiber to stop the spread of macrocracks. As a result, the composite's fracture toughness is significantly increased. Table 2.5 express the enhacned mechanical properties of HFC.

2.5.2 Fiber Length

The fiber's ability to bridge cracks is substantially influenced by its length. Due of the high fiber count in a given volume, short fibers cause the multi-cracking phenomenon of concrete in the elastic area. Long fibers, on the other hand, can bridge the post crack region. Previous researches [23], [79], [80]indicated that the enhancement in the CS and FS of HFC was always strengthened by fibers. Short and long fibers are both incorporated in hybrid fiber combinations, aiming for synergistic effects from all the included fiber types.

Table 2.5: Mechanical Properties of Hybrid Fiber Reinforced Concrete

Reference	**Limitations of Fiber Contribution**	**Major Conclusions**
Khan et al.,[37]	CaC03, SF, BF	Prominent improvement in compressive and flexural strengths observed.
Dawood et al.,[81]	SF (0.25-2%), palm / barchip, (0.25%, 0.5%)	Increased CS strength seen.
Afroughsabet etal.,[82]	SF (0.25-1%), PF (0.15-0.45%)	CS,TS,FS were improved.
Chi et al.,[80]	(0.5-15%) SF, (0.05-0.15%) PF by volume	CS increases. HFC showed better post-crack behaviour
Soe et al.,[83]	SF (0.5-0.58%), PVA (1.5-1.75%) by volume	Mix design having 1.75% PVA fibers and 0.58% steel fibers showed better results.
Bajaj et al.,[84]	SF (0-125-1-125%), PF by volume	HFC With equal quantity of both fibers best results are obtained.
Dawood et al.,[81]	SF (1-2%). Palm fiber (0.25-1%) by volume	HFC of 1.5% SF + 0.5% palm fiber prominently enhance the TI.
Banthia et al.,[85]	SF of different diameters (0.25—0.75%)	Toughness enhanced when large-dia fibers replaced by small-dia fibers.
Sivakumar[86]	(0.12-0.5%) SF, (0.12-0.5%) PF, (0.12—0.5%) GF	FS and toughness enhanced by HF.
Ahmed et al.,[87]	(05-2.5%) SE (1-2.5%) PEE (1-2.0%)	The steel—PVA hybrid expressed higher FS
Chen et al.,[22]	PF (0.03-0.09%), SF (03-1%) by volume	UHPC with 0.03% PF and 0.5% steel fibers showed best results compression and flexural strength.

In contrast to longer fibers, which have higher pullout qualities and can more effectively stop the spread of macrocracks, shorter fibers are better at bridging microcracks because they are small and numerous for the same fiber volume. By doing so, the fiber content may be reduced without affecting performance. Considering the literature, difference of length between two fibers are kept double of the other i.e., 10mm pine needle fiber and 25mm glass fiber.

2.6 Structural Design Capacity of Hybrid Fiber Reinforced Concrete

The requirements for designing reinforced concrete structures and members should be met in terms of the load carrying capability, stiffness, stability, and ductility. By increasing the ductility, the structure's serviceability is also somewhat improved. This is crucial for structural earthquake design. Numerous studies [85] have examined the published research papers on the flexural ductility of steel fiber reinforced concrete beams [88] studied the impact of steel fiber factor on the flexural ductility of beam and came to the conclusion that fiber factor increases lead to higher ductility indices. According to [89], who studied the flexural performance of a hybrid fiber-reinforced concrete beam with a longitudinal reinforcement ratio of 1.08%, the addition of steel fiber increases the beam's ductility. A.N. Dancygier [89] demonstrated that steel fiber increase beam brittleness in comparison to beams with minimum longitudinal reinforcement ratios in his study of the impact of steel fiber on the flexural performance of high strength concrete beams with low longitudinal reinforcement ratios.

2.6.1 Typical Role of Fibers on Design Capacity

Fiber reinforced concrete beams with steel rebars were explored by Beshara et al. [90]. For tensile reinforcement, the steel ratios employed were 0.0017, 0.0064, 0.0075, 0.012, 0.015, and 0.022. Additionally, steel ratios of 0.0045 and 0.0047 were used for compression reinforcement. By volume of wet concrete, the percentages of steel fibers employed were 0.5%, 1%, and 2%. Flexural strength significantly increased as a result of the investigation. This study suggested that the tensile strength of the fiber should also be taken into account when adjusting the Whitney stress distribution equation to calculate the effective height of the equivalent stress in the tensile zone as described by Nilson et al [91].

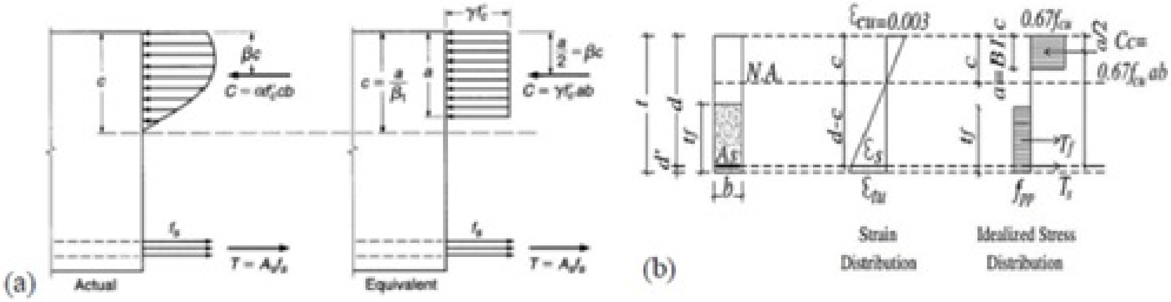

FIGURE 2.1: (a): Witney Stress Block
(b): Modified Block with Tensile Strength of Fibers

Nilsson's equation is as follows:

$$M = Ts(d - \frac{a}{2})Nm \tag{2.1}$$

Where T s =tensile strength=As × fy in 'N' and

$$a = \frac{A_s F_y}{0.85 f'_c b d^2} m \tag{2.2}$$

Whereas the modified equation by Beshara et al. is as follows:

$$M_{fiber} = T_s \left[d - \frac{a}{s}\right] + T_{fiber} \left\{\left[t - \frac{t_f}{2}\right] - \frac{a}{2}\right\} \tag{2.3}$$

Here, The equation is similar to the Whitney stress distribution equation, but with an additional term to factor in the tensile strength of the fibers within the effective height of equivalent stress in the tensile region. This allows for the calculation of the tensile strength of the fibers in the equation.

$$T_f l = 1.64 V_f I_f \varphi_f b t_f \tag{2.4}$$

Where: V_f = Volume of fibers in concrete

l_f = Fibers length and

φ_f = Fibers diameter.

The basic concept of modifying the equation developed by Nilson et al. for fiber reinforced concrete to effectively utilize tension region of concrete with the help of dispersed fibers by crack arresting mechanism is also illustrated in 2.1.

2.7 Summary

Much research has been conducted to identify the weaknesses of concrete related to its brittleness. Parameters have been studied to pinpoint these weaknesses and what steps can be taken to remedy them. A common issue with cement concrete is its tendency to crack early on, and steel reinforcement is normally used to counteract this. This, however, makes rigid pavement construction expensive, preventing its extensive use in developing countries. A major concern is the corrosion of steel and the formation of micro cracks. Adding hybrid fibers to the cement concrete can reduce cracking and increase structural strength. Research is now taking a turn towards sustainability and ways to reduce waste, with attention being given to the use of natural fibers such as plant and agricultural waste. Previous studies have established that the load-bearing capacities and post-cracking performance of natural fiber reinforced concrete is comparable to that of artificial fiber reinforced concrete. Little research has been done on pine needle when used in combination with glass fiber in concrete, and further exploration is suggested for possible civil engineering applications. Despite its organic, bio-degradable nature, plant fibers are deemed suitable for civil engineering structural applications.

Chapter 3

Materials & Methods

3.1 Background

The use of dispersed fibers in concrete is an effective way to improve the energy absorption of concrete, counteract crack development and propagation and increase its tensile strength. Combining natural and artificial fibers into a hybrid concrete gives the most optimal engineering properties while being cost-efficient. Number of researches have already been done on the mechanical properties of hybrid concrete but not on the hybridization of pine and glass fibers. Thus, further studies should be conducted to examine the effects of varying fiber lengths on the mechanical characteristics of hybrid fiber-reinforced concrete. The use of combination of short and long fibers in hybrid fiber reinforced concrete may lead to improved characteristics of the material, including increased tensile and flexural strength. The shorter fibers may be more effective for improving tensile strength while longer fibers are better for flexural strength, allowing for a balance of both properties. Additionally, the combination of fibers may also enhance toughness and impact resistance, which can be beneficial against tension or impact scenarios. This combination of fibers may result in a concrete with improved mechanical properties and enhanced performance in a variety of applications. In order to gain an extensive understanding of the behaviour of pine needles and glass fibre reinforced concrete for a variety of civil engineering applications, a comprehensive investigation is carried out. The effects of varying percentages of individual fibers (0.25%, 0.5%, 0.75% and 1% by volume of wet concrete) to optimize the mix design are studied along with control samples of plain concrete. The influence of fiber addition on the energy absorption capacity of concrete under compressive and flexural loadings are also determined experimentally. Scanning electron microscopy is used to study the fiber bond matrix mechanism of the tested specimens in order to gain a deeper insight of the behaviour. Furthermore, materials collection, preparation, mix proportions, casting, specimen details and testing are conducted in sequence. In Section 3.2, materials and methods are outlined. Section 3.3 contains tests and the standards followed for each test. Finally, Section 3.4 summarizes the findings.

3.2 Materials and Methods

3.2.1 Materials

Details of materials used in this research includes Ordinary Portland Cement (OPC) from Fauji Cements, sand from the Lawrencepur source, crushed aggregate from Margalla, tap water, super plasticizer, Pine needle from pine trees and woven roven glass sheet which is commercially available are used. Super plasticizer i.e., Sikament-512 PK from Sica company is used in this study. It is a high range water reducing and set retarding concrete admixture which is used to give long lasting control of slump loss and improves workability without adding more water. Sikament-512 complies with ASTM C-494 Type G and EN 934-2: 2001.The Fauji Cement plant produces OPC which meets the requirements of EN 1971: 2011-CEM I 425N with a 28 day strength of 52 ± 3 MPa. Chemical composition of Fauji Cement is given in Table 3.1 and Table 3.2 shows technical data of Sikament-512 super plasticizer. Aggregates used were varying in size between 25mm to 9.375mm properly washed for impurities. Pine needle used in present research is in fresh state having green color and the optimum length considered for pine needle is 12 mm. Glass fibers is commercially available in the form of glass mat and woven rove sheets. For the present research glass fibers available in the form of woven roven sheets is selected. Each strand of sheet are then separated and cut into the required length of 25mm. Table 3.4 and Table 3.6 shows physical properties of glass and pine needle respectively.

Table 3.1: Chemical Composition of Ordinary Portland Cement

Oxide	**Symbol**	**Percentage**
Calcium Oxide	CaO	61.7
Silicon Dioxide	SiO_2	21
Aluminum Oxide	Al_2O_3	5.04
Iron (III) Oxide	Fe_2O_3	3.24
Magnesium Oxide	MgO	2.56
Sulphur Trioxide	SO_3	1.51

Table 3.3: Technical Data of Super-Plasticizer

Technical Data of Super Plasticizer	
Density	1.16-1.2 kg/lit
PH Value	Approximately 7
Product Color	Brown Liquid
Type	Organic polymer blend

Table 3.4: Physical Properties of Glass

References	Palani kumar et al., [92]	Atewi et al., [93]	Ali et al., [94]	Kizilkanat et al., [41]	Madhkhan [95]
Specific gravity			2.6		2.7
Water Absorption (%)					-
Stiffness (KN/mm)	72			-	
Fiber length (mm)		12	6-18	12	
Density (g/cm3)	258			2.6	
Tensile strength (MPa)	2200	3400	1000-1700	3400	
Tensile modulus (GPa)	70			-	
Modulus of elasticity (GPa)	29	77	72	77	80.4

Table 3.5: Material Properties of Pine Needles[16]

Amount of Inorganic Material	0.053
pH	5.92
Hemicellulose	81
Lignin	13
Cellulose	52
Tensile Strength	36.72
Threshold Stress	36.94

3.2.1.1 Alkali treatment of Pine Needle Fiber

In most practical situations, pre-treatment of natural fibers is necessary to enhance their bond strength and improves the surface of the fibers. Various researchers have employed different techniques to modify the physical and chemical properties of the fiber surface. These studies demonstrated that pre-treatment can have a positive effect on the properties of plant fibers and their composites. The current work applies a simple pre-treatment, similar to those employed by [72, 73]. Soaking fresh pine needles into 2% NAOH solution for two hours was conducted in order to eliminate wax, impurities, and minimize water absorption of natural fibers. The fibers were then rinsed until the water flow was colorless or no adhesion between the fibers existed. Excess water was dried away from the surface of the fibers. Following the dilute alkali treatment of the fiber, the ends of the fibers were black and brown and the center remained light green and the scent and resin of the fibers were not detectable.

3.2.2 Mix Proportions and Casting Procedure

The mix proportions for plain concrete are 1: 2: 3 (cement: sand: aggregate) having w/c ratio of 0.45.

For making hybrid fiber reinforced concrete, having approximate length of 25 mm glass and 10mm pine needle and contents of 2% by volume of wet concrete along


(a) (b)

Figure 3.1: (a) Pine Needles in natural form (b) ALkali-treated Pine needles


(a) (b)

Figure 3.2: (a) Glass Fiber sheet (b) Chopped strands

with 2% super plasticizer are incorporated (as an additive) with 0.45 w/c ratio. Accordingly, the weights of cement, sand and aggregates are 47.4 kg, 103.2 kg and 147kg respectively, for the preparation of each batch of mix design. For the preparation of PC mix, cement, sand and aggregates are simultaneously put in the drum mixer and water is then added. The mixer is started to rotate for a period of five minutes. Whereas, for HFC 1/3rd of cement, sand, aggregates and fibers are put in the drum mixer in four layers. The remaining cement, sand, aggregates, and straw are then added in the drum mixer using the same layering technique. 2/3 rd of water is then added and mixer is rotated for three-minutes. The 1/3 rd water is then added and the drum mixer is started again to rotate for two minutes. Still the mix is not homogeneous and workable at this point. The mixer is then rotated again for three minutes to get better homogeneous mix. Mixing time is increased because addition of water at that stage could have resulted in bleeding of HFC.

Therefore, the increased mixing time came out to be a successful approach for a workable HFC. The slump test is performed for fresh PC and HFC. For preparation of PC and HFC specimens, prepared homogeneous mixture is then poured in the moulds. Each layer is then compacted by 25 blows of tamping rod. In addition to that, for removing air voids, the mould having HFC is lifted up to approximately 100 - 150 mm followed by free drop. The specimens are then demoulded after 24 hours and are kept for curing for 28-days. The water absorption test for hardened PC and HFC specimens are conducted thereafter.

3.2.3 Specimens

For compressive strength testing, cylinders having dimensions of 200 mm height and 100 mm diameter are prepared for six different batches with varying percentage of pine needles and glass fibers to optimize content of Hybrid Fiber Reinforced Concrete Mix. However, 100 mm wide, 100 mm deep and 450 mm long beam-lets are cast for performing flexural strength test. Labeling scheme of specimens are elaborated in table 2.1. Three cylinders and three prisms for each combination are cast. The average of three readings is used for hardened concrete properties. The average of three readings is also considered by other researchers as well. Mix design of all the 6 batches are given in Table 2.1.

3.3 Testing Methods

3.3.1 Fresh State Properties

3.3.1.1 Slump test

Slump test measures the flowability of concrete. The ASTM C143/C143M-15 is followed while performing slump cone test. A slump cone test was conducted on both PC and HFC to assess the workability of the fresh mix concrete. Prior to the test, the slump cone apparatus was carefully cleaned and lubricated. In this procedure, concrete layers are placed in three layers with each layer having compaction by 25 strokes to fill the voids.

Figure 3.3: Specimens for Each Casting

3.3.1.2 Water Absorption

The ASTM standard C1585 is used to determine the water absorption capacity of samples. Specimens were taken out from the tank after 28 days and oven dried at 100c. Dry weight of the cylinders were taken. After that, cylinders were submerged in water for 24 hours. After the time has elapsed, the cylinders are taken out and their weight is taken again to determine the amount of water that the concrete mix has absorbed. Difference of wet weight and dry weight was divided by wet weight to get the water absorption of cylinders.

3.3.2 Mechanical Testing

3.3.2.1 Compression Test

A Universal Testing Machine (UTM) equipped with a high precision displacement transducer, with a measurement range of 0-1500 mm and a resolution of 0.001 mm, is utilized to assess the compressive strength, absorbed compressive energy,energy absorption till the peak stress (CBE), energy absorption after the peak stress (CPE), and compressive toughness index (CTI) of cylindrical specimens.The cylinders are capped with sulfur prior to testing to ensure even load distribution. ASTM C39/C39M-20 (Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens) is employed to test the cylinders in compression. The test setup is depicted in Figure 3.5.

Table 3.7: Mix Design Proportions for Casting

Specimens	**Cement**	**Sand**	**Aggregate**	**Pine Needles**	**Glass fiber**
(1:2:3) with 2% SP except PC	**Kg**	**Kg**	**Kg**	**Kg**	**Kg**
PC	7.9	17.2	24.7	-	-
P 2%	7.9	17.2	24.7	0.2635	-
P1.5% - G 0.5%	7.9	17.2	24.7	0.1976	0.362
P 1% - G 1%	7.9	17.2	24.7	0.1317	0.724
P 0.5% - G 1.5%	7.9	17.2	24.7	0.0658	1.087
G 2 %	7.9	17.2	24.7	-	1.449

Note : Water cement ratio is kept same for all the batches i.e., 0.45.

3.3.2.2 Flexural Test

To conduct the flexural strength test on the 18 beam-lets, ASTM C293/C293M-16 (Standard Test Method for Flexural Strength of Concrete - Using Simple Beam with Centre-Point Loading) is adopted. A flexural testing machine is used to measure the flexural behaviour, modulus of rupture (MOR), flexural energy absorption, and flexural toughness index (FTI). The test setup is depicted in Figure 3.5.

(a) (b)

FIGURE 3.4: Flexural Test Setup

3.3.3 Dynamic testing

The resonance frequency of a system is a measure of the oscillation that takes place in the absence of external influence. This oscillation involves both kinetic and potential energy which is stored at various points. Resonance frequency devices are used to calculate the resonance frequency of concrete which is then used to calculate the damping ratio, modulus of elasticity, modulus of rigidity, and Poisson's ratio. The unit of measurement for the modulus of elasticity is Pascal and the equation [ASTM C215-14] can be used to calculate the dynamic modulus of elasticity when the transverse frequency, cylinder mass, and beam-lets are known.

$$E_{dyn} = CMn^2$$

The mass of the cylinder or beam-let (M) is measured in kilograms (kg), the fundamental transverse frequency (n) is measured in hertz (Hz), and C is either

1.6067 (L^3 T/d^4) for cylinders or 0.9464 (L^3 T/bt^3) for beam-lets. With these measurements, the torsional frequency is used to calculate the dynamic modulus of rigidity (G) by following ASTM C215-14, with the unit for G being Pascal. This is the method for determining G.

$$G_{dyn} = BM(n^{"})$$

The frequency of twisting (in Hertz) can be calculated by using the formula M × B / ml, where M is the mass of the beam-let or cylinder (in kilograms), B is (4LR/A), ml, R is 1 for circular cylinder and 1.183 for beam-lets, L is the length of the specimen (in meters), and A is the cross-sectional area of the tested specimens. m^2. The dynamic Poisson ratio of concrete can range from 0.20 to 0.25 and is based on the dynamic loading of different types of concrete. Generally, high-strength concrete has a value of 0.1 while weak strength concrete has a value of 0.2. Many researchers use 0.2 as the dynamic Poisson ratio. This ratio is an important part of building concrete structures and is calculated using the ASTM C215-14. Flexible materials tend to have a higher Poisson ratio than rigid materials. The formula for determining the dynamic Poisson ratio is:

$$Dynamicpoisonratio = (E_{dyn} = 2G)–1$$

Where E_{dyn} is dynamic modulus of The elasticity and G are referred to as the dynamic modulus of elasticity and the dynamic modulus of rigidity, respectively. Damping ratio, which is represented by ζ (zeta), is a material property. If this value is equal to 0, then the system is considered to be undamped. If ζ (zeta) is less than 1, the system is considered to be underdamped, and if it is greater than 1, it is over-damped. When damping is introduced, the motion of the vibratory system can be minimized, reduced, or even ceased. Studies into the dynamic properties of concrete should take into account peak ground acceleration and damping ratio, which are related to three properties of concrete: the dynamic modulus of elasticity, the dynamic modulus of rigidity, and damping ratio. These properties are correlated with each other. Damping is related to the dissipation of energy from the system or material. Researchers are looking into the importance of vibrational damping, as it can reduce hazards and make structures more comfortable for users. Damping is created by techniques that dissipate energy from the oscillating system, such as friction on automated structures, resistance on electrical oscillators, and a small amount of delicacy in visual oscillators. When studying rubberized concrete, the dynamic properties calculated were compared to those of regular concrete, using the elastic wave technique and beam elements. An investigation of the mechanical and dynamic properties of concrete reinforced with coconut fibres was conducted and compared to plain concrete. It was observed that the rubberized solid, which had been crushed, displayed enhanced damping characteristics. Additionally, the concrete dynamic modulus of elasticity and damping ratio were both increased by incorporating coconut fibre. The damping ratio, which expresses a system's response to the effects of an external force and the termination of its motion, is measured through common logarithmic decrement tests and is dimensionless.

FIGURE 3.5: Resonance Testing Machine

3.3.4 Microstructural Analysis

3.3.4.1 Scanning Electron Microscope (SEM) Test

The micro-structural analysis of optimized HFC for their bonding with concrete is done by performing scanning electron microscope imaging. This test is intended to study the fiber-matrix bond and pull out behaviour of fibers and nature of failure/cracking. The VEGA3 TESCAN having voltage of 10 kV is utilized for scanning electron microscopic imaging. Plasma coating is done on samples before testing.

3.3.4.2 Energy Dispersion X-Ray Test

Energy dispersive X-ray (EDX) is a type of spectroscopy that is used to determine the elemental composition of a material. It works by bombarding the sample with X-rays, which causes the atoms in the sample to emit secondary X-rays at specific energies. These emitted X-rays can then be used to identify the elements present in the sample and to determine their relative concentrations.The standard for EDX testing is ASTM E1251, which outlines the general principles and procedures for performing energy dispersive X-ray.

3.4 Summary

The mechanical properties including compressive and flexural properties,Dynamic properties including resonant frequencies, damping ratios, dynamic modulus of elasticity, dynamic modulus of rigidity, and poisons ratio of PC and HFC are determined through a mixture of cement, sand, coarse aggregate with a ratio of 1:2:3 and w/c ratio of 0.45 with varying percentages of 10 cm long pine needle and 25cm long glass fibers keeping a constant fiber content of 2% by volume of wet concrete. SEM and EDX analysis are then performed to evaluate the results in accordance with ASTM standards. The findings of the testing are presented and discussed in Chapter 4.

Chapter 4

Results and Analysis

4.1 Background

The ASTM standards are followed for mechanical and dynamic testing. For optimizing fibre content in terms of natural and synthetic fibres, the mechanical properties of HFC with different ratios of natural and synthetic fibres are studied against PC. This chapter presents a complete experimental investigation of the fresh state properties, hardened-state properties including mechanical and non-destructive dynamic properties and micro structural analysis of PC and HFC. SEM and EDX analysis are done to study the matrix bonding of HFC.

4.2 Fresh-State Properties

4.2.1 Workability

A concrete slump test analyze the consistency of a batch of concrete to ascertain how easily it will flow. In case of PC, super plasticizer was not added and w/c ratio was kept minimum i.e., 0.45 to gain maximum strength. Slump achieved was minimum. While in case of FRC mix designs, rather to enhance the w/c ratio without any rationale, 2% super plasticizer was added to cater the water absorption of fibers. Slump usually decreases in case of fibers that's why slump of fibers came out to be zero. The rheology of FRC is significantly different than that of similar

Table 4.1: Water Absorption Capacity for Mix Designs

Specimens	**Wet Weight(kg)**	**Dry Weight(kg)**	**%**
PC	3.93	3.75	4.85
P2%	3.82	3.61	5.99
P1.5%-G0.5%	3.75	3.59	4.46
P1%-G1%	3.63	3.49	3.95
P0.5%-G1.5%	3.56	3.43	3.79
G2%	3.54	3.42	3.63

mixes without fibers, even when only small fiber dosages are used, especially due to the relatively high stiffness and the geometry of the fibers [96].Therefore, it is often not convenient to characterize its workability in terms of parameters used for PC. [96], [97].

4.2.2 Water Absorption

The purpose of the test is to estimate the increase in sample density brought on by water absorption over the time period. Water contains many hazardous elements that soaks into concrete that is why concrete disintegrates and absorbs more water. P2% has maximum water absorption and it is evident from the literature that natural fibers have high water absorption capacity than synthetic fibers [98]. It can be seen that as far as PF content is reduced, water absorption capacity is also reduced and it is might be due to adding contents of GF in further specimens. Glass fibers are repellent to moisture and it doesn't absorb water and glass fiber has low weight. In comparison to control specimen PC, Pine fibers has 23% more water absorption while 8%, 18%, 22% and 25% reduction in water absorption can be seen in P1.5%-G0.5%, P1%-G1%, P0.5%-G1.5% and G2% respectively. Tabular data 4.1 depicts the water absorption capacity of all the specimens.

4.3 Mechanical Properties

4.3.1 Properties Under Compressive Loading

4.3.1.1 Compressive Behaviour

Figure 4.1 depicts the compressive behaviors of PC, P2%, P1.5%-G0.5%,P1%-G15,P0.5%-G1.5%,G-2%. At ultimate load, PC samples were divided into two pieces, while the specimens of HFC didn't break and showed more tough behavior during compressive loading. Compressive strength is the maximum stress in stress strain curve. It is quite obvious from the trend shown that compressive strength increases as glass fibre content rises and natural fibre content falls. Maximum compressive strength of glass comes out to be 21 MPa which is 12% more than control specimen. Remaining all the specimens showed less strength than PC. The addition of natural fibers in mix design results in a reduction of compressive strength when compared to plain concrete due to their tendency to weaken the concrete. Various studies have reported similar findings regarding reduction in compressive strength due to natural fibers [82], [99], [100]. However, compressive strength is not the sole determinant of a material's effectiveness in building construction. Toughness, along with compressive strength, is also considered an important parameter. In fact, a slight decrease in material strength can be compensated by a considerable increase in toughness and energy absorption capacity, leading to improved overall performance. Moreover, dispersed fibers have been observed to impede or slow down the formation of microcracks in the cross-section of concrete, which would have developed early on under service loading. This crack arresting mechanism of fibers also contributes to the matrix's ability to absorb energy. While glass fibres with replacement rates of 1.0 and 1.5 percent exhibited CS that was nearly comparable to control concrete. Glass fibres with a replacement rate of 0.5 percent demonstrated marginally superior CS than control concrete. This demonstrates that the effect of adding glass fibres on CS is minimal. According to the literature, no increase in CS was observed when the glass fibre concentration was increased from 1.5 percent to 2.5 percent, except in specific pozzolan-containing mix design [17]. P2%, which is solely made up of pine needles, has the lowest compressive strength which is 16% less than CS of PC. Since natural fibres are reported to have low strength this is why it has a lower compressive strength. P1.5%-G.5% showed 13% less CS than PC, P1%-G1% showed only 5% less CS than CS of PC and P0.5%-G1.5% exhibtis 11% less CS than PC. P1.5%-G.5% had shown the maximum energy absorption capacity because glass fibers enhances the post-cracking behaviour of material. Strain-hardening effect of glass fibers can be seen in this case.

4.3.1.2 Compressive Strengths, Compressive Energy Absorption and Compressive Toughness Index

The tabular display of energy absorptions including total energy(CTE) and toughness index (TI) is represented in Table 4.2. Calculations of compressive pre-crack absorbed energy (CBE) are made from the region under the stress-strain curve from the beginning until the point of maximum stress. From the first fracture until the failure load, the compressive cracked zone under the stress-strain curve gives post-cracking energy (CPE). P1.5%-G0.5% exhibits maximum toughness i.e., 183% more than PC and overall energy absorption capacity raised to 131% as compared to PC. Since P1.5%-G0.5% exhibited the best post-cracking behaviour thus incorporated towards the overall energy. P2% has less CS than PC but its toughness index is 61% more than TI of PC. It is due to the fact that concrete has brittle failure and its post-cracking energy is almost equals to zero thus total energy absorption is less while specimens having fibers showed better post cracking behavior as compare to plain concrete thus total energy remains more than total energy absorption of PC. It can be clearly observed that if CS is compromised, energy absorption capacity is somehow increased relatively so the overall toughness of material is enhanced. Cracking pattern can be seen in Fig 4.2 where bridging of glass fiber can be seen clearly.

4.3.2 Properties Under Flexural Loading

4.3.2.1 Flexural Behaviour

Figure 4.4 depicts the load-displacement curves for all specimens to show the flexural behaviours.

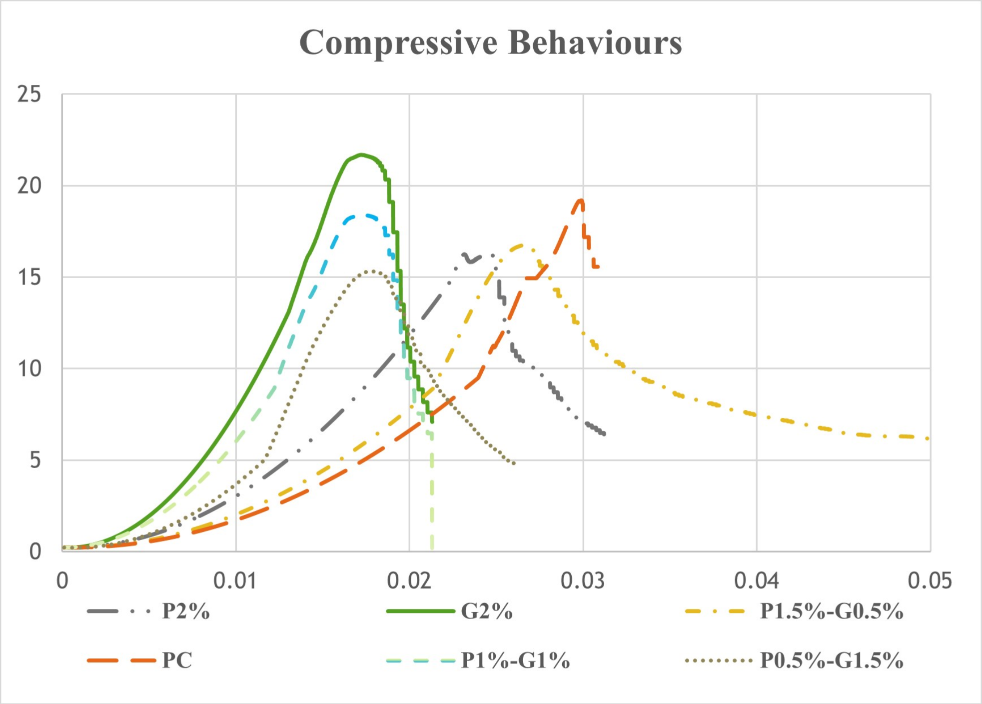

FIGURE 4.1: Compressive Behaviors

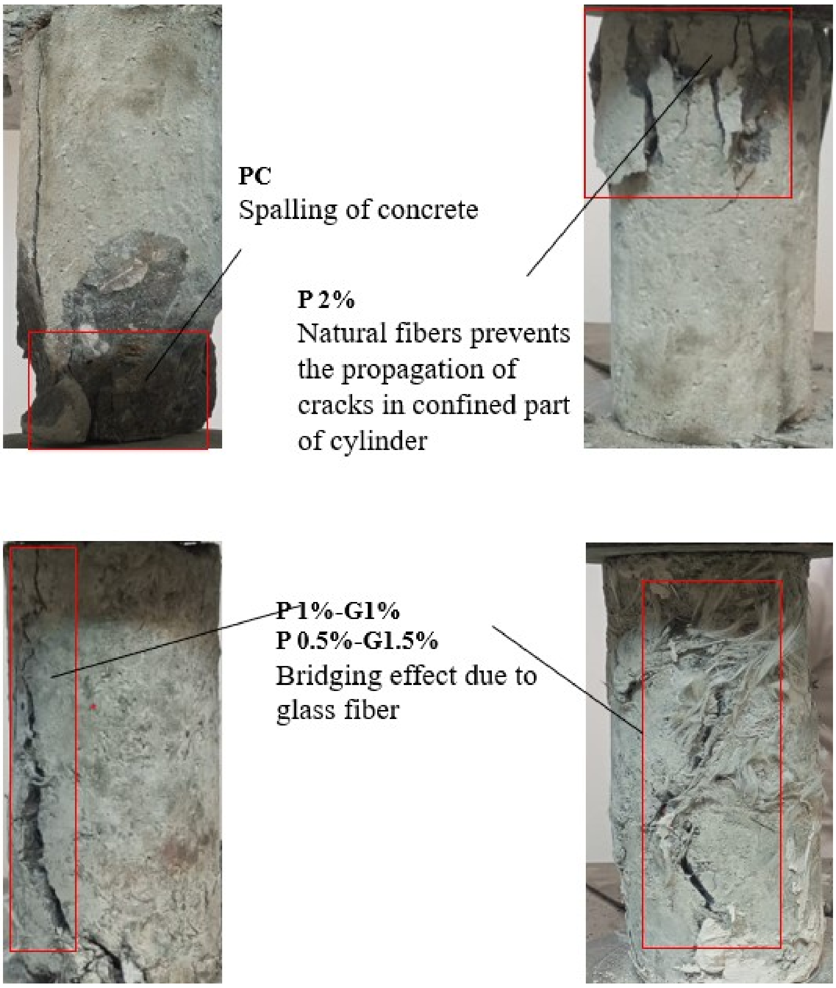

FIGURE 4.2: Cracking Patterns Under Compressive Loading

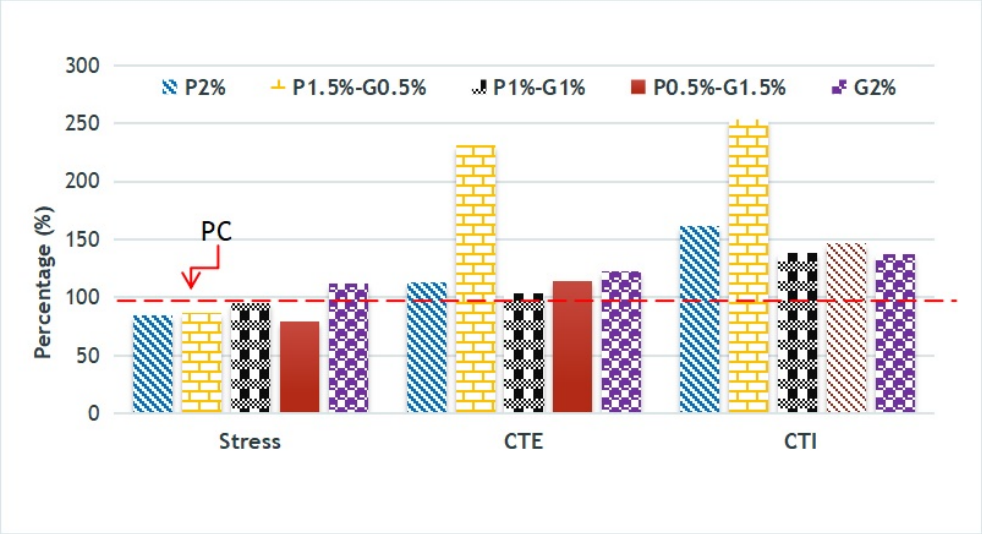

FIGURE 4.3: Comparison of CS,CTE and CTI

Values of maximum load for PC, P2%, P1.5%-G0.5%,P1%-G15,P0.5%-G1.5%,G-2% are 6.154kN, 8.122kN, 9.22KN, 7.696kN, 5.834 kN, 7.88kN respectively. Figure 4.4 depicts the load-displacement curves for all specimens to show the flexural behaviours. Values of maximum load for PC, P2%, P1.5%-G0.5%,P1%-G15,P0.5%-G1.5%,G-2% are 6.154kN, 8.122kN, 9.22KN, 7.696kN, 5.834 kN, 7.88kN respectively. Highest flexural strength is given by G2% and in case of HFC, P1.5%-G0.5% showed highest value because of the fact that natural fibers enhance the flexural strength of concrete while glass gives bridging effect as well [17]. Minimum flexural strength is shown by PC because of the fact that concrete is weak under flexural loading. P2% showed comparable flexural strength as compared to the maximum strength of P1.5%-G0.5%. Results of specimens having ratios of 1.5% and 2% showed maximum and comparable flexural strength because of the fact that they were alkali-treated. Alkali treatment of natural fibers enhances their flexural capacity as compare to same fibers when treated with boiled water as reported in literature [13], [16]. On the other hand, glass fibers usually gives more flexural strength than natural fibers but reduction is seen in this study might happened due to the improper mixing and balling effect of glass fibers [101]. Secondly, hybrid effect of glass might be the other factor of this reduction. Figure 4.4 demonstrates that PC exhibited the earliest occurrence of the first crack. While all FRC mix designs displayed a delay in the emergence of their initial cracks. The mix design P1.5%-G0.5% demonstrated the greatest delay in the occurrence of cracks and most probably it happened because of the addition of glass fibers at 0.5%.

Table 4.2: Compressive strength , Energy Absorptions (CBE,CPE,CTE) Toughness Index of all Specimens

Specimens	Stress	(CBE)	(CPE)	(CTE)	Toughness Index
	(Mpa)	(Kj/m3)	(Kj/m3)	(Kj/m3)	(CTI)
PC	19.19	76.15	9.07	85.22	1.119
P2%	16.26	53.37	42.98	96.35	1.805
P1.5%-G0.5%	16.74	69.61	127.76	197.37	2.835
P1%-G1%	18.24	57.07	31.26	88.33	1.548
P0.5%-G1.5%	15.31	58.93	38.4	97.33	1.652
G2%	21.68	67.79	36.21	104	1.534

In conventional reinforced concrete, the crack resistance comes into existence when the crack is propagated up to the steel rebars. However, in case of FRC, the presence of fibers resists the formation of first crack [103]. In addition to the formation of first crack, the crack propagation phenomenon is also delayed due to the arresting of cracks by fibers [98]. So, in this way, the load carrying capacity of FRC is increased. Furthermore, once the cracks reached up to the steel rebars, the tensile strength of fibers is also added with the steel rebars for resisting the cracks [28]. So, it is concluded that cracks can be delayed by the addition of fibers while tensile strength of fibers ultimately contributes towards the overall gain in flexural strength as well [99].

4.3.2.2 Modulus of Rupture (MoR), Flexural Energy Absorption and Flexural Toughness Index

Energy absorption from load displacement curve is calculated from the area beneath the load-displacement curve from start to the point of maximum load till where the specimen get its first crack.While area under the load-displacement curve from the maximum load sustained by the specimen to ultimate load is the flexural post-cracking energy (FPE). The sum of these two energies gives the total flexural energy absorbed by beamlets (FTE). When total energy is divided by precrack energy (i.e. FTE/ FBE) flexural toughness index (FTI) is obtained. Table 4.4 shows the values of MoR, FBE, FPE, FTE and FTI respectively. Flexural pre-crack absorbed energy (FBE) of PC,P2%, P1.5%-G0.5%, P1%-G15, P0.5%-G1.5% and G-2% are 4.959 MJ , 4.947 MJ , 5.56 MJ , 6.732 MJ , 3.12 MJ , 8.227 MJ respectively. Flexural post-crack absorbed energy (FPE) for PC, P2%, P1.5%-G0.5%, P1%-G15, P0.5%-G1.5% and G-2% are 0.402,0.7477,2.1448,4.51,0.47 and 5.01 respectively.Least values of post crack energy is given by PC and P0.5%-G1.5% because prisms are divided into two equal parts after implementation of maximum load while glass fiber beamlets gave the maximum post cracking energy because G2% showed the ductile behavior and sustained for a long time even after the first crack appeared and glass fiber showed the highest bridging effect. Total flexural energy (ET) absorbed by beam-lets of PC, P2%, P1.5%-G0.5%,P1%-G15,P0.5%-G1.5% and G-2% are 5.361 MJ , 5.695 MJ , 7.7088 MJ , 11.24 MJ , 3.5909 MJ and 13.243 MJ respectively. Due to the presence of fibers which usually absorb energy in concrete, HFC has a higher overall energy absorption capacity than PC. Fibers help concrete fill cracks and increase its ability to support loads. Due to the glass fiber's bridging effect, mixes with equal amounts of pine and glass fiber absorb greater total energy when subjected to flexural loading. Result shows the optimum content for hybridization for glass fibers is 1% because increasing content of glass fiber shows decreased strength and it is may be due to the balling effect of glass fibers [101]. Flexural toughness index (FTI) for PC, P2%, P1.5%-G0.5%, P1%-G15,P0.5%-G1.5% and G-2% mixes are 1.081,1.151,1.386,1.670,1.151 and 1.610 respectively. Flexural toughness index (FTI) is maximum for P1%-G1% because of the fact that glass content when crossed 1% , it gave less strength. Fig 4.5 shows the comparison of energy absorptions and toughness indices of all mix designs against PC. Fig 4.6 shows the cracking pattern of beamlets.

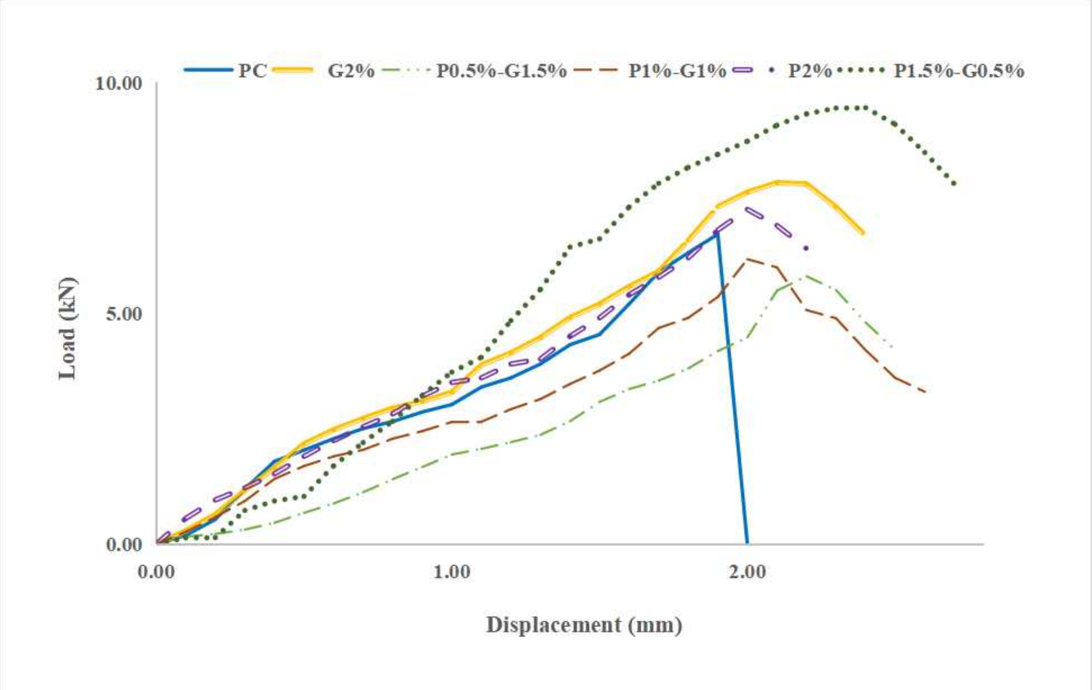

Figure 4.4: Flexural Behaviours

4.4 Dynamic Properties

Table 4.5 is showing the tabular data related to dynamic characteristics of concrete cylinders with glass and pine needle fiber including frequencies, damping ratio and dynamic modulus of rigidity for cylinders and beamlets.

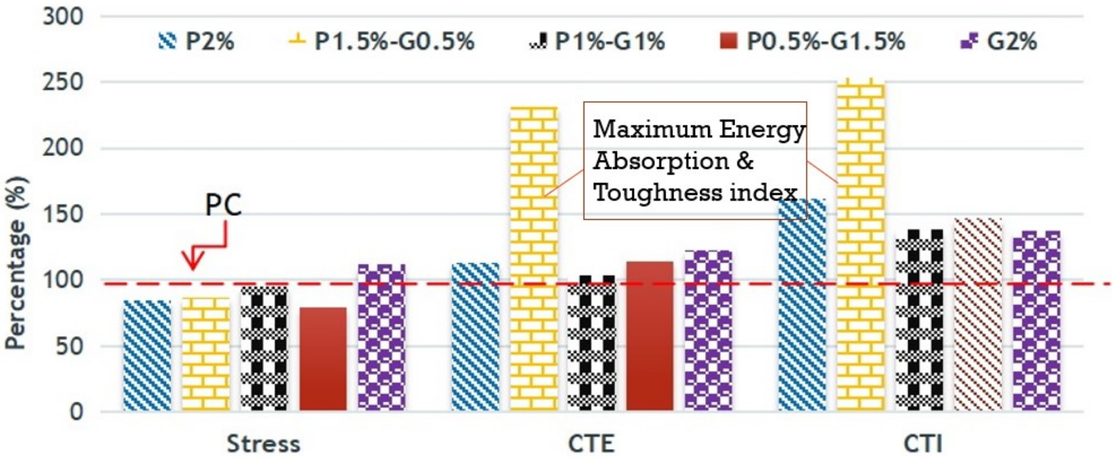

FIGURE 4.5: Comparison of Energy Absorptions and Toughness Index

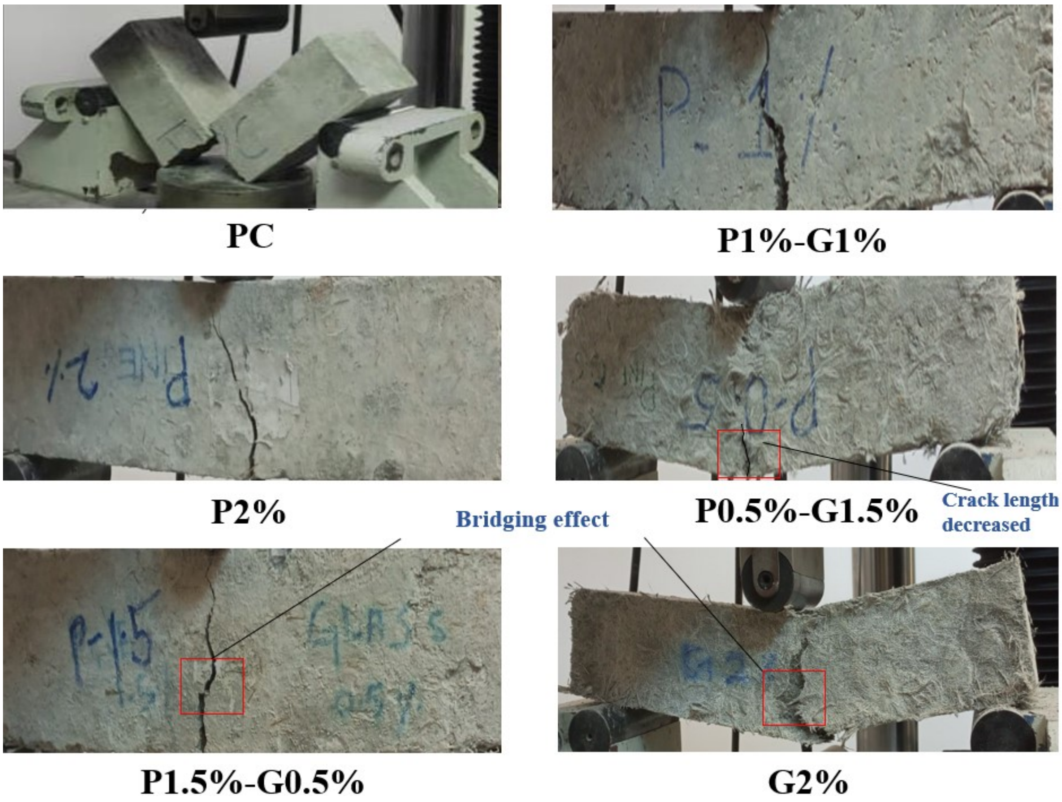

FIGURE 4.6: Cracking Pattern of Beamlets

Table 4.3: Flexural Strength,Energy Absorptions and Toughness Index

Specimens	**MOR**	**Deflection**	**FBE**	**FPE**	**FTE**	**FTI**
	Mpa	**(mm)**	**MJ**	**MJ**	**MJ**	-
PC	3.181	1.85	4.959	0.402	5.361	1.081
P2%	3.833	1.65	4.947	0.7477	5.695	1.151
P1.5%-G0.5%	4.351	2.15	5.56	2.1448	7.7088	1.386
P1%-G1%	3.632	2.2	6.732	4.51	11.24	1.670
P0.5%-G1.5%	2.753	2.3	3.12	0.47	3.5909	1.151
G2%	3.719	2.15	8.227	5.01	13.243	1.610

The longitudinal frequency of the G2% mix is maximum while PC and P2% showed same longitudinal frequencies. All mixes having hybrid fibers have less value of rotational and tranverse frequencies than that of PC and in case of beams resonant frequencies, P2% showed least longitudinal frequency while PC and G2% showed almost equal frequencies.in case of torsional frequency of beamlets, PC showed the maximum value and all the remaining mix designs have almost equal tranverse frequencies. For prisms, Gdyn of PC is 31.17 GPa. All Gdyn values of all mixes are more than that of PC except P2%. The values of poisons ratio for cylinders of PC is 0.48. Poisons ratio for P1.5%-G0.5%,P1%-G1%,P0.5%-G1.5% and G2% mixes are 5%, 13%, 20%, 46%, 56%, and 73% more than that of PC. Poisons ratio for beam-lets of PC is 0.31. Value of poisons ratio of remaining mix design is 5%, 67%, 41%, 25%, and 29% more than that of PC. Edyn for PC is 1.13 GPa and Edyn for remaining mix designs are more than PC While Edyn in case of beamlets have maximum value of 6.07 GPa which is attained by G2%. For beam-lets, Edyn for PC is 5.34 GPa which is nearly equals to G2% value. The torsional frequency of concrete is used to compute the dynamic modulus of rigidity.. Gdyn for ordinary concrete cylinders is 1.17 GPa while values of Gdyn for P1.5%-G0.5%,P1%-G1%,P0.5%-G1.5% and G2% mixes are 26%, 33%, 34%, 67%, and 68% more than PC.

4.5 Microstructural Analysis

4.5.1 SEM Analysis

SEM analysis of optimized mix design is performed to examine the pull-out behavior of fibers in this. In Fig 4.7, beginning from the top-left corner, lumps of glass fiber are visible exhibiting the balling effect of GF. This might happened due to the improper mixing of fibers leading to an uneven distribution in the mixture. The image in the middle shows the extraction of fibers, with glass fiber having a bridging effect due to its extended length compared to pine fibers. At the top right, the slippage of concrete is visible, likely due to the presence of a smooth surface and round-shaped aggregates in the concrete mix.

Table 4.5: Dynamic Properties

	Parameters						
Specimens	**RFL (Hz)**	**RFT (Hz)**	**RFTr (Hz)**	**(%)**	**Edyn (GPa)**	**Gdyn (GPa)**	**Poisson Ratio(-)**
Cylinders							
PC	3462	3417	3440	2.86	0.70	4.55	0.922
P 2%	3528	3507	3439	2.59	0.74	4.55	0.918
P 1.5 - G 0.5	3306	3439	3506	2.73	0.68	4.52	0.924
P 1% - G 1%	3462	3462	3329	2.91	0.66	4.05	0.915
P 0.5% - G1.5%	3307	3506	3529	3.11	0.64	4.36	0.922
G 2 %	3373	3351	370	3.29	0.63	4.78	0.934
Beams							
PC	3350	1531	3440	1.85	14.43	5.50	0.311
P 2%	3417	1443	3439	1.40	12.43	4.74	0.311
P 1.5 - G 0.5	3351	1398	3506	1.93	11.33	4.45	0.271
P 1% - G 1%	3573	1442	3329	2.04	11.94	4.27	0.398
P 0.5% - G 1.5%	3462	1398	3529	2.10	10.99	4.32	0.271
G 2 %	3595	1376	3706	2.25	10.53	4.14	0.27

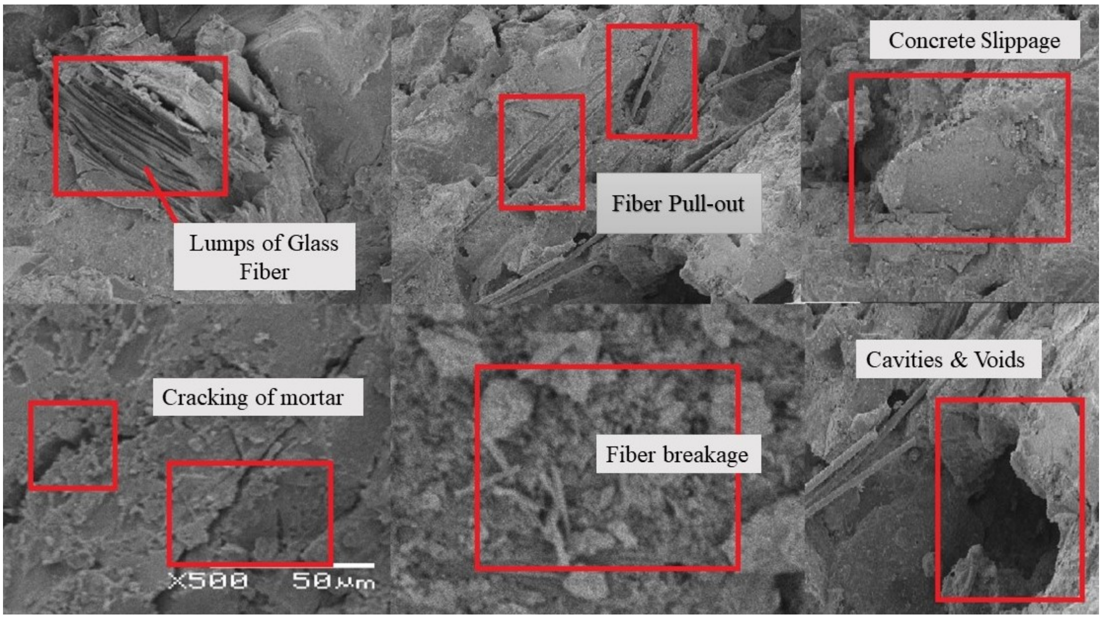

FIGURE 4.7: SEM Analysis of P1.5%-G.5%

On the bottom left, cracking in the mortar is evident, and at the bottom right, cavities and voids are discernible likely caused by inadequate mixing or compaction during casting. In hybrid combinations, glass fiber plays a vital role in determining flexural properties. The majority of the load was absorbed by these fibers, after its failure the remaining load was transferred to the Pine fibers From the above picture it is evident that the presence of voids, improper adhesion between the fibers and matrix and improper mixing are the major causes for the anomalies in results.

4.5.2 Energy Dispersive X-Ray (EDX)

EDX analysis shows the chemical composition of material.Results shows the highest percentages of calcium and oxygen and carbon. Maximum content is of oxygen and that is 39.93% making it a prominent content than remaining other elements. Second being the calcium content i.e., 22.68%. Percentages of carbon and oxygen indicates the presence of high percentage of carbohydrates i.e cellulose, hemicellulose and lignin. Chemical composition of P1.5%-G0.5% is shown in table given below and it is obtained from EDX analysis. Table 4.6 represents the detailed chemical composition of the optimized sample.

Table 4.6: Chemical Composition of P1.5%-G0.5%

Element	Weight (%)	Atomic(%)
C	8.78	17.29
O	27.01	39.93
Na	0.41	0.42
Mg	0.98	0.95
Al	4.53	3.97
Si	13.9	11.7
S	0.73	0.54
K	1.66	1.01
Ca	38.42	22.68
Fe	3.59	1.52

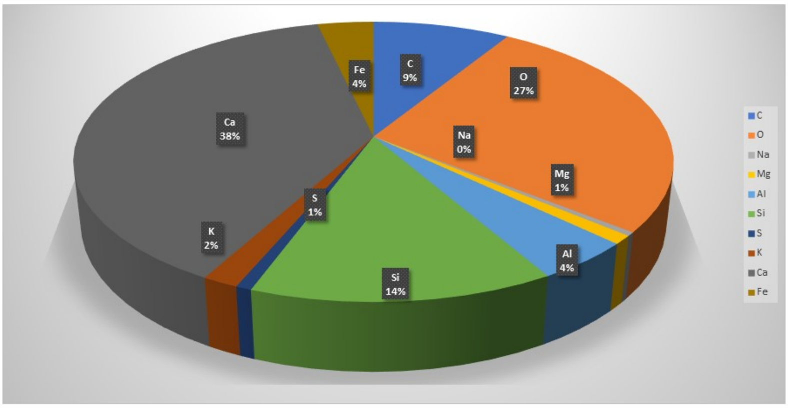

Figure 4.8: Optimization of Mix Design

4.6 Summary

The conducted experimental study is aimed to investigate the mechanical and dynamic properties, as well as the structural capacity, of hybrid fiber reinforced concrete (HFC). The HFC used in this study contained a total fiber content of 2% by volume of wet concrete, with two types of fibers utilized, i.e., Pine needle fibers and Glass fibers. The amount of each type of fiber used ranged from 0.5% to 2%, with Pine needle fibers chemically treated with NaOH to enhance their properties. The mechanical properties that are evaluated in the study includes the strength, energy absorption, and toughness index of the HFC under compressive and flexural loadings. The dynamic properties, on the other hand, are measured in terms of poison's ratio, modulus of rigidity, and damping ratio. Lastly, the structural capacity of the HFC is evaluated in terms of the potential reduction in required steel for the optimized mix. Following conclusions are drawn:

- The results of the study shows that, compared to plain concrete (PC), the highest water absorption is observed in the P2% mix design, at a rate of 23%. Conversely, all the other mix designs showed lower rates of water absorption than the PC, with rates of 8%, 18%, and 22% observed in the P1.5%-G0.5%, P1%-G1%, and G2% mix designs, respectively. Furthermore, the G2% mix design exhibits the lowest rate of water absorption, at 25% less than the PC.
- The results of the study indicates that the G2% mix design of HFC has the highest compressive strength, 12% greater than PC. CTE is found to be highest in the P1.5%-G0.5% mix design, with a rate of 131% greater than the PC. Additionally, the P1.5%-G0.5% mix design shows a 150% increase in CTI compared to the PC. The study also found that GF at a volume of 0.5% showed the maximum post-cracking energy. However, using GF at a high percentage, greater than 1%, did not result in an enhancement in compressive strength in HFC, which is consistent with previous literature. On the other hand, the P2% mix design has the least compressive strength, at 16% lower than the PC. This can be attributed to the fact that natural fibers generally have less compressive strength than plain concrete.
- The study shows that compared to PC, the HFC mix designs exhibited increased flexural strength. Specifically, an increase of 20%, 36%, 14%, and 16% is observed for P2%, P1.5%-G0.5%, P1%-G1%, and G2%, respectively. The mix design P1%-G1% exhibits the highest toughness index, at 54%, while all other specimens also showed enhanced flexural strength compared to PC. The study suggests that the optimal percentage of GF used in the P1.5%-G0.5% mix design resulted in improved properties, leading to its high flexural strength and toughness index.

- The study also investigates the dynamic modulus and properties of both PC and HFC. The damping ratio for HFC is found to be higher than that of PC. The results indicates that the type and volume content of fibers have an effect on the dynamic values of the modulus of elasticity and the Poisson's ratio. The dynamic elastic modulus, dynamic rigidity modulus, and dynamic Poisson's ratio are found to be increased for HFC.

- The Scanning Electron Microscopy (SEM) analysis conducted in the study reveals the pull-out behavior of glass fibers, which can be attributed to their elongated length. The analysis also shows the balling effect of glass fibers, which is likely due to improper mixing of the fibers with the concrete. Additionally, slippage of the concrete is observed, which can be attributed to the smooth surface of the aggregates used in the mix.

- The EDX analysis conducted on the sample shows that the highest percentage of elements present are calcium, oxygen, and carbon. Carbon is found in significant amounts along with oxygen, indicating the presence of high percentages of carbohydrates such as cellulose, hemicellulose, and lignin.

Chapter 5

Discussion

5.1 Background

Chapter 4 suggests the potential use of hybrid fibers in structural applications based on evidence of improved properties discussed in Chapters 3 and 4. To further investigate the behaviour and capacities of hybrid fiber reinforced concrete that incorporates glass and pine needle, research needs to be conducted. However, no such study has been conducted yet. Furthermore, optimization of the mix design should consider aspects such as economy, environment and social sustainability.

5.2 Optimization of Hybrid Fiber Mix Design

The optimization of concrete mixture design is a process of finding the most cost-effective mixture that meets the required performance of concrete, such as workability, strength and durability. Fig 5.1 shows the experimental data of six different mix designs, comparing strengths and energy absorption capacities. As the content of pine needles and glass fibers varied across the mixes and two batches had a total fiber content of one type, the results are varied. While one batch may have shown maximum results for compressive strength, the other batch may have had excellent flexural strength. Keeping sustainability in mind, parameters for optimization are selected. Concrete generally performs well under compression, but its behavior under tension, its brittle nature and corrosion due to steel reinforcement are issues that needs to be addressed. Enhancing flexural capacity and reducing the amount of steel in concrete structures can reduce the cost and prevent corrosion. Therefore, the modulus of rupture (MoR) and Toughness Indices (CTI and FTI) are major considerations when optimizing the mix designs. It was found that P1.5%-G.5% had the highest MoR and compressive toughness index with comparable CS, FTE and FTI. On the other hand, in addition to compressive strength, toughness is also used as a parameter of a material's effectiveness in building construction [102], [103]. Slight decrease in material's strength but considerable increase in the toughness and energy absorption capacity of material gives better performance overall. Dispersed fibers are reported to slow down or sometimes inhibits the progression of microcracks in the cross-section that otherwise would have developed at an early age when subjected to the service loadings. The crack arresting mechanism of the fibers also contribute towards the matrix's energy-absorbing ability [104].

5.3 Nominal Moment Capacity of Fiber Reinforced Concrete

Fiber reinforced concrete beams with steel rebars were explored by Beshara et al. [90]. For tensile reinforcement, the steel ratios employed were 0.0017, 0.0064, 0.0075, 0.012, 0.015, and 0.022. Additionally, steel ratios of 0.0045 and 0.0047 were used for compression reinforcement. By volume of wet concrete, the percentages of steel fibers employed were 0.5%, 1%, and 2%. From experimental results, it is found that flexural strength increased significantly.This study suggested that the tensile strength of the fiber should also be taken into account when adjusting the Whitney stress distribution equation to calculate the effective height of the equivalent stress in the tensile zone as described by Nilson et al [91]. Nilson's equation is as follows:

$$M_r = Ts(d - \frac{a}{2}) \tag{5.1}$$

where, Ts = As × fy and

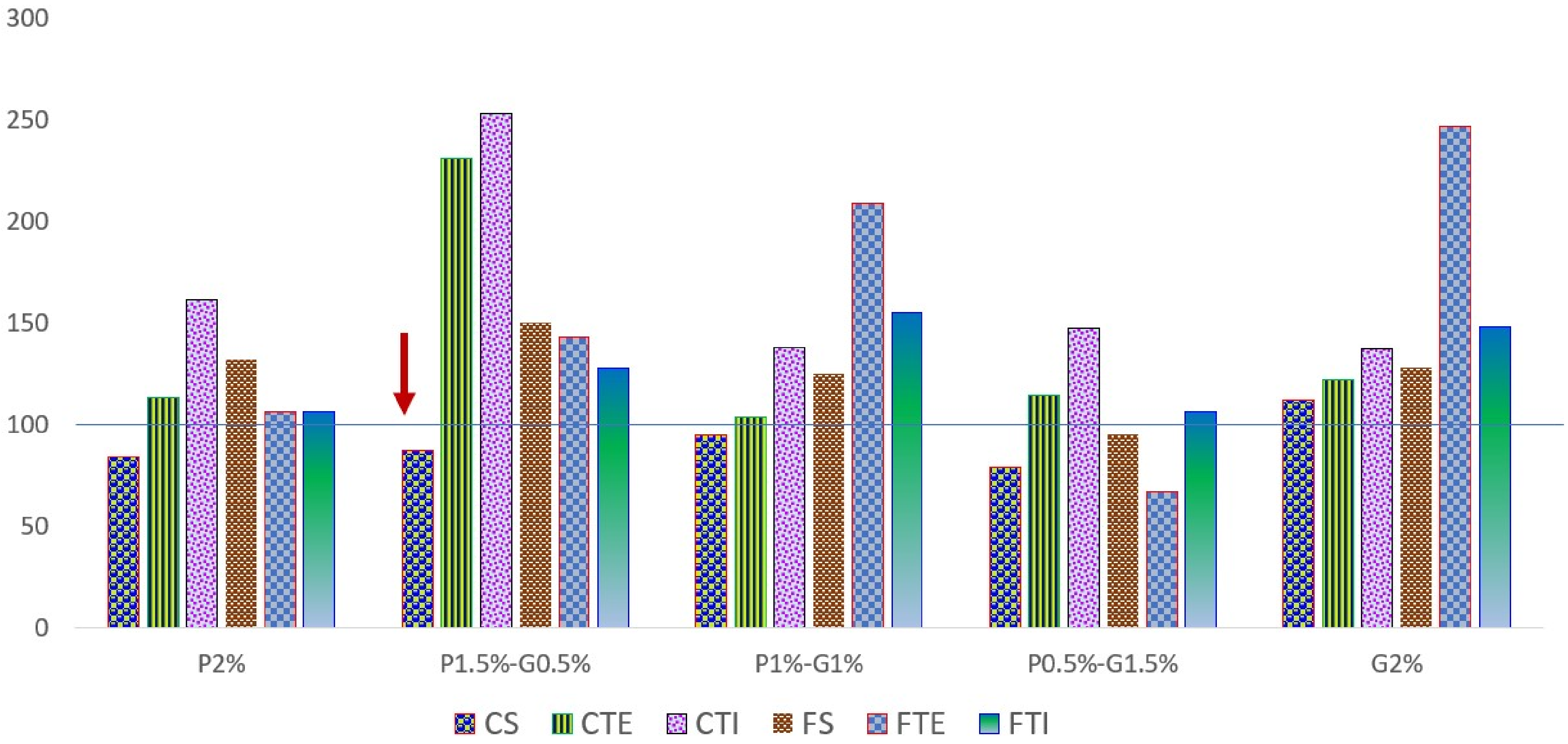

FIGURE 5.1: Optimization of Mix Design

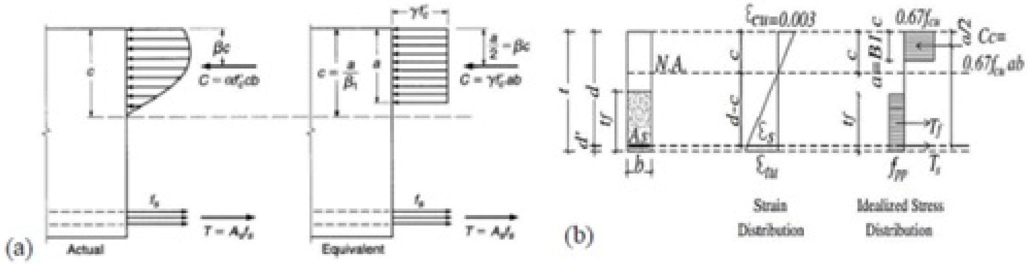

FIGURE 5.2: (a): Witney Stress Block
(b): Modified Block with Tensile Strength of Fibers

$$a = \frac{A_s F_y}{0.85 f_c' bd} \tag{5.2}$$

Beshara et.al [90] proposed the modified equation to calculate the moment capacity of fiber reinforced concrete as fiber adds to the tensile strength of concrete which was not incorporated in equ.5.1. Modified equation by Beshara et al.is as follows:

$$M_{fiber} = T_s \left[d - \frac{a}{2}\right] + T_{fiber} \left\{\left[t - \frac{t_f}{2}\right] - \frac{a}{2}\right\} \tag{5.3}$$

Here, the equation is similar to the Whitney stress distribution equation, but with an additional term to factor in the tensile strength of the fibers within the effective height of equivalent stress in the tensile region. This allows for the calculation of the tensile strength of the fibers in the equation.

$$T_f l = 1.64 V_f I_f \varphi_f b t_f \tag{5.4}$$

Where,

V_f = Volume of fibers in concrete
l_f = Fibers length and
φ_f = Fibers diameter.

The fundamental idea behind changing Nilson et al equation's for fiber-reinforced concrete is to better utilise the tension region of the concrete with the aid of dispersed fibers by a crack arresting mechanism [91]. However, Farooqi et.al [100] adjusted equation proposed by Beshara [90] in terms of Tf to determine the effective height of equivalent stress of fiber reinforced concrete in the tension area. For the purpose of determining the tensile strength of HFC Beshara et al. combined the volume, length, and diameter of the fibres. However, more straightforward technique is proposed by next author [100] to determine the tensile strength of fibers. The modified equation for moment capacity of fibers comes out to be:

$$M_{fiber} = T_s\left[d - \frac{a}{2}\right] + T_{fiber}\left\{\left[t - \frac{t_f}{2}\right] - \frac{a}{2}\right\} \tag{5.5}$$

Where

$$T_{fiber} = \left[\frac{MOR_{fiber} - MOR_{pc}}{2}\right] bt_f \tag{5.6}$$

The rationale behind the addition of the factored MOR of fibers with respect to PC is that cracks begin to form when the applied load exceeds the concrete's moment capacity. When the crack spreads up to the steel rebars, the dispersed fibres in HFC resists the propagation of initial crack. The crack's propagation is also delayed because of crack arresting by fibres. Hence, the load carrying capability of HFC is improved in this manner. Moreover, the tensile strength of fibres is added to the steel rebars to help resist cracks once they reach the steel reinforcement. Modified equation of Farooqi et.al [100] is further used by the author of this study to calculate the required area of steel in fiber reinforced concrete.

$$M_{fiber} = T_s\left[d - \frac{a}{2}\right] + T_{fiber}\left\{\left[t - \frac{t_f}{2}\right] - \frac{a}{2}\right\} \tag{5.7}$$

Putting value of $a = \frac{A_s F_y}{0.85 f_c' bd}$in eq. 5.3:

$$M_{fiber} = T_s\left[d - \frac{0.5 A_s F_y}{0.85 f_c' bd}\right] + \frac{MOR_{fiber} - MOR_{pc}}{2} bt_f \left\{\left[t - \frac{t_f}{2}\right] - \frac{0.5 A_s F_y}{0.85 f_c' bd}\right\} \tag{5.8}$$

5.4 Formulation of Approach

From equ. 5.5, it can be deduced that factor T_{fiber} is added for tensile strength of fibers and this factor will indicate the enhanced tensile strength of concrete due to fiber addition by increasing the nominal moment capacity of beams thus reduces the required area of steel. With the assumption that fibres increase the tensile strength of concrete by increasing the moment capacity of the beam which in turns reduces the area of steel, data of experimental study explained in Chapter

4 were utilised to calculate $T_{fiber}$and are listed in the table 5.2 below. Compressive strength and modulus of rupture values from all five batches are used for fibre reinforced concrete beams. Graphical data are obtained to select the optimized mix design and parameters studied for the selection of optimized mix design are compressive strength of respective batch and their modulus of rupture.

Table 5.2: Parameter Considered for Fiber Reinforced Concrete beams

Specimens	**MOR (MPa)**	**Fc'(MPa)**
PC	3.1694	19.19
P2%	3.8193	16.26
P1.5%-G0.5%	4.3356	16.74
P1%-G1%	3.6190	18.24
P0.5%-G1.5%	2.7434	15.31
G2%	3.7055	21.68

According to the graph, the MOR and T_{fiber} for mix design P1.5%-G0.5% is highest. That is why for further calculations, mix design P1.5%-G0.5% is considered as optimized.

5.5 Validation Studies

The governing equilibrium equation 5.8 is rearranged in order to create the equation for the area of steel for hybrid fibers reinforced sections, and the quadratic equation is then obtained for the area of steel of concrete beams with fibre addition. The nominal moments of numerous CC beams are collected from the literature together with their compressive strengths, yield strength of the steel utilised, dimensions, and area of steel using the suggested method and the results of 21 beams are compared with the optimized beam data.The relation shown in equation 5.9 below is used to calculate modulus of rupture of beams where not provided.

$$F_r = 0.633\sqrt{f_c} \tag{5.9}$$

Data covers a broad spectrum of non fibrous beams including variations in concrete strength (34 $\leq$ fc' $\leq$ 90 MPa), steel yield stress (360 $\leq$ f y $\leq$ 437 MPa), tensile steel area (25 $\leq$ As $\leq$ 628 mm2), compression steel area (0 $\leq$ $As \leq$

100$mm2), beamwidths($110$\leq$ b $\leq$ 250 mm), beam depth (100 $\leq$ to $\leq$ 300 mm). Moreover, Table ?? shows that the required area of steel is reduced for fibrous beams with the increase of flexural strength of concrete. The study of the results listed in the table showed that nominal moment capacity of HFC beams have reduced area of steel as compared to beams without fibers.By closely examining the data, it is divided into different categories and represented with different colors. While considering this investigation, it is essential to understand that when a higher MOR is indicated, a bigger difference in MOR is also indicated due to the data being compared with the optimized MOR of hybrid fiber reinforced concrete. In this study, the MOR of the fiber is kept constant. Therefore, when increased MOR is referred to, it is actually referring to reduced difference in MOR which refers to the smaller value of T_{fiber}. If the top three beams A,B,C are analyzed, it can be seen that they share similar cross sections and compressive strengths of concrete, but MOR of concrete is varying which affects the Tf of fibers, differs significantly. The other parameter, Fy, exhibits minimal variations among the three beams. As the T_{fiber} of beams a and b increases, the area of steel required also decreases. When T_{fiber} is 5.548, there is a 10% reduction in steel, and when T_{fiber} is 6.86, the reduction increases to 13.73%. In the case of beam C, the trend and hypothesis generated show that as T_{fiber} increases, the % reduction steel should also increase. However, when T_{fiber} reaches 12.424, the steel reduction decreased to 7.9%. This can be attributed to the increased moment and the larger area of steel than required to check effects of steel ratios. Therefore, it could be related to the steel ratio, such as min, bal, and max. If the data of beams D and E is studied, it can be seen that both beams have the same cross-sections, the same concrete strength and a similar yield strength of steel. Furthermore, with an increase in the T_{fiber} factor, the reduction in % steel does not increase. This is due to the area of steel kept to study behaviors of beams; one beam with the same parameters having an area of steel of 1.95 in2 resulted in a 6% reduction, while the other beam with an area of steel of 2.5 in2 had a reduction of only 4%.This is again linked with steel ratios. If beam F and G are observed, the cross section, compressive strength and Modulus of Rupture of concrete remains the same but the yield strength of steel varies. A decrease in the yield strength of steel results in a reduction of 1.8% when Fy is 72 ksi and 3.4% when Fy is 68 ksi. Comparing beams H and I to beams F and G, the data regarding cross-sections, fc' and fy are the same. The only difference is the Modulus of rupture which is the same within the group but different from the above mentioned group.. This shows how fy and MoR affect the area of steel. As the MoR is lower in comparison to the group above, increasing the T_{fiber} factor, the percentage reduction of 1.8% increased to 2.35%, while it increased from 3.4% to 4.35%. Examining the trend within the group, it is evident that with increased T_{fiber},reduction in steel is also increasing. When beams j and k are taken into account, they have the same parameters as the group containing beams f, g and h, I, except for Fy. Additionally, the MOR of concrete for these beams is different from the other two groups. The results for beams F,G,H,I,J,K shows that when MOR of concrete is 0.711 ksi, the T_{fiber} reduction is 1.8%. When the MoR is reduced to 0.67 ksi, the T_{fiber} increases and the % reduction of steel also increases to 2.35%. Lastly, when the MoR is reduced to 0.552 ksi, the T_{fiber} increases and the% reduction of steel increases to 4.3%. When fy is 68 ksi, with MoR of 0.711 ksi, a 3.4% reduction in steel is observed. If the MoR is decreased to 0.67 ksi, then the T_{fiber} increases, resulting in a 4.35% reduction in steel. If the MoR is further decreased to 0.552 ksi, the T_{fiber} again increases and the % reduction in steel is approximately 7%. If a comparison is made within the group, it is observed that increased fy, causes less steel reduction, whereas a reduced fy gives more steel reduction. For beams L and M, the cross-sectional area and compressive strength of the concrete are the same, as are the yield strength and MoR. The only difference is in the area of the steel, which is related to the steel ratio. As the area of steel increases, the percentage reduction also increases, while reducing the steel area reduces the percentage reduction in steel. When comparing beams N and O, it is evident that an increase in Fc' has caused a decrease in the percentage of steel reduction. Furthermore, there has been a decrease in the difference of MoR, leading to a decrease in T_{fiber}. This has resulted in a decrease from 30% to 2% steel reduction when considering min, and from 50% to 23% when considering bal. This data indicates that MoR and T_{fiber} are more influential than Fc' in reducing the percentage of steel. Taking into account beams P and Q, it is evident that the increase in MOR of the fibers is causing an increase in T_{fiber}, which consequently leads to a decrease in fc' and a rise in the reduction in the area of steel. The role of T_{fiber} is significant in this relationship, while Fy and fc' also play a role. However, further research is necessary to make any more specific predictions, thus more data should be collected and experiments should be conducted.

5.6 Discussion

Fibers increases the tensile strength of concrete which in turn increases the moment capacity as well [27]. To account for the higher moment capacity, the required area of steel in HFC may be lowered, but not below than p_{min} as compared to reinforced concrete without fibers [27], [96], [105]. Yet, the cracking pattern and post-cracking behavior of reinforced concrete beams are both affected by fiber addition, resulting in a robust composite with high resistance to cracking, enhanced ductility and unique post-cracking behavior before failure [100]. Its primary function is to bridge over cracks in FRC giving post cracking ductility, which in turn controls the cracking of FRC and modifies the behavior of the material after the matrix has fractured. The investigation of the structural capacity of concrete cross sections following fiber addition requires experimental verification. Addition of fibers alters the effective stress area in tensile region. According to Bashara's equation [92], the additional factor added in moment capacity of cross-section is to add up the additional tensile strength due to addition of fibers by adding effective height of equivalent stress due to tensile strength of fibers. Furthermore, tensile strength of fibers is modified by using different approach of incorporating factored MOR as expressed in eq. (5.8). The logic behind the addition of factored MOR difference of fibers with respect to PC is that, when the applied load exceeds the moment capacity of concrete, the cracks start to appear. The crack resistance comes into existence when the crack is propagated up to the steel rebars. However, in case of fiber reinforced concrete, the presence of fibers resists the formation of first crack [10]. In addition to the formation of first crack, the crack propagation phenomenon is also delayed due to the arresting of cracks by fibers. So, in this way, the load carrying capacity of fiber reinforced concrete is increased which in turns can reduce the required area of steel in fiber reinforced concrete as compared to concrete without fibers. Furthermore, eq. (5.8) is used to calculate the area

Table 5.3: Considered Data of beams

Beam	L	W	D	d	M	fc'	fy	MoR (conc)	MoR (fiber)	fc' (fiber)	Tf	Reduced Steel	Actual Steel	Reduction
	in	in	in	in	kip-in	ksi	ksi	ksi	ksi	ksi		in2	in2	%
A	59	7.87	11.81	10.08	271.79	9.52	57.72	0.67	0.91	2.41	5.55	0.43	0.48	10.12
B	59	7.87	11.81	10.47	247.16	9.66	58.27	0.61	0.91	2.41	6.86	0.36	0.41	13.73
C	59	7.87	11.81	10.16	812.87	9.59	54.17	0.38	0.91	2.41	12.42	1.46	1.58	7.91
D	59	7.87	11.81	9.84	1023	9.94	58.27	0.36	0.91	2.41	12.90	1.82	1.95	6.60
E	59	7.87	11.81	9.84	1121.49	9.94	53.5	0.46	0.91	2.41	10.40	2.24	2.36	4.86
F	76.7	4.72	7.874	6.37	259.59	9.02	72.5	0.71	0.91	2.41	1.84	0.61	0.62	1.87
G	76.7	4.72	7.874	6.37	143.91	9.02	68	0.71	0.91	2.41	1.84	0.34	0.35	3.45
H	76.7	4.72	7.874	6.37	51.6	9.02	53.2	0.71	0.91	2.41	1.84	0.14	0.16	9.76
I	76.7	4.72	7.874	6.37	256.64	8.16	72.5	0.68	0.91	2.41	2.17	0.61	0.62	2.31
J	76.7	4.72	7.874	6.37	143.09	8.16	68.	0.68	0.91	2.41	2.17	0.34	0.35	4.15
K	76.7	4.72	7.874	6.37	51.5	8.16	53.2	0.68	0.91	2.41	2.17	0.14	0.16	11.57
L	76.7	4.72	7.874	6.37	240.91	5.42	72.5	0.55	0.91	2.41	3.33	0.60	0.62	4.31
M	76.7	4.72	7.874	6.37	138.72	5.42	68	0.55	0.91	2.41	3.33	0.33	0.35	6.95
N	76.7	4.72	7.874	6.37	51.36	7.14	53.2	0.55	0.91	2.41	3.33	0.13	0.16	17.96
O	133	7.87	9.84	8.46	512.9	7.04	76.85	0.64	0.91	2.41	5.23	0.81	1.18	31.38
P	133	7.87	9.84	8.46	502.7	7.04	76.85	0.64	0.91	2.41	5.23	0.79	1.57	49.61
Q	133	7.87	9.84	8.46	707.26	11.38	76.85	0.81	0.91	2.41	1.87	1.15	1.18	2.26
R	133	7.87	9.84	8.46	732.48	11.38	76.85	0.81	0.91	2.41	1.87	1.20	1.57	23.66

[H] Note : L= Length, W=Width, D=Depth, d=Effective Depth, M=Moment

* Beams A-H [106], Beams I-P[97] , Beams Q-R[107]

of steel required which causes reduction in area of steel required as compared to "As" in plain concrete.

5.7 Summary

The data show that the largest reduction seen was 49.2%, while the least reduction was 1.5%. Since several types of beams were used to collect the data, no obvious trend regarding the pattern of steel reduction could be identified. Compressive strength, modulus of rupture, and design moment of each beam vary from one another, but it is obvious that the MOR value and the difference in MOR between plain concrete and fiber reinforced concrete beams plays a significant role. Experimental verification and validation is required in this area of research because fibers have high tensile strength and they can reduce steel significantly.

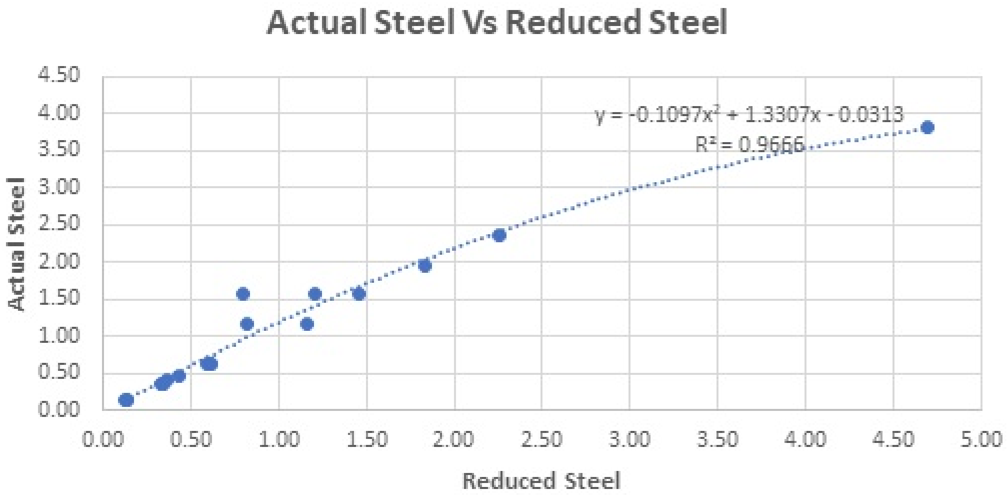

FIGURE 5.3: Beams Data Considered

Chapter 6

Conclusion and Future Work

6.1 Background

The overall aim of this research thesis is to provide the sustainable construction material in terms of economy, environment and performance. Combination of fibers are added to have improved and better mechanical performance and improved structural capacity. However, efforts have been done to investigate two correlated tasks. The identification of concrete flaws and possible remedial measures led towards the exploration of alternative economical construction material i.e., use of hybrid fibers. Pine needle is selected in case of natural fibers and glass fiber is selected in case of synthetic fibers to start with. The optimization in terms of fiber content and residual strengths and energy absorption is done to achieve sustainable mix design for concrete.

6.2 Conclusion

The conducted experimental study is aimed to investigate the mechanical and dynamic properties, as well as the structural capacity, of hybrid fiber reinforced concrete (HFC). The HFC used in this study contained a total fiber content of 2% by volume of wet concrete, with two types of fibers utilized, i.e., Pine needle fibers and Glass fibers. The amount of each type of fiber used ranged from 0.5% to 2%, with Pine needle fibers chemically treated with NaOH to enhance their properties. The mechanical properties that are evaluated in the study includes the strength, energy absorption, and toughness index of the HFC under compressive and flexural loadings. The dynamic properties, on the other hand, are measured in terms of poison's ratio, modulus of rigidity, and damping ratio. Lastly, the structural capacity of the HFC is evaluated in terms of the potential reduction in required steel for the optimized mix. Following conclusions are drawn:

- The results of the study shows that, compared to plain concrete (PC), the highest water absorption is observed in the P2% mix design, at a rate of 23%. Conversely, all the other mix designs showed lower rates of water absorption than the PC, with rates of 8%, 18%, and 22% observed in the P1.5%-G0.5%, P1%-G1%, and G2% mix designs, respectively. Furthermore, the G2% mix design exhibits the lowest rate of water absorption, at 25% less than the PC.

- The results of the study indicates that the G2% mix design of HFC has the highest compressive strength, 12% greater than PC. CTE is found to be highest in the P1.5%-G0.5% mix design, with a rate of 131% greater than the PC. Additionally, the P1.5%-G0.5% mix design shows a 150% increase in CTI compared to the PC. The study also found that GF at a volume of 0.5% showed the maximum post-cracking energy. However, using GF at a high percentage, greater than 1%, did not result in an enhancement in compressive strength in HFC, which is consistent with previous literature. On the other hand, the P2% mix design has the least compressive strength, at 16% lower than the PC. This can be attributed to the fact that natural fibers generally have less compressive strength than plain concrete.

- The study shows that compared to PC, the HFC mix designs exhibited increased flexural strength. Specifically, an increase of 20%, 36%, 14%, and 16% is observed for P2%, P1.5%-G0.5%, P1%-G1%, and G2%, respectively. The mix design P1%-G1% exhibits the highest toughness index, at 54%, while all other specimens also showed enhanced flexural strength compared to PC. The study suggests that the optimal percentage of GF used in the P1.5%-G0.5% mix design resulted in improved properties, leading to its high flexural strength and toughness index.

- The study also investigates the dynamic modulus and properties of both PC and HFC. The damping ratio for HFC is found to be higher than that of PC. The results indicates that the type and volume content of fibers have an effect on the dynamic values of the modulus of elasticity and the Poisson's ratio. The dynamic elastic modulus, dynamic rigidity modulus, and dynamic Poisson's ratio are found to be increased for HFC.
- The Scanning Electron Microscopy (SEM) analysis conducted in the study reveals the pull-out behavior of glass fibers, which can be attributed to their elongated length. The analysis also shows the balling effect of glass fibers, which is likely due to improper mixing of the fibers with the concrete. Additionally, slippage of the concrete is observed, which can be attributed to the smooth surface of the aggregates used in the mix.
- The EDX analysis conducted on the sample shows that the highest percentage of elements present are calcium, oxygen, and carbon. Carbon is found in significant amounts along with oxygen, indicating the presence of high percentages of carbohydrates such as cellulose, hemicellulose, and lignin.

6.3 Future Recommendations

The never-ending field of research can always be used to investigate a range of horizons. The same is true for this research thesis because there is still work to be done in order to produce sustainable and higher performing structures employing the readily accessible fibres as raw materials. With the aforementioned scenario in mind, the following suggestions for the future are made:

- It's important to assess the structural behaviour of HFC structures, notably the behaviour of the beams in real-world scenarios.
- The experimental confirmation of the theory developed for this study must be done first and foremost. It is important to investigate experimentally how hybrid fibres can have improved flexural strength.
- For sustainable development, a thorough investigation of the easily accessible natural fibres' durability should be done.

- In order to have more optimised mix designs across the board, pre-treatment approaches for natural fibres that aims to increase durability should also be further investigated.
- Investigating the possibilities for using various locally available natural and plant fibres as an alternative building material for civil engineering is also crucial for achieving sustainable development.
- A fascinating study would be to combine both natural and synthetic fibres, as well as natural and natural fibres for improved performance in concrete.

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