CAPITAL UNIVERSITY OF SCIENCE AND TECHNOLOGY, ISLAMABAD

Improving the Concrete Properties by Using Hybird Fibers for Rigid Pavement Applications

by

Abubakar Sattar

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This thesis is a tribute to:

My loving parents, whose unwavering love, encouragement, and sacrifices have been my guiding light. To my friends, for their constant support, laughter, and shared challenges, which made this journey memorable. And to my dedicated supervisor, whose wisdom, guidance, and belief in my abilities have been invaluable. This achievement is a testament to the collective strength of your influence on my life and academic journey. Thank you for being the pillars of my success.

CERTIFICATE OF APPROVAL

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Abstract

Concrete pavements are recommended for their long service life comparatively flexible pavements. Micro shrinkage cracks are tiny cracks that form on the surface of concrete in the early stages caused deterioration in rigid pavement. Both natural and synthetic fibers can resist the appearance of minor shrinkage cracks. By utilizing a combination of Hybrid Natural and Synthetic Fibers Reinforced Concrete (HNS-FRCs) significantly reducing the appearance of micro-cracks. Jute and glass fibers can enhance concrete performance in terms of energy absorption, while glass fibers have high tensile strength. The overall aim of this research to develop sustainable concrete to mitigate the development of macro-cracks that can enhance the performance of concrete pavements at a later stage. To the best of the author knowledge hybrid natural and synthetic fibers are rarely studied for such application.

The evaluation of destructive and non-destructive tests performed on HNS-FRC specimens. This study consists of 50mm length of jute fibers and 25mm of glass fibers but a varying percentage of fiber content in the concrete mix. The evaluation of microstructural analysis such as SEM and XRD have been performed to asses the bonding effect of fibers with concrete. The use of PCC as a reference specimen to assess the impact of jute and glass fibers on various concrete properties, including mechanical and dynamic properties of HNS-FRCs. The multiple HNS-FRC specimens labeled A1, A2, A3, A4, A5, and A6, with different fiber content ranging from 1% to 4% by mass of cement. The mix design ratio for both PC and HNS-FRCs is 1:2:3 ratio (cement: sand: aggregate) with water-cement ratio of 0.45. Furthermore, SEM and XRD were performed to observe microstructure analysis. This study's results demonstrate significant improvements in compressive energy absorption, splitting tensile strength, and flexural strength in HNS-FRCs specimens. Among the tested specimens, A2, A3, A4, A5, and A6 showed a reduction in cracks and overall enhancement in concrete performance. However, the incorporation of these fibers yielded quantifiable improvements in mechanical properties, such as an 8.5% increase in compressive strength and a 51% increase in MoR, with specimen A4 emerging as the most optimized mix among the considered mix designs. However, further research is essential to explore durability and support the commercial use of HNS-FRCs in the construction industry.

Keywords: Rigid Pavement Application, Glass Fiber, Jute Fibers, Sustainability, Hybrid Fiber Reinforcement, Environmental Issues, Fiber Reinforced Concrete.

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Abbreviations

CE1	Compressive Energy Before Failure
CE2	Compressive Energy After failure
CS	Compressive Strength
CTE	Compressive Total Energy
CTI	Compressive Toughness Energy
FE1	Flexural Energy Before Failure
FE2	Flexural Energy After Failure
FS	Flexural Strength
FTE	Flexural Total Energy
FTI	Flexural Toughness Index
GFRC	Glass Fiber Reinforced Concrete
GPa	Giga Pascal
HNS-FRC	Hybrid natural-synthetic fiber reinforced concrete
JFRC	Jute Fiber Reinforced Concrete
JGFRC1	Jute and Glass Fiber Reinforced Concrete
KN	Kilo-Newtons
mm	Milimeter
MOE	Modulus of Elasticity
MOR	Modulus of Rupture
MPa	Mega Pascal
OPC	Ordinary-Portland Cement
PCC	Portland Cement Concrete
RD	Modulus of Rigidity

RFL	Longitudnal Resonance Frequancy
RFR	Rotational Resonance Frequancy
RFT	Transverse Resonance Frequancy
SE1	Splitting Tensile Energy Before Failure
SE2	Splitting Tensile Energy After Failure
SEM	Scaning Electron Microscopy
So	Standard Error of Traffic Prediction
SP	Super-Plasticizers
STI	Splitting Tensile Toughness Index
STS	Splitting Tensile Strength
V%	Damping Ratio
WA	Water Absorption
W/C	Water Cement Ratio
Zr	Standard Deviation

Chapter 1

Introduction

1.1 Background

Rigid pavements are recommended over flexible pavements because of their better functionality and capacity to carry heavy loads. Because of their exceptional performance and ability to carry heavy load, rigid pavement surfaces are suggested as the preferred choice compared to flexible pavement. But so far, concerns like cracking caused due to heavy loading and environmental concerns reduce the performance of rigid pavement [1, 2]. Although concrete has several flaws, like low tensile strength, weak in tension, and brittle in nature. The researcher has endeavored to address these flaws effectively by utilizing various materials with partial substitution cement. One of these materials is fiber-reinforced concrete (FRC). It has become a promising material because of its superiority including energy absorption, tensile strength, durability, and toughness [3]. FRC is concrete having dispersed short discrete fibers, this makes FRC to be studied carefully taking into consideration the functionality of fiber within the mix. Improving the properties of concrete, like flexure, tensile, and compression can enhance the overall performance of concrete for the rigid pavement application [4, 5]. The tensile and flexural strength exhibit improvement in post crack energies [6].

Concrete has weak in tension due to low tensile strength, rigid pavements made of concrete sometimes caused cracking when subjected to heavy cyclic traffic loads flexural strength is a key feature. The use of fibers can enhance concrete's flexural strength and reduce the thickness of pavement [7, 8]. Flexural strength improves due to the addition of fibers and also enhance the tensile strength of concrete [9]. According to literature studies, the addition of fibers in concrete improve the crack resistance ability and toughness index reduce concrete's spalling rate [10, 11]. Natural fibers are being used in civil engineering applications, according to studies. There are very few studies on hybrid fibers for use in rigid pavement applications. Hybrid fibers can be utilized in construction, as illustrated by the literature. However, research is still needed to utilize it effectively in large-scale construction projects [12]. This will facilitate the cost-effective construction of rigid pavements, which is crucial for developing countries Thus, the utilization of fibers can enhance the properties of concrete and improve the structure's performance.

1.2 Research Motivation and Problem Statement

Pavements are a principal mode of transportation in any country. Construction of these pavements requires a huge amount of budget. The concrete pavements are constructed to reduce the cost of pavements but their repair cost is quite expensive. These issues are primarily brought on by early cracking, which leads to significant cracks and potholes later on. To overcome the damaging problems of rigid pavements, there is a need to adopt modern methods that help in improving the performance of rigid pavements. There is a need to enhance the performance of concrete to reduce the appearance of cracks and improve its suitability for use in rigid pavement effectively. Furthermore, the utilization of hybrid fibers improve the tensile strength of concrete, increasing its ability to withstand against cyclic loading in rigid pavement. So, the problem statement are as given:

Micro-cracks are a result of drying shrinkage and volumetric changes in the concrete mixture. These micro-cracks amalgamate and turned into major cracks under traffic loading. Increased tensile stresses as a result of this phenomenon are greater than concrete's tensile strength and ultimately potholes are formed on the surface of rigid pavements. If these types of micro-cracks are not addressed at their initial stage, that can cause structural failure.

1.3 Research Questions

1. What are the most frequently occurring rigid pavement flaws?
2. What would be the combined effect of glass fiber and jute fiber on the compressive strength of concrete?
3. How the varying percentages of natural and synthetic fibers will affect the pre and post-cracking behavior of concrete?
4. What is the effect of the hybrid fibers on the compressive toughness index, splitting tensile toughness index, and flexural toughness index?
5. How much splitting tensile and flexural strength can be enhanced in comparison to compromise with compressive strength after incorporation of natural and synthetic fibers?

1.4 Overall Objective of the Research Program and Specific Aim of this Research

The objective of this research program is to develop cost-effective and sustainable rigid pavements. This will be achieved by incorporating locally sourced natural and synthetic fibers that can serve as construction materials.

The specific aim of this MS thesis research program is to investigate the mechanical and dynamic properties of hybrid fiber-reinforced concrete for the possibility of rigid pavement applications.

1.5 Scope of Work and the Study Limitations

The mechanical and dynamic properties will be investigated by taking the average of three specimens for each combination of jute-glass hybrid fiber reinforced concrete (JGH-FRC). The dynamic properties will be studied before the investigation of mechanical properties. The specimen will be considered as a failure after the appearance of a fist crack due to load application. SEM and XRD will also be performed. Table 1.1 explains the detailed breakdown of samples that are utilized for further testing and also shows the investigated properties for these samples. According to the table, 54 samples are prepared in total, where 36 are cylinders and 18 are beams. This study focuses exclusively on assessing the mechanical properties, dynamic behavior, and water absorption capabilities of specimens composed of hybrid nat-ural and synthetic fibers (HNS-FRCs). HNS-FRCs durability is not covered by this project. A single combination of mix design, water cement ratio, and locally available fibers are considered.

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Table 1.1: Mix Design of PC and HNS-FRCs

			Mix Design				**Investigated Properties**			
Test	PC 1:2:3 w/c 0.45+SP 1.5%	Jf1% + Gf 4% +SP1.5%	Jf 2% + Gf 3% + SP1.5%	Jf 2.5% + Gf2.5% + SP1.5%	Jf3% + Gf2% + SP1.5%	Jf 4% + Gf1% + SP1.5%	Total No of Specimen	Mechanical Properties	Dynamic Properties	Micro Structural Analysis
Compression	3C	3C	3C	3C	3C	3C	18C	Properties of Loading	NDT	SEM, XRD
Splitting Tensile	3C	3C	3C	3C	3C	3C	18C	Properties of Loading	NDT	SEM, XRD
Flexural	3B	3B	3B	3B	3B	3B	18B	Properties of Loading	NDT	SEM, XRD

1.6 Rationale Behind Selected Variables

The combination of jute and glass fibers in Hybrid Natural and Synthetic Fibers Reinforced Concrete (HNS-FRCs), are preferred over independent fibers due to their balancing properties. Jute fibers offer enhanced energy absorption capabilities [140], while glass fibers contribute high tensile strength to the concrete mix [141]. The interaction between these natural and synthetic fibers leads to improved overall performance, addressing both micro shrinkage and macro-crack concerns in rigid pavements [142].

The combination allows for a more balanced and optimized concrete mix, showcasing superior mechanical properties compared to using independent fibers alone, making it a practical choice for enhancing con-crete durability and performance in construction applications. These fibers have been chosen based on availability superiority based on physical characteristics [8] in comparison to other fibers. The inclination towards Hybrid Natural and Syn-thetic Fibers Reinforced Concrete (HNS-FRCs), incorporating a blend of jute and glass fibers, instead of using independent fibers, stems from the balanced charac-teristics of the former. The 50 mm and 25 mm lengths of jute and glass fibers, respectively, have been used in this research.

The choice of different lengths of fibers in HNS-FRCs, is grounded in the aim to take advantage of the unique char-acteristics of each fiber type. Research indicates that varying fiber lengths can enhance the overall performance of the concrete matrix by optimizing the distri-bution and interaction of fibers within the mix [143, 155]. Shorter fibers like glass contribute to improving tensile strength [141], while longer fibers like jute aid in energy absorption and crack control [140]. This combination of lengths ensures a more comprehensive reinforcement effect, addressing multiple aspects of concrete behavior for increased performance and durability [156]. Various lengths help in good mixing [11] to achieve better-improved properties by bridging micro-cracks along with macro cracks [12].

1.7 Novelty of Work, Research Significance and Practical Implementations

Concrete is characterized by its brittleness, limited strain capacity, and modest toughness due to its inherent low tensile strength. This deficiency renders it susceptible to micro-cracking [11]. Notably, experimental investigations have indicated that the inclusion of natural fibers derived from agricultural waste into concrete matrices enhances its capacity to withstand impact loading [12]. Furthermore, the introduction of discrete, short fibers into concrete compositions has demonstrated the potential to augment its mechanical properties [13]. Prior scholarly inquiries have underscored the viability of enhancing concrete's attributes through the integration of natural fibers, thereby bolstering its structural efficacy. This study aims to contribute to the comprehension of hybridizing agricultural waste fibers of 50mm lengths. This utilization of agricultural waste fibers holds promise as ecologically sound construction materials, addressing both the ecological ramifications of concrete utilization and the adverse implications of improper agricultural waste disposal practices. Additionally, this research seeks to ameliorate concrete's intrinsic limitations through the integration of hybridized agricultural and synthetic fibers. It is noteworthy that there exists a paucity of research concerning the hybridization of jute fiber (JF) and glass fiber (GF) of diverse lengths, followed by their incorporation into concrete matrices. This study endeavors to bridge the research gap by elucidating the effects of divergent lengths of hybridized JF and GF mechanical, dynamic, and absorption properties. The anticipated outcome is the formulation of an improved construction material with applications in civil engineering and the broader construction industry.

Despite its structural deficiencies, including inadequate properties of concrete susceptibility to lateral loads, concrete also poses environmental concerns. Concurrently, the improper incineration or disposal of agricultural waste compounds environmental pollution. Notably, concrete compositions reinforced with natural fibers have exhibited superior attributes relative to PCC. The amalgamation of diverse natural fibers has yielded enhanced outcomes compared to singular fiber variations [14, 15].This Research initiative is to harness agricultural waste as sustainable construction components, thereby enhancing concrete's attributes, mitigating its drawbacks, optimizing rigid pavement performance, and enhancing safety considerations. This research builds upon prior investigations that yielded improved attributes for rigid pavements [10].

Prior research endeavors have primarily focused on hybridizing jute and glass fibers across varying proportions. However, the present study seeks to leverage the optimal fiber content combinations recommended by previous research, while simultaneously varying the fiber lengths. This investigation strives to advance the pragmatic utilization of agricultural waste materials to enhance the mechanical and dynamic attributes of concrete across diverse structural applications. Upon meticulous analysis of the findings, an array of jute-glass fiber-reinforced concrete (JG-FRC) formulations with distinct jute length combinations can be proposed. These recommendations will cater to specific attributes and applications pertinent to the construction industry. Nevertheless, the current research aims to utilize the recommended optimal combinations of fiber content from prior studies, all the while introducing variations in fiber lengths.

1.8 Brief Methodology

In this study are investigated the intrinsic mechanical, dynamic, and absorption attributes of two distinct concrete compositions: plain concrete (PC), the combination of jute and glass fibers. The investigation is conducted within a controlled laboratory environment. We incorporate glass and jute fibers to manufacture fiber-reinforced concrete (FRC) samples. The FRC preparation entails utilizing uniform jute fibers, each measuring 50mm in length, a parameter derived from relevant prior research [12–14]. In parallel, FRC specimens are created featuring glass fibers measuring 25mm in length. The FRC specimens encompass various fiber proportions 4% glass fibers combined with 1% jute fibers, 3% glass fibers combined with 2% jute fibers, 2.5% glass fibers combined with 2.5% jute fibers, 2% glass fibers combined with 3% jute fibers, and 1% glass fibers combined with 4% jute fibers. These proportions are determined in relation to the weight of cement for jute fibers, as advised by [10]. Notably, these fiber ratios align with those employed by other researchers [25, 28].

Throughout the mixing process, tap water at ambient temperature is used in the production for PC and all HNS-FRCs. The manufacturing process entails two distinct water-cement ratios. For plain concrete and FRC alike, a W/C of 0.45 is adopted. Additionally, super-plasticizers are introduced at a concentration of 1.5% to enhance workability and flow characteristics. The critical role of workability in determining the concrete's ultimate properties, as well as its ease of handling during placement and transport, is acknowledged [18]. Consequently, we evaluate the workability of fresh plain concrete and all FRC compositions through the implementation of the slump cone test.

In strict adherence to ASTM standards, a total of 54 specimens are meticulously cast, encompassing both plain concrete and FRC samples. Within each FRC combination, a set of three beamlets and six cylinders are meticulously cast. Among these, three cylinders undergo testing to assess compressive properties, while the remaining three employed to utilize the splitting tensile properties of both plain concrete and FRCs. Moreover, the flexural characteristics of each variant of FRC are examined using a three-point loading setup on the cast beamlet specimens. The mechanical assessment is ex-ecuted employing a servo-hydraulic testing machine, ensuring rigor and accuracy in the results. **Figure 1.1** shows that detailed methodology.

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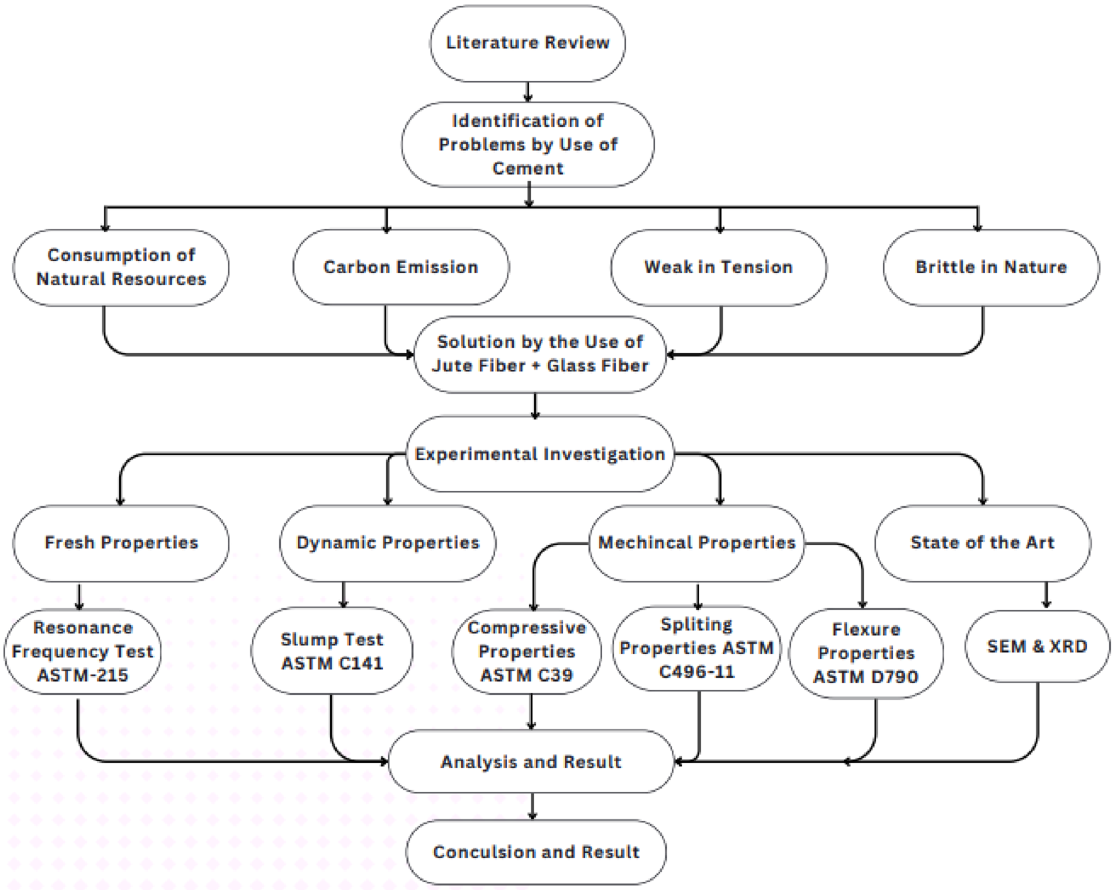

Figure 1.1: Adopted Methodology

Prior to conducting analyses on mechanical properties and various ancillary attributes such as linear shrinkage, mass loss, and water absorption, the initial focus of investigation is directed towards dynamic properties. This inquiry is facilitated through the utilization of an accelerometer in tandem with a hammer. The accelerometer is affixed to the specimens, and controlled hammer impacts are employed to elicit response frequencies along distinct orientations such as longitudinal (RFL), transverse (RFT), and torsional (RFR). Subsequent employment involves the leverage of these recorded frequencies to discern the dynamic characteristics inherent to both Portland cement Concrete (PCC) compositions and the complete spectrum of cast Jute and Glass Fiber Reinforced Concrete (JG-FRC) specimens. Thereafter, a meticulous examination is performed on the fractured surfaces of these specimens, aimed at scrutinizing several crucial aspects. These encompass the dispersion of short discrete fibers in the concrete matrix, the efficacy of fiber bonding with the encompassing matrix, instances of fiber pull-out phenomena, and occurrences of fiber rupture. These analyses encompass both jute and wheat straw hybrid fibers.

1.9 Thesis Outline

The outlines of this thesis consists of six chapters.

Chapter 1 Comprises a background that encompasses various components, such as providing context, elucidating the motivation of this research and problem statement, delineating both the overarching and research objectives, defining the scope of the study along with its limitations, outlining the research methodology, and presenting the structure of the thesis

Chapter 2 The document encompasses a literature review that covers various aspects, including the background information, shortcomings observed in rigid pavements, the main concrete attributes and impact on performance of pavement, factors related to durability of pavement and consideration for design perspective, the efficacy of incorporating fibers to enhance concrete properties, and a summarizing section

Chapter 3.Integrates the testing approach, encompassing aspects such as the background, raw materials, fiber treatment, the processes involved in mixing and casting PC and HNFRCs, specimen particulars, testing procedures, and a summary.

Chapter 4 Comprises the outcomes derived from examinations and their subsequent analysis. It provides an account of the context, material characteristics of the blends (such as PC and HNS-FRC), mechanical attributes (CS, SS, and FS), dynamic features, WA, and the conduct of the specimens during testing, along with a concise overview.

Chapter 5 Comprises a conversation covering topics such as the background, the optimization of different fiber percentages, the fiber content ratio's role in controlling concrete cracking in rigid pavements, the bond mechanism between fibers and concrete mixes, practical implementation, and a summary.

Chapter 6 Concludes with recommendations for future actions, and it includes a list of references.

Chapter 2

Literature Review

2.1 Background

Concrete pavements often tend to high attention in comparison to flexible pavements owing to their heavy load-bearing capacity and better serviceability. However, these pavements have substantial serviceability challenges, with cracking being a predominant issue. The appearance of cracking significantly reduce the efficiency of rigid pavements. Addressing these issues, the approach to enhance and improve basic mechanical properties including resistance to compressive strength, resistance to tension, and resistance to bending. A viable avenue for achieving this enhancement involves strategically defining fibers as additives within concrete matrices. Additionally, this fiber incorporation augments the dynamic properties of concrete, with increased resistance against vibration effects. The imperative to harness natural fibers as construction materials has gained attention due to their cost-effectiveness, environmental-friendly, and local availability. The trend of utilization of natural waste such as jute and glass fibers, both of which are locally available by-products taken from various agriculture waste materials. These properties make them particularly utilized in Asian countries where their accessibility is easily available. While prior research has been explored across a field of civil engineering applications, comprehensive research of the mechanical, dynamic behavior of JG-FRCs remains pivotal for their practical incorporation in rigid pavements. To the best of author knowledge, comprehensive investigations encompassing the content of jute and glass fibers in JG-FRCs have not yet been explored.

2.2 Flaws in Concrete

2.2.1 Issues in Material properties of Concrete

Cement is experiencing a continuous surge in usage due to the readily available raw materials, driven by the demands of the construction industry. However, the growth of this industry comes at a significantly contributes to the emission of carbon dioxide (CO_2), a greenhouse gas that has a severe impact on our environment [129]. The released of CO_2 emission directly contributes to greenhouse gases, global warming, and ozone layer depletion. These consequences has a substantial threats to human health and environmental stability [130]. Concrete, a widely employed construction material, possesses inherent brittleness with low strain capacity. The susceptibility of the material to micro-cracking, by its reduced tensile strength, makes it less resilient and durable over time. Remarkably, the volume of carbon dioxide (CO_2) emissions resulting from concrete production approximately generated during cement manufacture process. Notably, this process demands a substantial energy input, further compounding its adverse environmental impact [131]. Despite its widespread use, concrete, characterized by abundant constituent elements and diverse applications, remains burdened by certain shortcomings. Its brittleness and compromised strain capacity, in conjunction with low toughness, its susceptibility to abrupt failures. Compounding this is its low tensile strength, giving rise to minor cracks even in the initial stages due to external loading. **Figure 2.1 a**, illustrating the mechanism of cracking in rigid pavements or slabs [132]. The concrete pavements has significant growth in developed countries from last few decades [1–3]. Concrete pavements, in addition, exhibit robust structural durability. However, the extensive uptake of rigid pavement continues to be impeded by the substantial costs associated with its construction [4, 5]. Plain concrete, prioritized by its inherent brittleness, exhibit limited strain capacity and notable tensile strength. Consequently, rigid pavements frequently encounter fatigue failure due to their vulnerability to environmental conditions [6–8]. This vulnerability arises due to the complex factors such as temperature curling, drying shrinkage, volumetric changes, and temperature gradients [9]. Despite their the advantages of rigid pavements are not exempt from limitations. Instances where the water-cement ratio of concrete falls below 0.40 lead to insufficient water content for the comprehensive hydration of concrete particles [10–12]. Consequently, inadequate hydration arise shrinkage phenomena, Subsequently, this amplifies the likelihood of concrete cracking. **Figure 2.1** visually represents noticed fractures within the solid concrete roadway surface [13, 14]. Concrete structures, particularly rigid pavements, are vulnerable to various damaging effects throughout their operational lifespan [5, 15–17]. These effects necessitate subsequent measures for repair and maintenance. Micro-cracks often emerge even before structural loads are applied, resulting from volumetric changes caused by the drying shrinkage mechanism [18, 19].

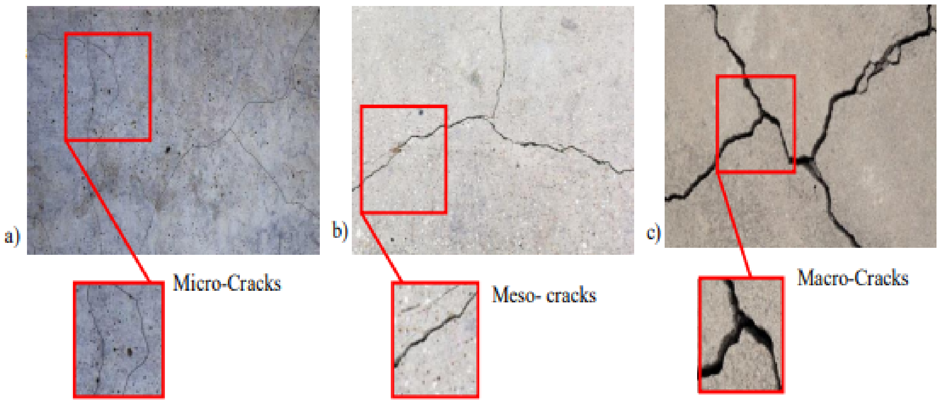

Figure 2.1: Cracks in Rigid pavement; a) tiny cracks, b) intermediate cracks, c) large cracks. [13, 14]

The variations in volume result from moisture evaporation on the concrete surface. This challenge becomes particularly significant in structures exposed to external conditions, further intensifying the potential for gradual structural degradation. [20, 21]. This issue becomes more critical in regions with change in environmental conditions, as these conditions can lead to higher tensile stress that exceeds the tensile strength of concrete. Addressing such structural deterioration requires significant investments in terms of both time and resources for corrective actions [22–24]. Despite efforts to restore the structure, it remains vulnerable to severe problems due to inconsistencies in the shrinkage behavior between the repaired material and the underlying concrete. This phenomenon of shrinkage cracks leads to increased stress within the repaired material, ultimately causing detachment from the structural concrete matrix [25–27]. Micro-cracks within structures can give rise to structural issues. The robust pave-ments are to impede the propagation of these cracks [27, 28, 30]. These cracks emerge as a result of both substantial loads exerted on the pavements and en-vironmental influences. The inherent strength of the concrete employed in the pavements holds significant importance, as it contributes to the durability of the pavements under heavy loads [31, 32]. There is a growing trend in the incor-poration of synthetic and natural fibers into rigid pavements. The utilization of these fibers in concrete enhance the tensile strength of concrete and resist minor shrinkage cracks [33, 34]. The integration of FRC is increasingly being adopted to improve the ability of the rigid pavements [35]. These composites blend concrete and fibers substantially enhance mechanical properties, fatigue resistance, impact load resistance, and resistance to shrinkage cracks [36, 37].

Fiber-reinforced concrete offers a distinct edge over conventional concrete, and enhance toughness and energy absorption capacities [38]. This superiority becomes particularly evident during assessments of split tensile and flexural strength, where the composite containing fiber-reinforced concrete exhibits high tensile strength as compared to plain concrete [39–41]. Concrete formulations emerge as a pivotal strategy to improve their structural integrity and enhance resistance against shrinkage cracks [42, 43]. This advantage assumes particular significance within the realm of rigid pavements. The engineering properties of concrete experience substantial enhancement through the integration of fibers, with the customization of these improvements by parameters depending on fiber type, quantity, orientation, geometry, and distribution [44, 45]. JG-FRCs composites assume a central role in retarding the initiation of corrosion processes. This is attributed to their crack resistance capabilities, and reduction in minor shrinkage cracks appearance [46–48].

2.2.2 Governing Properties of Concrete for Pavement Applications

Over time, the evolution of a micro-crack within concrete into a macro crack is a phenomenon well-recognized. The enduring implications of cracking on concrete's material properties and structural functionality persist irrespective of the scale of the crack [61]. Consequently, the progressive propagation of cracks inherent strength of the concrete. It is important to note that concrete's intrinsic properties exert a pivotal influence on the initiation and progression of structural cracking. Furthermore, the interplay of these concrete properties significantly molds various aspects of concrete structure design. Given concrete's inherent susceptibility to tensile strength and its robustness under compressive loads, the strategic emphasis on flexural strength gains paramount importance to ensure superior structural performance, particularly in the context of rigid pavements [63]. The of compressive, splitting-tensile, and flexural properties forms the bedrock of rigid pavement performance evaluation. The splitting-tensile property emerges as the foremost determinant governing concrete's crack formation [64].

The comprehensive assessment of concrete structural cracking relies on the two fundamental attributes of the material: tensile strength and tensile strain capacity. The latter quantifies the extent to which a concrete structure can endure tensile deformation without instigating the formation of cracks. An alternative solution that enhances the efficacy of cracking evaluation involves the utilization of tensile strain as a primary parameter, as opposed to relying solely on tensile strength [72]. This approach unveils the forces at play through volumetric deformations. Significantly, a correlation exists between the concrete structure's capacity to bear tensile loads and the resulting crack width under specific loading conditions. The quantification of concrete's tensile strain capacity on the modulus of rupture, a technique initially embraced by engineers to gauge the material's resilience against tensile strain. This approach entails the direct measurement of strains on the external surfaces of tensioned test specimens [71]. This method involves directly measuring the strains on the outer surfaces of tensioned test samples.

During the initial 24 hours following the placement of concrete, micro-cracks emerge on its surface. Within this timeframe, the concrete mix displays heightened susceptibility to cracking. At this stage, the concrete lacks the requisite strength to counteract stresses induced by shrinkage. The incorporation of supplementary cementitious materials (SCMs) into the concrete mix may potentially exacerbate the shrinkage phenomenon [112]. The liquid intake capability of cement is hastened by the process of hydration and the reactions involving pozzolanic materials, resulting in constrained moisture infiltration in uncracked concrete compared to its cracked counterpart of significant import to reinforced concrete structures is the quantification of crack width. This parameter exhibits a close correlation with the structural durability of the element. The width of a crack is contingent upon the concrete's tensile load-bearing capacity under specific loading conditions [113]. Both crack width and the structural characteristics of pores contribute to the assessment of structural durability.In hostile ecological conditions, the strengthening metal experiences decay and rust because of the existence of fissures within the cement framework [81]. In scenarios involving damaged, unsupported concrete structures [71, 114].

2.2.3 Possible Remedial Measures

Fiber-reinforced concrete imparts a distinct advantage over conventional concrete by significantly enhancing toughness and energy absorption capacities, as highlighted in reference [38]. This superiority becomes particularly pronounced when evaluating split tensile and flexural strength [133]. In this context, the composite incorporating fiber-reinforced concrete demonstrates notably higher tensile strength when compared to plain concrete. To elevate structural integrity and resistance against shrinkage cracks, a pivotal strategy emerges through the incorporation of a hybrid mixture of jute and glass strands into concrete formulations

[134]. Particularly in the realm of rigid pavements, this strategic integration assumes paramount significance [135].
Engineering properties of concrete undergo substantial augmentation through the synergistic amalgamation of both jute and glass fibers. The customization of these enhancements hinges upon various parameters, including fiber type, quantity, orientation, geometry, and distribution [135]. In this regard, steel fibers bring their remarkable reinforcing effects to bear, contributing to enhanced tensile strength and crack resistance [136]. Similarly, the inclusion of polypropylene fibers instills superior toughness and mitigates the development of minor shrinkage cracks [137]. Polyester fibers, on the other hand, offer the distinctive capability of further improving fatigue resistance and durability, especially within rigid pavement applications [138].

Nylon fiber play a pivotal augmenting the performance of FRCs for rigid pavements [139]. Their incorporation contributes to improved impact resistance and overall load-bearing capacity. Furthermore, the introduction of JG-FRCs stands out as a central strategy for retarding the onset of corrosion processes [49]. This notable benefit can be attributed to their exceptional crack resistance capabilities, effectively reducing the occurrence of minor shrinkage cracks, as detailed in references [46–48]. The utilization of numerous varieties of fibers, encompassing steel, polypropylene, polyester, and nylon, in the formulation of FRCs holds tremendous potential for enhancing the performance of rigid pavements. By harnessing the distinct attributes of these fibers, such as enhanced tensile strength, crack resistance, and durability, engineers can significantly improve the structural integrity and longevity of pavements, ensuring their resilience against various forms of stress and deterioration over time [136–140].

The integration of jute, and glass fibers into concrete has gained attention as a strategic approach towards sustainable development. This method involves the utilization of JG-FRCs to enhance the capacity of rigid pavements to withstand against both dynamic and static loading conditions [49–51]. The primary aim is to establish a bridging mechanism within the concrete matrix, thereby augmenting its crack-resistance capabilities [52, 53]. Although the application of these fiber-reinforced concretes (JG-FRCs) has shown promise in enhancing rigid pavement performance [54]. Combining synthetic and natural fibers, however, has demonstrated effectiveness in mitigating environmental pollution due to concrete matrices. This approach serves to enhance the tensile strength of rigid pavements [55–57]. To enhance the inherent toughness of concrete, while using dispersed fibers plays a pivotal role by creating a bridging effect that significantly contributes to crack resistance [58]. The integration of fibrous materials, within concrete alongside thoughtfully chosen supplementary enhancements, possesses the capacity to improve characteristics of structure. [59]. The intentional incorporation of jute fibers (J-FRC) and glass fibers (G-FRC) into concrete presents a promising strategy for both repurposing waste materials and generating environmentally-friendly, cost-effective construction elements [60, 61]. These elements effectively mitigate the occurrence of minor shrinkage cracks in rigid pavements. The strategic introduction of fibers, particularly hybrid fibers with uniform lengths such as the combination of glass and jute fibers (JG-FRCs), has demonstrated enhancement of cementitious composites [62, 63]. Contemporary civil engineering practices prioritize sustainability in construction methodologies. Over the last decades, numerous people have diligently pursued methodologies to reduce cement consumption in concrete formulations without compromising the material's inherent structural strength parameters.

The judicious integration of waste materials, both from industrial and agricultural sources, into concrete formulations represents a noteworthy advancement towards sustainable development objectives [64]. This integration is particularly focused on enhancing early-age concrete strength and mitigating the occurrence of minor shrinkage cracks in rigid pavements [65]. Due to concrete's intrinsic susceptibility to low tensile strength, the incorporation of reinforcing constituents becomes imperative to bolster its overall structural performance [66]. The assessment of cracks in rigid pavement systems is intricately linked to the strength capacity of concrete [67]. Tensile strain capacity denotes the magnitude to which a concrete rigid pavement can endure tensile deformation [68]. Consideration of tensile strain is imperative in conjunction with tensile strength when scrutinizing the crack initiation process, as the former parameter more precisely elucidates the stresses induced by fluctuations [69].

2.3 Fiber Reinforced Concrete

In the contemporary era, the paramount consideration revolves around sustainable development. Each stride taken towards achieving the paramount goal of sustainable development carries distinct significance. Within this global endeavor to attain sustainable solutions, the primary parameter lies in waste , a pivotal factor contributing to the overarching issue of global warming. Presently, the focal point rests upon reusing and recycling, engrossing the attention of individuals in tackling issues pertinent to the environment [56–59]. Over the past few years, a remarkable surge in interest has emerged concerning the utilization of both natural and synthetic fibers in cement composites, as a means to procure alternative sustainable and ecologically-friendly construction materials [35]. Both natural and synthetic fibers hold substantial potential for serving as reinforcement elements, mitigating the traditional weaknesses observed in concrete structures. By integrating agricultural waste-derived natural fibers and commercially manufactured synthetic fibers, brittle cementitious composites can be fortified to enhance capabilities [60]. Numerous researchers have explored the application of these fibers in various contexts, considering them as viable alternatives.

The array of natural and synthetic fibers harnessed in cementitious composites includes but is not limited to bamboo, banana, vakka, palm, jute, hibiscus cannabinus, abaca leaf, sisal, coir, date, malva, pineapple leaf, as well as glass, nylon, polypropylene, and steel fibers [56–59, 136–140]. Natural fibers offer cost-effectiveness and abundant local availability in numerous nations, while synthetic fibers are commercially accessible. These fibers can be instrumental in enhancing the properties of cementitious composites, constituting a renewable and economical construction material [101]. Beyond their affordability and availability, these fibers are easy to handle both superior outcomes, as corroborated by [111]. Moreover, their application can actively contribute to sustainable development due to their economical nature and possession of desired attributes that render them compatible with cement composites [62]. In the realm of rigid pavement applications, the integration of specific materials steel fibers, polypropylene fibers, polyester fibers, and nylon fibers merits elaboration [136–138]. Steel fibers, renowned for their exceptional strength and durability, can be effectively incorporated into cement composites for rigid pavements. These fibers reinforce the concrete matrix, augmenting its load-bearing capacity and crack resistance. Similarly, polypropylene fibers, characterized by their inherent flexibility and resistance to chemical degradation, a pivotal to improving the toughness and durability of rigid pavements [1]. These fibers enhance the concrete structure, increasing its ability to bear loads and resist cracks. Likewise, polypropylene fibers, play a crucial role in enhancing the toughness and longevity of rigid pavements.

2.3.1 Steel/Artificial Fiber Reinforced Concrete

Within the realm of civil engineering, the utilization of advanced materials and techniques has brought about a profound revolution in the construction of transportation infrastructure [141]. An integral element of road networks, rigid pavements necessitate robust solutions that can effectively withstand the formidable forces imposed by heavy traffic loads, temperature fluctuations, and other dynamic impacts. A pioneering and ingenious approach in this regard entails the incorporation of fibers in the concrete mix, thereby elevating the performance and longevity of rigid pavements to unprecedented levels [142]. The assimilation of steel fibers within the concrete composition for rigid pavements engenders remarkable enhancements in structural integrity [143]. These minuscule reinforcements of steel seamlessly disperse throughout the concrete matrix, functioning as diminutive yet robust load-bearing components [126]. This even dispersion serves to effectively counteract the propagation of cracks, thereby elevating the pavement's resilience against fatigue and dynamic loading. As a result, the pavement system is capable of enduring substantial vehicular loads without succumbing to premature deterioration[144].

The challenge of cracking in rigid pavements persists as a significant concern, with the potential to undermine both their lifespan and functionality [145]. Herein, steel fibers play an instrumental role in mitigating cracking and fracture due to their exceptionally high tensile strength. Under the influence of imposed loads, the steel fibers intricately distribute stress and strain in a more uniform manner, thus inhibiting the inception and progression of cracks. This not only elongates the service life of the pavement but also diminishes the necessity for frequent maintenance and reparative interventions [146]. Rigid pavements frequently confront dynamic forces stemming from heavy vehicular traffic and impact loads. In this context, steel fibers assume the role of reinforcement agents, profoundly augmenting the pavement's capacity to withstand impacts and distribute loads effectively. These fibers adeptly disperse and transmit the energy arising from impact loads, thereby mitigating the concentration of stress in localized areas. Consequently, the pavement retains its resilience even under demanding traffic conditions, thereby diminishing the likelihood of surface deterioration and distress [147]. Rigid pavements have consistently served as foundational components of transportation infrastructure due to their exceptional strength and high load-bearing capacity. However, the escalating demands placed on these pavements have driven the exploration of innovative strategies to further enhance their performance [82, 83]. One such promising approach involves the deliberate incorporation of glass fibers into the concrete matrix utilized during rigid pavement construction. The utilization of glass fibers to reinforce concrete's structural integrity is not a novel concept [73]. Originating as early as 1931, glass fibers have been systematically employed to augment concrete's mechanical properties. This process intricately involves the intertwining of multiple individual glass filaments, meticulously pro-duced by drawing molten glass through specialized pores [84]. The outcome is a composite material characterized by exceptional mechanical attributes. The incorporation of glass fibers into rigid pavements offers a multitude of advan-tages. Chief among these concrete, particularly crucial within pavements subjected to heavy vehicular loads [85]. This heightened strength mitigates the propensity for cracking and structural deterioration, thereby operational of the pavement for frequent maintenance [86]. Moreover, the domain of glass fiber-reinforced concrete (GFC) presents an intriguing avenue for advancing rigid pavement performance. GFC exhibits heightened resilience and reduced density when compared to conventional concrete formulations [77]. For a comprehensive representation of glass fiber attributes **Table 2.2**.

TABLE 2.1: Fresh & Mechanical Properties of Glass Fiber Reinforced Concrete

References	**Glass Fibers**	**Compressive Strength (MPa)**	**Flexural Strength (MPa)**
Kizilkanat et al.[41]	0%	63	5
	0.25%	62	6.5
	0.50%	62	6.5
	0.75%	67	6
	0.25%	64	6.3
Asokan et al.,[42]	0%	54.8	-
	5%	66.17	-
	15%	59.77	-
Kumar et al.,[81]	0%	39.85	3.02
	0.5%	34.07	3.76
	1%	41.63	6.63
	1.5%	36	6.48

These attributes hold paramount significance within the realm of rigid pavements. GFC's ability to withstand temperature fluctuations, resist corrosion, and effectively manage solar radiation positions it as an astute choice for enduring the adverse environmental conditions inherent to road networks. A comprehensive assessment of the economic implications of integrating glass fibers into rigid pavements reveals a nuanced perspective [87]. While the initial costs associated with adopting GFC may experience a marginal increment, the prolonged service life and diminished requirement for ongoing maintenance translate into substantial cost savings over the long term. Additionally, GFC's minimal water absorption and fortified durability collectively confer heightened resistance against environmental degradation, thereby substantiating its sustained functionality over extended periods [88]. The compilation of research, illustrated through the work conducted by Khan and Ali [40], seeks to elucidate the latent advantages presented by the incorporation of glass fiber reinforcement within pavement frameworks. Their findings underscore augmented resistance against fissures and heightened flexural strength. These attributes synergistically enhance a pavement's load-bearing capacity, concurrently impeding the onset of micro-cracks [89]. This dynamic equilibrium significantly amplifies the overall robustness of the pavement structure. The integration of glass fibers into rigid pavements introduces a wealth of potential aimed at elevating their performance [90]. This strategic trajectory seamlessly aligns with multifaceted considerations encompassing structural integrity, environmental responsibility, and economic viability. As the trajectory of research and innovation continues to ascend, the utilization of glass fibers within concrete matrices stands as a testament to the unceasing pursuit of optimal pavement solutions. This serves as an emblem of the harmonious synthesis between strength, sustainability, and enduring functionality in pavement engineering [91].

2.3.2 Natural Fiber Reinforced Concrete

Agricultural waste, often referred to as agro waste, constitutes surplus or byproducts from crops and is notably abundant in developing nations. These residual materials require significant land for disposal, and approximately 9% of the total energy production can be attributed to agrowaste. Conversely, agro wastes contribute to about 36% of overall energy dissipation [92]. Global crop production reaches approximately 2.9 billion tons annually, with roughly 66% of these waste being utilized for energy generation through combustion. However, the practice of open burning of jute fibers raises concerns due to valuable implications, threats to road traffic safety, and potential adverse effects on human health [93]. The diverse spectrum of agricultural waste encompasses materials such as bagasse straw, olive stones, grape seeds, cotton stalks, pine sawdust, pecan, almond, hazelnut shells, sunflower shells, jute, wheat straw, rice straw, rice husk, corncob, and cassava rhizome [94]. Studies highlight that rice crop residues consist of approximately 59% rice straw and 20% rice husk, underscoring their substantial presence within the composition of agricultural waste [95].

Over recent years, a notable upsurge in interest has been observed in the incorporation of natural fibers and agro-residues into cementitious products, focus has shift to environmentally friendly sustainable materials [96]. Simultaneously, the substantial potential of natural fibers as effective reinforcements for mitigating conventional vulnerabilities inherent to concrete rigid pavement structures has gaine Agricultural waste-based natural fibers are adeptly assimilated into inherently brittle cementitious matrices, thereby conferring augmented toughness and energy dissipation characteristics. researchers have diligently undertaken extensive investigations into these natural fibers, probing their viability and efficiency across diverse applications. Illustrative instances of such agricultural waste-based natural fibers integrated into cementitious materials, such as bamboo, banana, vakka, palm, jute, hibiscus cannabinus, abbaca leaf, sisal, coir, date, malva, pineapple leaf, hemp, ramie bast, wheat straw, sansevieria leaf, and kenaf bast [97–108].

The utilization of waste material in concrete has reduce the cost of construction. Sustainable construction is the key facto to secure environment. In terms of augmenting the mechanical attributes of cementitious matrices, of agricultural waste-based natural fibers emerges as a compelling avenue, facilitating the development of renewable, economically viable construction materials. The amalgamation of diverse natural fibers has demonstrated the propensity to yield synergistic outcomes, substantiated by empirical research endeavors. A noteworthy illustration can be found in an empirical study investigating the utilization of agricultural waste from date palm trees to engineer sound-absorbing construction materials [107, 109].

Natural fibers inherently possess properties that render them amenable to synergistic incorporation within cementitious matrices. A comprehensive compendium of the properties pertinent to select natural fibers is elucidated in **Table 2.3**.

Table 2.2: Composition of Jute and Glass Fibers

SR No	Natural Fibers	Properties	References
1	Wheat Straw	High energy absorption, high toughness index, strong, high water absorption capacity, easily available.	M.U Farooqi and M.Ali[111]
2	Jute Fibers	Lighter than steel, higher breaking strength, easily available, high energy absorption	Won et al.,[69]
3	Coconut Fiber	High toughness index, high damping ratio, economical, good flexural strength	Lucia et al.,[64]
4	Flax Fiber(%)	High tensile strength, elongation property up to 2.7-3.2%, biodegradable, cost-effective	Mahmoud et al.,[70]

Another facet of scholarly inquiry delved into the dynamic and mechanical attributes of coir fiber-reinforced concrete [110]. Optimal content determination revealed a zenith at 5%, optimized fiber length of 5 cm. This deliberate inclusion into a notable enhancement, as evidenced by the substantial augmentation in compressive toughness exhibited by the coir fiber-reinforced concrete matrix [78]. The strategic incorporation of bamboo fiber within the realm of asphalt road construction yielded transformative results, conferring heightened road performance through ameliorated resistance against cracking, fatigue, and dynamic modulus-related challenges. The blending of diverse natural fibers has proven promising, as it can generate synergistic outcomes. This phenomenon is substantiated by empirical research endeavors, suggesting that when different natural fibers are combined, their unique properties can complement each other, leading to improved performance, durability, and versatility in various applications. The amalgamation of a variety of natural fibers has shown great potential, as it has the ability to produce collaborative and advantageous results. Empirical research supports the concept that blending diverse natural fibers can enhance their distinct attributes, resulting in superior performance, increased durability, and enhanced adaptability across a range of applications.

2.4 Hybrid Fiber Reinforced Concrete

The hybridization of natural and synthetic fibers represents a deliberate strategy aimed at harnessing synergistic effects resulting from the coexistence of two or more distinct fiber types [55]. This strategic approach involves the integration of both natural and synthetic fibers into concrete formulations, with the overarching objective of enhancing specific properties inherent to the concrete matrix. The inclusion of jute and glass fibers in HNS-FRCs is favored over using separate fibers because of their corresponding properties. Jute fibers excel in absorbing energy [140, 158], while glass fibers add considerable tensile strength to the concrete elements [141, 160]. When combined, these natural and synthetic fibers work together to enhance overall performance, effectively tackling both micro-shrinkage and macro-cracking issues in rigid pavements [142, 165]. This combination results in a more balanced and optimized concrete mix, demonstrating superior mechanical properties compared to using individual fibers independently. Consequently, HNS-FRCs prove to be a practical choice for improving concrete performance in various construction applications [166, 167]. Another investigation encompasses a diverse array of fibers, including polyester, polypropylene, glass, and jute, spanning varying lengths of 5mm, 10mm, 20mm, 25mm, and 50mm [31]. The experimental results yield compelling insights into the impact of hybridization on the flexural properties of concrete. Of particular significance is the discernible improvement observed when glass and jute fibers are introduced through the hybridization process [32]. Remarkably, the most noteworthy elevation in flexural strength is achieved through the hybridization of fibers with lengths spanning 25mm and 50mm. In the context of fiber-reinforced concrete (FRC), formulations encompassing fiber lengths ranging from 5mm to 50mm exhibit an appreciable enhancement in flexural strength, showcasing improvements of up to 18% [14]. Notably, compositions characterized by fiber lengths within the range of 25mm to 50mm display even more remarkable gains, exhibiting a substantial 38% increment in flexural strength. Consequently, it becomes evident that FRC compositions incorporating fiber lengths within the 25mm to 50mm range emerge as superior candidates for augmenting flexural attributes [18]. Delving further into the investigation, a comprehensive exploration of hybrid fibers was undertaken, varying the proportions at 0.3%, 0.4%, and 0.5%. Strikingly, the findings underscore that the optimal inclusion of hybrid fibers at the 0.3% proportion leads to the most pronounced enhancements in strength. Expanding on the scope of inquiry, the study encompassed the hybridization of natural and synthetic fibers, involving two distinct fiber lengths [21]. Empirical evidence unequivocally establishes that the hybridization of these fibers yields a discernible enhancement in flexural strength when contrasted with conventional concrete compositions. The collective influence exerted on concrete performance post-hybridization is intrinsically tied to the specific chemical composition and inherent attributes resident within the constituent fibers. A comprehensive elemental analysis, showcased in **Table 2.4**, provides insight into the constituent elements within glass fiber and jute fibers, further illuminating their potential contributions to the hybridization process [22]. Hybridizing natural and synthetic fibers within concrete introduces an advanced paradigm, where the resulting hybrid fiber-reinforced concrete becomes an adept substitute for plain concrete (PC). The strategic inclusion of macro fibers serves a dual purpose: addressing macro-cracks and significantly augmenting the concrete's overall toughness. An in-depth analysis ventures into remedial strategies through the integration of natural and synthetic fibers of varying lengths providing multifaceted solutions. In the domain of hybrid synthetic and natural fiber-reinforced concrete, a profound interplay of forces emerges across cracks, stemming from both the aggregate's contribution and the reinforcing fibers [23]. The progression of crack propagation involves intricate phenomena, encompassing and the occurrence of de-bonding within the fiber-matrix interface.

The physical presence and the nuanced surface attributes of the fibers play a central role in modulating energy dissipation patterns and the subsequent deformation phenom-ena post-cracking [38]. Particularly significant is the phenomenon of fiber pull-out, a mechanism that engenders a ductile response in concrete, ascribed to the energy dissipation facilitated during the post-cracking phase. Embedded within the con-text of fiber-reinforced concrete, the structural integrity persists until the fibers themselves eventually undergo fracture. The structural integrity remains intact until the fibers themselves undergo eventual fracture.

TABLE 2.3: Composition of Jute and Glass Fibers

Fibers	**Elements**	**Weight (%)**	**Reference**
Glass Fibers	SiO2	55-71	Shah et al.,[7]
	AL2O3	8-25	Zhong et al., [19]
	CaO	14-18	Arooj and ali [14]
	MgO	3-10	Arooj and Ali[14]
	Na2O	0.3-8.5	Shah et al.,[7]
	K2O	0.2	Zhang et al.,[19]
	Li2O	5-7	Zhang et al., [19]
Jute Fiber	Moisture	12.6	[70]
	Pectin	0.2	Zhong et al., [70]
	Wax	0.5	Khalid et al.,[71]
	Ash	0.5-2	Todor et al.,[72]
	Cellulose	61-71	Yamada et al.,[78]
	Hemicellulose	13.6-20.4	Zhong et al.,[70]
	Lignin	Dec-13	Phoung et al.,[79]

Using jute and glass fibers in concrete production can help reduce carbon emissions in several ways [145]. Firstly, jute fibers come from natural sources and require less energy-intensive processing compared to synthetic fibers, which reduces the carbon footprint associated with fiber production [146]. Additionally, incorporating these fibers into concrete mixes probably improves the durability of structures [147], leading to reduced maintenance needs over time. This means less frequent repairs, which typically involve energy-intensive processes and thus contribute to carbon emissions. Moreover, addition of jute fibers will result in less consumption of raw materials i.e. cement and coarse aggregates. Overall, the use of jute and glass fibers supports sustainability efforts in the construction industry by promoting more environmentally friendly practices [148, 149]. A comprehensive experimental study has been conducted, involving a hybrid combination of jute, polypropylene, polyester, sugarcane, coconut, flax, and glass fibers. The incorporation of cellulosic natural fibers, notable for their inherent characteristics, exhibits a noteworthy elevation in all properties of FRC [44]. This strength enhancement is contingent upon the precise ratio of these fibers integrated. Particularly intriguing are the findings associated with the hybridization of jute and glass fibers, showcasing remarkable enhancements of 11.6% and 22.2% in compressive strengths, respectively [46]. These outcomes underscore the immense potential of these hybrid fiber combinations, substantiating their applicability in critical areas such as pavements and flooring slabs [67].

2.5 Summary

Enhancing the performance of rigid pavements hinges significantly on the mitigation of cracks. The occurrence of cracks can be effectively managed through the amelioration of the mechanical attributes of concrete. Mitigating the occurrence of cracks in rigid pavements can be facilitated by minimizing linear shrinkage values. Previous researchers have demonstrated the notable improvements in concrete properties by the incorporation of fibers. The individual effect of each fiber type was considered in the literature of this study. However, the preference for hybrid fibers, such as the mix of jute and glass fibers in HNS-FRCs, was emphasized over the use of separate fibers. This preference aims to balance the properties offered by hybrid fibers. Jute fibers are known for their excellent energy absorption capabilities, while glass fibers contribute significant tensile strength to the concrete mixture. By combining these natural and synthetic fibers, the overall performance of the concrete is enhanced, effectively addressing both micro-shrinkage and macro-cracking concerns in rigid pavements. This mixture results in a more balanced and optimized concrete mix, showcasing superior mechanical properties compared to using individual fibers alone. These enhancements exert a positive influence on the overall structural performance. Within this chapter, a comprehensive exploration of various facets pertinent to rigid pavements is undertaken. This encompasses the identification and assessment of weaknesses inherent to rigid pavements, an in-depth comprehension of the pivotal properties of concrete and their profound repercussions on rigid pavement behavior, meticulous consideration of factors encompassing design and durability, and an extensive examination of the efficacy of integrating fibers into concrete to bolster the performance of rigid pavements.

Chapter 3

Experimental Methodology

3.1 Background

The construction industry has gaining interest to utilize waste material such as natural and synthetic fibers for application purposes from past few years. This attention gains due to their cost-effectiveness, environmental friendly characteristics, ease of manipulation, commendable mechanical properties, and easily availability. Among the fibers subjected to scrutiny within this study are jute and glass fibers. These fibers have good mechanical properties, such as efficient energy absorption, low density, and high tensile strength at breaking points. Notably, a comprehensive overview into the compatibility of hybrid natural-synthetic fiber reinforced composites (HNS-FRCs) with a diverse assessment of fiber types for rigid pavement applications has not been explored yet as well as in previous chapters they conducted research approaches has concluded that the utilization of hybrid natural and synthetic fibers improves properties of concrete products. In this chapter examination of the mechanical and dynamic properties inherent to HNS-FRCs. Moreover, due regard is accorded to parameters encompassing linear shrinkage, water absorption, and mass loss. The current chapter upon the methodological approach that explores this research endeavor, encompassing the aspects such as raw material selection, fiber treatment method techniques governing the mixing and casting of PC and HNS-FRCs, specification delineation for specimen configuration, and a comprehensive outline of testing protocols.

3.2 Raw Materials

The preparation of ordinary Portland cement concrete involves several key materials: typical Portland cement, Lawrencepur sand, coarse aggregates with sizes maximum of 12.5 mm and below, and water. The selection of fibers, including both jute and glass, constitutes a crucial step in this process, influenced by factors such as local availability and material suitability. Choosing fibers, encompassing both jute and glass, is a pivotal aspect of this process, influenced by factors such as local accessibility and material appropriateness. When produce Hybrid Natural and Synthetic Fiber-Reinforced Concrete (HNS-FRC), the goal is to maintain uniformity in the constituents while adjusting the proportions of jute and glass fibers. In the mixture, jute fibers are introduced at a length of 50mm, while glass fibers are incorporated at a length of 25mm. The decision to use these specific fiber lengths is likely based on their mechanical characteristics, which are presented in **Tables 3.1** and **Table 3.2**. These tables likely provide information on the tensile strength, modulus of elasticity, and other relevant mechanical properties of both jute and glass fibers [113]. The incorporation of both natural and synthetic fibers into concrete has gained significant traction in various industrial applications.

Table 3.1: Mechanical Properties Jute Fiber

Variables	**Jute Fiber**	**Reference**
Diameter (um)	21-210	Dittenber et al. [122]
Density (kg/m^3)	1250-1495	Mittal et al.[123]
Tensile Modulus (MPa)	310-810	Li et al.[124]
Young Modulus (GPa)	10-80	Dittenber et. [122]
Max Elangation	1.5-2.5	Dittenber et. [122]

Table 3.2: Mechanical Properties Glass Fiber

Variables	**Jute Fiber**	**Reference**
Density (kg/m^3)	258	Palani kumar et al.,[123]
Stiffness	72	Atewi et al.,[124]
Tensile Modulus (MPa)	70	Kizilkanat et al.,[125]
Young Modulus (GPa)	77	Asokan et al.[126]
Fiber strength	6-18	Atewi et al.,[124]

3.2.1 Preparation of Fibers

The methodology employed for fiber treatment in this specific study revolves around a water treatment approach, a technique that fibers selected due to its easy availability and has been extensively reported by different researchers [149]. Within this context, the raw jute and glass fibers undergo careful cutting to attain precise lengths of 50mm and 25mm, respectively. The criteria for selecting fiber lengths, with jute fibers chosen at 50mm and glass fibers at 25mm in HNS-FRCs, were primarily based on achieving a balanced ratio that aligns with the desired performance targets of the concrete mix. This selection was guided by considerations such as practicality in manufacturing processes, cost-effectiveness, and ensuring an appropriate distribution of fibers within the concrete matrix to achieve optimal reinforcement effects. Additionally, the chosen lengths aimed to strike a balance between maximizing the benefits of each fiber type while minimizing any potential drawbacks associated with excessive fiber lengths or densities [144]. The 50mm length of jute fibers is come out with favorable outcomes, as reported in literature [157–159]. Similarly, the 25mm length of glass fibers is derived with favorable outcomes, as reported in literature [160–162]. Accordingly, the procedure for cutting the jute fibers involves a combination of combing and straightening to ensure a uniform length distribution. Following this, the cut fibers are immersed in water for a period approximately 24 hours. Visual representations include the untreated fibers, fibers prepared for treatment, and the respective cut lengths for both jute and glass fibers. The selection of fiber lengths, namely 50mm and 25mm, is founded upon the hypothetical halving of these lengths. This selection plays a pivotal role in exploring the resistance forces exhibited by fibers against tensile failure, encompassing both the fiber pull-out force and fiber breakage. **Figures 3.1**[a] and **Figure 3.1**[b] provide depictions of the jute and glass fibers, accompanied by the treatment procedure specifically applied to the jute fibers. In the formulation of Fiber-Reinforced Concrete (FRC), both jute and glass fibers are integral components. The preparation of FRC involves employing 50mm jute fiber lengths, while HNS-FRCs incorporate glass fibers with lengths of 25mm. The proportions of glass fiber, maintained at levels of 1%, 2%, 2.5%, 3%, and 4% in relation to jute fibers across all JWG-FRCs, adhere closely to recommendations set forth in [10].

FIGURE 3.1: Considered Natural and Synthetic Fibers; a) Jute Fiber, b) Glass Fibers

For the production of Plain Concrete (PC) and all JWG-FRCs, conventional tap water at room temperature is utilized. Employing consistent water-cement ratios, coupled with a 1.5% superplasticizer content, facilitates the creation of distinct specimen categories. A water-cement ratio of 0.45, in accordance with findings from [12], is employed for fabricating PC specimens. A consistent ratio is rigorously maintained across all specimens of Jute and Glass Fiber-Reinforced Concrete (JG-FRC). The same ratio is meticulously upheld in all samples of Jute and Glass Fiber-Reinforced Concrete (JG-FRC). The deliberate adjustment of the water-cement ratio within JG-FRC formulations, coupled with the incorporation of superplasticizers, is driven by the objective of enhancing water absorption characteristics intrinsic to jute and glass fibers. This precise adjustment aligns with established findings in the literature, providing empirical support for the necessity of fine-tuning the mixture to effectively exploit the unique water-absorbing attributes of these fibers in the context of JG-FRC [16, 17]. It is important to note that an elevated water-cement ratio has the potential to induce concrete bleeding and, subsequently, could lead to a reduction in Compressive Strength (CS), as highlighted by [112].

3.3 Preparation of Concrete

3.3.1 Mix Design

The preparation of PCC specimens involved adhering to a mix design ratio of 1:2:3 (cement:sand:aggregate), accompanied by a consistent water-cement (w/c) ratio of 0.45. It is worth noting that the inclusion of superplasticizers was calibrated at 1.5% relative to the cement weight. The incorporation of the superplasticizer ”Sikament-520” in the mix significantly enhances both the workability and strength of the concrete mixture [152]. SPs like Sikament 520 are known for their ability to improve flowability without increasing water content, facilitating easier placement and compaction while maintaining the desired water-cement ratio. This improvement in workability is crucial for achieving proper consolidation and reducing the risk of segregation during construction. Additionally, the use of SPs promotes better particle dispersion and reduces interparticle friction within the concrete matrix, leading to enhanced packing density and improved bond between

Table 3.3: Quantities of each mix

	P.C.C	**A2**	**A3**	**A4**	**A4**	**A5**
Cement (Kg)	428	395	394.25	393.87	393.52	392.7
Sand (Kg)	720	711.50	710.25	709.61	709	707.76
Aggregate (Kg)	1045	1032.12	1030.26	1029.31	1028.38	1026.50
Jute Fibers (Kg)	0	4.28	8.56	10.70	12.84	17.12
Glass Fibers (Kg)	0	17.12	12.84	10.70	8.56	4.28
Super-Plasticizers (Lit)	6.42	6.42	6.42	6.42	6.42	6.42
Water (Kg)	192.6	192.6	192.6	192.6	192.6	192.6

cementitious materials and aggregates. Consequently, the inclusion of this superplasticizer optimized the overall performance of concrete, ensuring not only ease of construction but also long-term durability and structural integrity. Superplasticizers were employed in all compositions, including PC specimens, contributing to the enhanced performance of the specimens. This improvement corresponds to varying percentages of cement replacement with fibers, ranging from 1% to 4%. JG-FRCs, a combination of jute and glass fibers, were utilized, each with fiber lengths of 50mm and 25mm, respectively, proportional to the cement weight. The use of superplasticizers not only improves workability but also enhances the strength of concrete specimens. The determination of an optimized water-cement (w/c) ratio for JG-FRCs, as utilized by different researchers, helps prevent undesired bleeding, a potential consequence of additional water content. In this study, the correlation between the inclusion of jute and glass fibers is considered in relation to the mass of cement, strategically aimed at improving bonding properties. Researchers have extensively employed natural fibers from agriculture along with synthetic fibers from commercial waste, with a focus on enhancing the pozzolanic reaction to optimize concrete strength while conserving natural resources. The incorporation of fibers into the concrete matrix serves a dual purpose: partial cement replacement and the enhancement of overall structural performance. The selection of natural and synthetic fiber lengths, as well as the water cement (W/C) ratio, was reported in published literature [30, 61, 67], with the overarching objective of sustainable construction techniques, improve energy absorption capacity, and improve the aggregate toughness indices.

3.3.2 Specimens

To conduct compressive strength tests, cylinders having 200 mm in height and 100 mm in diameter are cast across six different batches. These batches feature varying percentages of jute and glass fibers, aiming to optimize the content of the Hybrid Fiber Reinforced Concrete Mix. In addition, for the flexural strength test, beam-lets with dimensions of 100 mm width, 100 mm depth, and 450 mm length are cast. Each combination is represented by three cylinders and three prisms. The average of three readings is utilized to determine the properties of hardened concrete, a methodology consistently adopted by other researchers as well

3.4 Test Methods

3.4.1 Non-Destructive Testing

The dynamic testing procedure precedes the destructive evaluation of the specimens in accordance with ASTM standard 215-14, delineated within **Table 3.3**. In **Figure 3.2b**, an intricate process unfolds, revealing the intricate measurement of response frequencies governing rotation (RFR), lateral displacement (RFT), and transverse movement (RFL). These dynamic attributes are meticulously quantified through the strategic utilization of an accelerometer and a hammer. A pivotal aspect of the investigation involves the application of this technique to both beamlet and cylinder specimens. In this context, a specialized accelerometer is meticulously affixed to one side of each specimen, meticulously capturing the manifestation of lateral motion. Simultaneously, the opposing side is subjected to the controlled impact of a hammer, effectively gathering a cascade of measurements that are subsequently relayed to a computer infrastructure seamlessly integrated with the accelerometer. The procedural framework governing the deduction of RFT and RFR values, underscored by the intricate positioning of the accelerometer in conjunction with the precise point of hammer impact, evolves distinctly for beamlet and cylinder specimens. This pivotal step within the non-destructive assessment meticulously mandates the attachment of an accelerometer to a designated side, thereby unveiling the latent manifestations of lateral motion. Concomitantly, the symmetrical side of the specimens experiences the calculated impact of a hammer, instigating a responsive cascade of measurements. In this orchestrated interplay, the discerning accelerometer functions as a sentinel, skillfully recording the nuanced frequencies that underlie the specimens' dynamic response.

A critical element of the study revolves around employing this method on both beamlet and cylinder specimens. In this scenario, a specialized accelerometer is precisely attached to one side of each specimen, carefully recording the expression of lateral movement. At the same time, the opposite side experiences a controlled impact from a hammer, efficiently collecting a series of measurements that are then seamlessly transmitted to a computer infrastructure integrated with the accelerometer.For cylinder specimens, the precise positioning of the accelerometer becomes in RFT measurements. This strategic placement mandates adherence to a fixed distance of at least 25 cm from the edge, ensuring accurate readings. In tandem, the application of the hammer precisely targets this designated side, orchestrating an impact aimed at the central region of the cylinder's length-facing surface. However, the RFR measurement protocol deviates subtly in its execution. An accelerometer, meticulously installed along the uppermost facet of the cylinder, mirrors the spatial parameters governing RFT. This nuanced alignment facilitates a perpendicular orientation relative to the cylinder's length, enabling strategic hammer strikes from the opposing side. In the realm of beamlet testing, the orchestrated choreography assumes a nuanced execution. The accelerometer's strategic placement, aligned with the corresponding distance parameters established for the cylinder, becomes a pivotal determinant in RFT measurements.

The orchestration of a hammer strike, precisely targeted at the midpoint of this aligned side, becomes the focal point. In contrast, the application of the hammer on the opposing side manifests as a precise, calculated impact at the bottom corner. This strategic maneuvering engenders a geometric alignment that positions the hammer's impact point and the accelerometer in a fashion that reflects the diagonal axis of the corresponding rectangle. This tactical maneuver results in a geometric alignment that situates the impact point of the hammer. The deliberate positioning of the accelerometer, in harmony with the defined distance parameters for the cylinder, plays a crucial role in RFT measurements. The focal point is the orchestrated hammer strike, precisely aimed at the midpoint of this aligned side. In contrast, the impact of the hammer on the opposing side is a meticulously calculated strike at the bottom corner. The critical aspect lies in a precisely targeted hammer strike at the aligned midpoint, serving as the focal point.

Table 3.4: Studied Parameter and Testing Standard

Test	**Allowed Standards**	**Focused Parameters**	**Additional Parameters Considered for the Study**
Compressive strength	ASTM C39	Compressive strength	Curves depicting stress-strain relationships, energy absorption during compressive pre-cracking (CE1), energy absorption after cracking in compression (CE2), overall energy absorption in compression (CTE), toughness indices in compression (CTI), and the modulus of elasticity (MOE).
Splitting-tensile properties	ASTM C496	Split-tensile strength	(STS) and the load-deformation curves, as well as the energy absorption before cracking in split-tensile tests (SE1), energy absorption after cracking (SE2), total energy absorption (STE), and toughness indexes in split-tensile tests (STI).
Flexure properties	ASTM C78 ASTM C1609	Flexure strength	Load-displacement graphs, energy absorbed before flexural cracking (FE1), energy absorbed after flexural cracking (FE2), total energy absorbed during flexural testing (FTE), and measures of flexural toughness (FTI).
Dynamic Properties	ASTM C215-14	RFL, RFT and RFR, damping ratio	No additional parameter studied.
Dynamic Properties	ASTM C215-14	RFL, RFT and RFR, damping ratio	No additional parameter studied.
Dynamic properties	ASTM-C1548	modulus of rigidity, and Poisson ratio	No additional parameter studied
Water absorption and mass loss test	ASTM C622-13	Water absorption and density	No additional parameter studied

The extracted frequencies, an intricate embodiment of the dynamic behavior under examination, form the foundational basis for the computation of critical engineering parameters. The ensuing calculation encompasses the damping ratio, the dynamic modulus of rigidity, and the Poisson's ratios. This analytical pathway, resolute in its scientific rigor, yields insights of paramount significance.

3.4.2 Mechanical Testing

3.4.2.1 Compressive Strength Test

A Universal Testing Machine (UTM) is utilized for the evaluation, with a high-precision displacement transducer with a measurement range from 0-1500 mm and a resolution of 0.001 mm. This apparatus is utilized to measure the compressive strength, absorbed compressive energy, energy absorption until the peak load (CBE), energy absorption after the peak load (CPE), and compressive toughness index (CTI) of cylindrical specimens. The compression testing of the cylinders with ASTM C39/C39M-20 standard, specifically outlined for assessing the compressive strength of cylindrical concrete specimens. The configuration of the test setup is illustrated in **Figure 3.2a**.

Compressive Splitting tensile Flexural

Longitudinal Transverse Torsional

FIGURE 3.2: Tests Arrangement; a) Mechanical Properties b) Dynamic Properties

3.4.2.2 Splitting Tensile Strength Test

To perform the Splitting Tensile Strength test on 18 cylinders, ASTM C496 standards are followed. Firstly, we shift the sample to the Universal Testing Machine lab. Then position the samples in a line on the floor according to their combinations. Following that have start the UTM machine and connect it to a computer system. After that, clear the UTM machine using a brush to remove dust particles. Subsequently and change the loading plates on the UTM. Following the plate change, calibrate the machine and apply the load gradually. Finally, we recalibrated the machine. The technician handles the machine through the computer system, while the researcher observes any cracks on the sample. A universal testing machine is employed to assess the tensile behavior, measuring Splitting Tensile Energy before peak failure (SE1), Splitting Tensile Energy after peak failure (SE2), and the Splitting Tensile Toughness Index (STI). The experimental arrangement is illustrated in **Figure 3.2a**.

3.4.2.3 Flexural Strength Test

To carry out the flexural strength test on the 18 beams, we employ ASTM C293 (Standard Test Method for Flexural Strength of Concrete - Using Simple Beam with Centre-Point Loading). Initially, we transfer the beam sample to the Universal Testing Machine (UTM) lab for the flexural strength test on concrete beam specimens. Once in the lab, the beam samples are systematically arranged in a line on the floor according to the specified combination. Subsequently, we connect supports on both sides and carefully position the beamlet specimens. The application of load at the center point follows, revealing initial cracks in the beam specimens from the weak portion. After placing the beam samples into the UTM machine, we establish a connection with a computer system for monitoring and control. With the samples in place, we proceed to clear the UTM machine using a brush, ensuring the removal of any dust particles that might affect the accuracy of the test. After this cleaning process, we switch the loading plates on the UTM and embark on the calibration of the machine. Calibration involves the gradual application of load while meticulous adjustments are made to ensure precise measurements. Once the machine is calibrated, the technician takes charge, manipulating it through the computer system. Concurrently, the researcher closely observes the samples, keenly noting any further cracks or changes in response to the applied load **Figure 3.2a**

3.5 Microstructural Analysis

3.5.1 Scanning Electron Microscopy (SEM) Test

The optimized HNS-FRCs are subjected to micro-structural analysis to investigate their interaction with concrete through the utilization of scanning electron microscope (SEM) imaging. This testing procedure aims to delve into the bond between fibers and the matrix, the pull-out behavior of fibers, and the underlying nature of failure and cracking mechanisms. Employing the VEGA3 TESCAN SEM operating at a voltage of 10 kV facilitates the imaging process with high precision and detail. Prior to conducting the imaging tests, the samples undergo a plasma coating procedure to enhance their surface characteristics and ensure accurate results.

3.5.2 X-Ray Diffraction Analysis (XRD) Test

The methodology of X-ray diffraction (XRD) testing for specimens of fiber reinforced concrete involves subjecting the material to X-rays, subsequently examining and interpreting the resultant diffraction patterns. This sophisticated technique facilitates not only the discernment but also the quantification of crystalline phases present within the concrete matrix, thereby providing valuable insights into its elemental composition and underlying structural characteristics. Through meticulous analysis of the peak positions and intensities apparent in the diffraction pattern, one can extract profound understanding concerning the mineralogical constitution, phase distribution, and crystallographic attributes.

XRD testing stands as a pivotal tool for the comprehensive assessment of the impact of fiber incorporation on the intricate microstructure of the concrete and its holistic performance metrics. This assessment, in turn, contributes significantly to an elevated comprehension of the complex interplay between fibers and the concrete matrix, consequently fostering avenues for refining and optimizing formulations of fiber-reinforced concrete.

3.6 Summary

The mechanical properties, encompassing both compressive and flexural characteristics, as well as dynamic attributes including resonant frequencies, damping ratios, dynamic modulus of elasticity, dynamic modulus of rigidity, and Poisson's ratio of Portland Cement (PC) and Hybrid Natural Synthetic Fiber-Reinforced Composites (HNS-FRCs), are meticulously determined. This determination is achieved using a composite blend of cement, sand, and coarse aggregate, adhering to a precisely balanced water cement (w/c) ratio of 0.45 along with 1.5% of superplasticizers. Furthermore, varying proportions of 50mm long jute fibers and 25mm long glass fibers are incorporated into the mixture, with the fiber content varying by weight relative to the cement quantity. Subsequently, a comprehensive analysis encompassing Scanning Electron Microscopy (SEM) and X-ray Diffraction (XRD), is conducted to systematically evaluate the obtained results in accordance with the rigorous standards outlined by the ASTM. These analytical techniques provide insightful details regarding the micro structural characteristics, crystallographic properties, and thermal stability of the PC and HNS-FRCs composites. The extensive findings derived from these rigorous testing procedures are elaborately presented and critically discussed in Chapter 4 of the research. This chapter serves as a platform for interpreting the outcomes, unveiling meaningful insights, and drawing scientifically sound conclusions.

Chapter 4

Results and Analysis

4.1 Background

The study follows ASTM standards for mechanical and dynamic testing. It explores the mechanical properties of HNS-FRCs compared to traditional PC, including fresh and post-curing properties, along with mechanical analysis. Non-destructive dynamic characteristics and micro-structural analysis are examined for both PC and HNS-FRCs. To assess matrix bonding in HNS-FRCs, advanced techniques like SEM and XRD are systematically employed

4.2 Fresh Properties

4.2.1 Workability Test

For plain concrete, superplasticizers were introduced, and a minimum water-cement (w/c) ratio of 0.45 was upheld for optimal strength, leading to a minimum slump value in JG-FRCs specimens. Conversely, for HNS-FRCs mix designs, a distinct approach was taken. To offset fiber water absorption tendencies, 1.5%

superplasticizer was incorporated.A concrete slump test serves the purpose of analyzing the consistency of a concrete batch, allowing us to determine its flow characteristics [13]. In the case of plain concrete, superplasticizers were added, and a minimum water-cement (w/c) ratio of 0.45 was maintained to achieve optimal strength. This approach resulted a minimium slump value in JG-FRCs specimens. Conversely, when considering HNS-FRCs mix designs, a different strategy was employed. To counteract the water absorption tendencies of the fibers, 1.5% super-plasticizer was included. The value of the slump is measured carefully shown in **Figure 4.1** To the best of the author's knowledge, there is not any standard test available for the determination of the workability of HNS-FRC fresh properties. Hence, the same procedure and test standard are used for the determination of the workability of all HNS-FRCs combinations. **Table 4.1** illustrates the labeling of specimens along with the ratio of aggregates, which is consistently maintained at 1:2:3 in all combinations.

The percentages of jute and glass fibers vary from 0% to 4%, with a noticeable trend as the percentage of jute fibers increases, the percentage of glass fibers decreases. The water-cement ratio held constant at 0.45 in all combinations, and super-plasticizers has utilized the same percentage in all specimens. The slump value decreases as the percentages of jute and glass fibers increase. The highest slump value observed is 16mm for PC. Conversely, specimens with higher fiber percentages experience a reduction in slump values. The decrease in slump with the increase of jute fiber content can be attributed to the tendency of jute fibers to absorb water from the concrete mixture, leading to a reduction in its fluidity and workability [150, 163]. This phenomenon is well-documented in the literature, where it has been observed that the presence of natural fibers like jute can act as water absorbers, thereby reducing the water available for lubricating the concrete particles and facilitating flow [151, 164]. Consequently, higher concentrations of jute fibers result in greater water absorption, leading to a decrease in slump and making the mixture less fluid. This observation aligns with previous studies on fiber-reinforced concrete, where the addition of natural fibers has been shown to decrease slump values due to water absorption properties. The hardened density of concrete is calculated based on the wet weight of specimens, and it also decreases as the fiber percentage increases. In terms of slump, the concrete exhibited a value of 16mm, 12mm, 9mm, 4mm, 0mm and 0mm for A1 to A6, respectively. This indicates that slump is decreasing along with the increase in content of jute fiber. This reduction in slump values due to addition of jute fiber is well supported by literature [172, 173]. Whereas, in terms of workability, the concrete demonstrated good to adequate workability, except A5 and A6 which shown zero slump, facilitating ease of placement and compaction during construction activities. This favorable workability can be attributed to the use of superplasticizer and the optimal mix design. Moreover, the water absorption of the concrete was measured at 10%-12%. This value falls within the acceptable range for ASTM C1585 [174], indicating that the concrete possesses adequate resistance to moisture ingress, which is crucial for its long-term durability. Overall, the fresh properties of concrete, including its slump, workability, and water absorption, contribute to its suitability for pavement application, ensuring proper placement, compaction, and long-term endurance.

FIGURE 4.1: Measuring Value of Slump of HNS-FRCs

Table 4.1: Labeling of Specimens, percentage of fibers, water-cement ratio, Slump Values and harden densities

Labeling of Specimen	**C:S:A**	**Jute Fiber(%)**	**Glass fibers(%)**	**W/C Ratio**	**Super-Plasticizers(%)**	**Slump values (mm)**	**Density (Kg/m^3)**
PCC	1:2:3	0	0	0.45	1.5	16	2344.2
A2	1:2:3	1	4	0.45	1.5	12	2337.186
A3	1:2:3	2	3	0.45	1.5	9	2336.4
A4	1:2:3	2.5	2.5	0.45	1.5	4	2328.2
A5	1:2:3	3	2	0.45	1.5	0	2238.8
A6	1:2:3	4	1	0.45	1.5	0	2210.86

4.3 Dynamic Properties

The dynamic properties of Jute-Glass Fiber Reinforced Composites (JG-FRCs) have been thoroughly investigated in order to assess the impact of hybridizing glass and jute fibers on the concrete specimens' characteristics. To determine the dynamic properties of plain concrete (PC) samples, ASTM standard C215-14 has been employed [23]. However, due to the absence of a specific standard for assessing the dynamic properties of JG-FRCs, the same ASTM standards have been adopted as a reference for evaluating the dynamic properties of JG-FRCs. **Figure 4.2** illustrates the typical graphical responses recorded by the accelerometer during the testing process.

The comprehensive overview of the calculated dynamic properties for both PC and all JG-FRCs as shown in **Table 4.2**. To ensure accuracy, an average of three specimens obtained values has been taken for each JG-FRC specimen combination to yield representative results for each corresponding dynamic property [29]. Notably, the difference in damping ratio between PC and the A2 specimen, which comprises 4% glass fiber and 1% jute fiber (JG-FRC1), is increased by 125% for cylinder specimens. Similarly, A3 (3% glass fibers and 2% jute fibers - JG-FRC2) exhibits a 75% increase, A4 (2.5% jute and glass fibers - JG-FRC3) shows a 34% increase, A5 (2% glass fibers and 3% jute fibers - JG-FRC4) experiences a 128% increase.

A6 (1% glass fibers and 4% jute fibers - JG-FRC5) demonstrates a 108% increase in damping ratio compared to PC. Furthermore, the modulus of elasticity has witnessed improvements in all specimens containing hybrid fibers, with A2, A3, A4, A5, and A6 showing increases of 30%, 20%, 32%, 30%, and 34%, respectively. In a similar way, the modulus of rigidity has shown considerable improvement in all specimens containing hybrid fibers. Specifically, when compared to plain concrete (PCC), the modulus of rigidity has improved by 53% for A2, 7% for A3, 12% for A4, 16% for A5, and 20% for A6. The Poisson ratio has also exhibited notable enhancements, with respective increases of 90% for A2, 20% for A3, 31% for A4, 10% for A5, and 16% for A6.

Table 4.2: Dynamic Properties of PC and HNS-FRCs

Concrete Specimens	**Studied Parameter**						
	RFL (HZ)	RFT (HZ)	RFR (HZ)	ζ%	RD (GPa)	ED (GPa)	Poisson Ratio (-)
Cylinder							
PCC	5203	3545	3767	4	4.75	4.3	0.45
A2	4794	4184	1394	9	6.13	6.58	0.54
A3	3480	3585	3425	7	5.7	4.58	0.51
A4	3355	3407	3244	5.35	6.24	4.8	0.7
A5	3305	3297	3294	9.09	6.19	4.97	0.47
A6	3355	3412	3439	8.33	6.29	5.13	0.5
Beams							
PCC	3371	3268	3346	1.78	13.8	4.06	0.41
A2	3463	3289	3339	3	20	5.04	0.58
A3	3289	3200	1786	4.35	22.3	7.06	0.64
A4	4119	2517	3396	3.81	24.51	5.18	0.69
A5	3820	1997	3576	5.26	26.8	4.64	0.77
A6	3545	2012	3332	5.15	28.16	6.38	0.81

It is important to note that PC serves as the reference specimen for these properties, as depicted in **Figure 4.3**. The damping ratio in concrete refers to the measure of energy dissipation during vibration or dynamic loading, indicating the material's ability to dampen oscilla-tions and resist excessive vibrations [153]. A higher damping ratio signifies better energy dissipation and greater damping capacity, which are desirable character-istics for structures subjected to dynamic loads or seismic events [154].

In our study, mix A5 exhibited the maximum damping ratio due to its optimized com-bination of jute and glass fibers, which effectively enhance energy absorption and damping properties within the concrete matrix. The presence of both fiber types contributes to enhanced damping capacity by promoting crack bridging, fiber pull-out mechanisms, and fiber-matrix interactions, all of which dissipate energy and mitigate vibrations effectively.

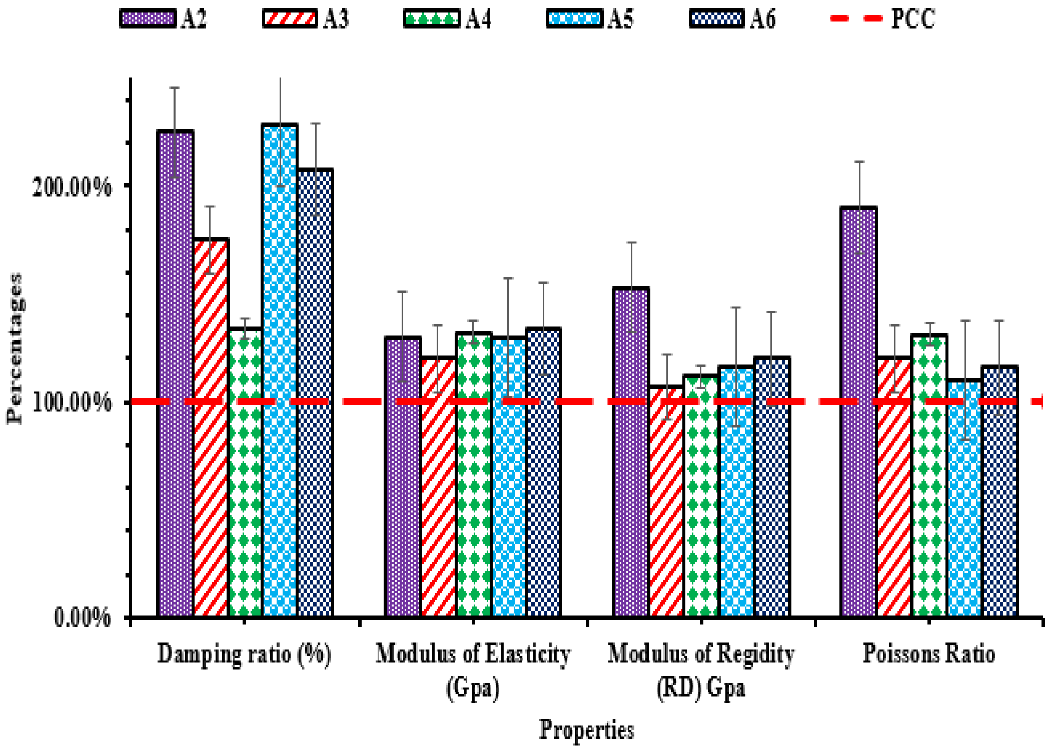

Figure 4.2: Dynamic Properties of Cylinder Specimens

The damping ratio value has increased due to inclusion of natural and synthetic fibers because fibers have ability to improve the interfacial transition zone [20]. In the case of beamlets, the damping ratios for A2 (JG-FRC1), A3 (JG-FRC2), A4 (JG-FRC3), A5 (JG-FRC4), and A6 (JG-FRC5) are significantly enhanced, with increases of 68%, 145%, 114%, 190%, and 180%, respectively. Notably, JG-FRC4 exhibits the most substantial increase among all combinations of JG-FRCs. This increase in damping ratios signifies a substantial improvement in the resistance of these specimens to dynamic loading [20] **Figure 4.4**

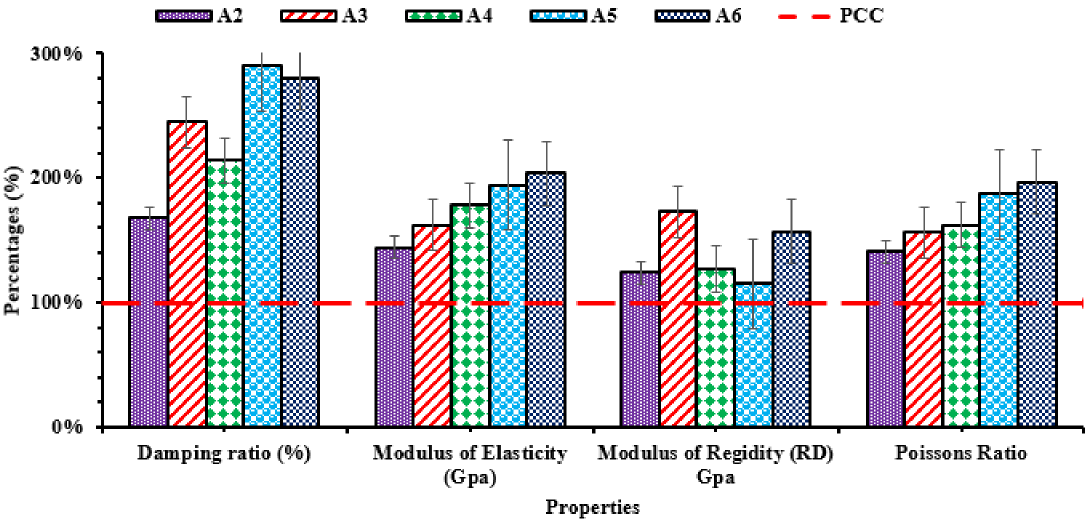

FIGURE 4.3: Dynamic Properties of Beamlet Specimens

Furthermore, specimens containing 25 mm glass fibers demonstrate an increase in dynamic loading resistance with the extension of jute fiber length. Remarkably, the performance of jute fibers at a length of 50 mm surpasses that of specimens with 25mm of glass fibers

4.4 Mechanical Properties

4.4.1 Properties under Compressive Loading

The stress-strain relationships for PC, A2 (JG-FRC1), A3 (JG-FRC2), A4 (JG-FRC3), A5 (J-FRC4), and A6 (JG-FRC5) are illustrated in **Figure 4.5**. In this figure it is evident that PC and A6 (JG-FRC5) exhibit the highest compressive strength (C-S) when compared to all types of JG-FRCs [26]. Specifically, the compressive strength of A2 (JG-FRC1), A3 (JG-FRC2), and A5 (JG-FRC4) has reduced by 22%, 18%, and 2%, respectively, when compared to PC. On the other hand, A4 and A6 have shown an increase in compressive strength by 8.5% and 7.5%, respectively, compared to PC, and they boast the highest compressive strength among all other JG-FRC variants. When utilizing 50 mm jute fibers in JG-FRCs, we observed a 8.5% and 7.5% increase in compressive strength compared to PC, which includes 25 mm glass fibers. In contrast, JGS-FRC1, JG-FRC2, and JG-FRC4 demonstrated reductions in compressive strength by 26%, 21%, and 6%, respectively, when compared to JG-FRC3. A similar trend was noticed in JG-FRC5, with a 30% reduction in compressive strength compared to JG-FRC3. However, when JG-FRC5 incorporated 1% glass fiber in addition to 50 mm jute fibers, there was a 7% increase in compressive strength compared to PC, which utilizes 25 mm glass fibers.

This shift towards higher jute fiber percentages and lower glass fiber percentages resulted in increased compressive strength, with the highest recorded value in A6 (JG-FRC5). The inclusion of glass fibers had a diminishing effect on compressive strength overall [31]. Notably, JG-FRC3 and JG-FRC5 exhibited higher compressive strengths than JG-FRC1, JG-FRC2, and JG-FRC4. The modulus of elasticity (MOE) values for plain concrete (PC) and all JG-FRCs indicate noticeable differences. Specifically, A2 (JG-FRC1), A3 (JG-FRC2), and A5 (JG-FRC4) demonstrate lower MOE than PC. In contrast, A4 and A6 exhibit MOE values that are 4% and 8% higher than PC, respectively. This is likely due to the presence of longer jute fibers, specifically 50 mm in length, which act as more effective crack arrestors [37]. JG-FRC3 and JG-FRC5 incorporated 2.5% and 4% jute fibers, alongside 25 mm glass fibers. **Table 4.3** presents the modulus of elasticity (MOE) values for PC and all JG-FRCs. It is evident that the MOE of A2 (JG-FRC1), A3 (JG-FRC2), and A5 (JG-FRC4) is lower than that of PC. Conversely, A4 and A6 exhibit MOE values 4% and 8% higher than PC, respectively. The modulus of elasticity (MOE) values for Jute and Glass Fiber-Reinforced Concretes (JG-FRCs) reveal distinct variations. A2 (JG-FRC1), A3

(JG-FRC2), and A5 (JG-FRC4) exhibit lower MOE compared to plain concrete (PC). In contrast, A4 and A6 display MOE values 4% and 8% higher than PC, respectively.

TABLE 4.3: Compressive Loading Variation of PCC and HNS-FRCs

Specimens	MOE (GPa)	CS (MPa)	CE1 (MJ/m^3)	CE2 (MJ/m^3)	CTE (MJ/m^3)	CTI (-)
A1	30	17.19	0.068	0.0363	0.104	1.539
A2	23.45	14.2	0.061	0.18	0.24	3.959
A3	24.85	14.74	0.066	0.085	0.149	2.289
A4	31.2	18.02	0.088	0.063	0.152	1.71
A5	29.4	20.22	0.12	0.055	0.171	1.471
A6	32.25	21.244	0.086	0.073	0.159	1.85

The MOE of JG-FRC1, JG-FRC2, and JG-FRC4 is more reduced compared to other JG-FRC3 and JG-FRC5 variants. This difference can be attributed to the presence of 50 mm jute fibers.

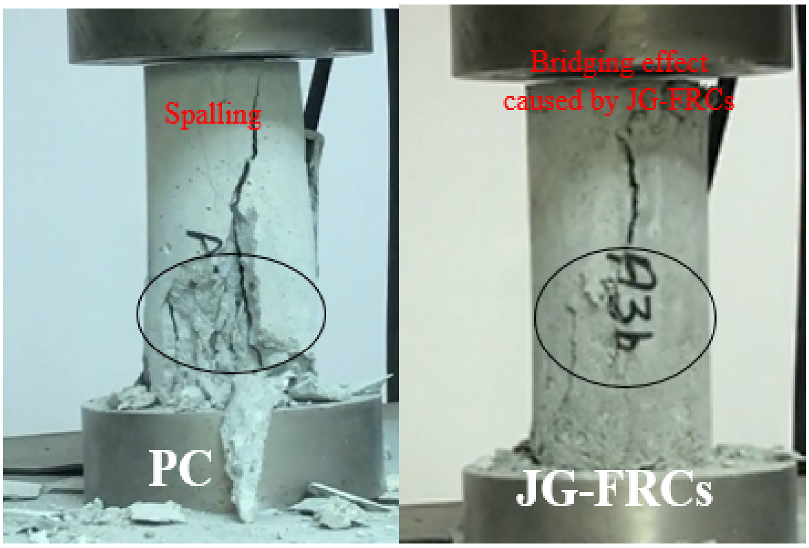

FIGURE 4.4: Typical compressive failure of PCC and JG-FRCs

Figure 4.6 shows typical compression failures of PC and JG-FRCs. The values for compressive pre-crack absorbed energy (CE1), compressive post-crack absorbed energy (CE2), compressive total absorbed energy (CTE), and compression toughness index (CTI) is represented in the above table which are, calculated according to the method described by [99] and [100].

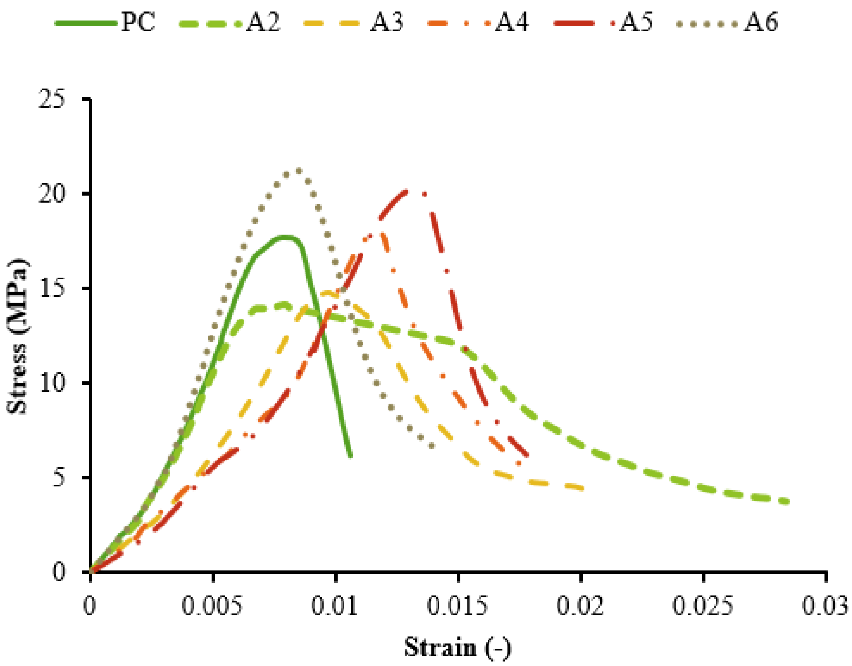

Figure 4.5: Compressive response of PCC and JG-FRCs

There is a reduction of 10%, and 26%, respectively, and increase CE1 as8%, 35% and 30% in CE1 for JG-FRC2, JG-FRC3, JG-FRC4, when compared with PC. On the other hand, CE2 exhibits significant increases of 394%, and 33%, and reduced in A3, A4 and A5 by 53%, 25% and 15% respectively, compared to PC. The compressive total energy (CET) values have consistently increased across all combinations of JG-FRCs by 131%, 1%, 12% and reduced in A2 and A6 by 38% and 7%, respectively, when compared to Portland Cement Concrete (PCC). Simultaneously, the compressive toughness index (CTI) exhibited remarkable enhancements of 157%, and 25%, in A2 and A6 respectively, in combinations of JG-FRCs compared to PCC specimens. These findings are visually presented in **Figure 4.7**, which illustrates the comparative behavior of compressive strength properties among all FRC specimens, with PCC serving as the reference specimen. This notable increase can be attributed to the presence of hybrid agricultural and commercial waste components, specifically glass fibers and jute fibers, within the

JG-FRCs [40]. In contrast to PCC, which tends to exhibit spalling under compressive loading, the JG-FRC specimens displayed diagonal and shear cracks of particular interest is the observation that JG-FRCs containing 25mm glass fibers and 50mm jute fibers consistently demonstrated the highest CTI values. This indicates that the inclusion of 50mm long jute fibers has a positive impact on CTI, suggesting their significant contribution to enhancing the compressive toughness of the composite.

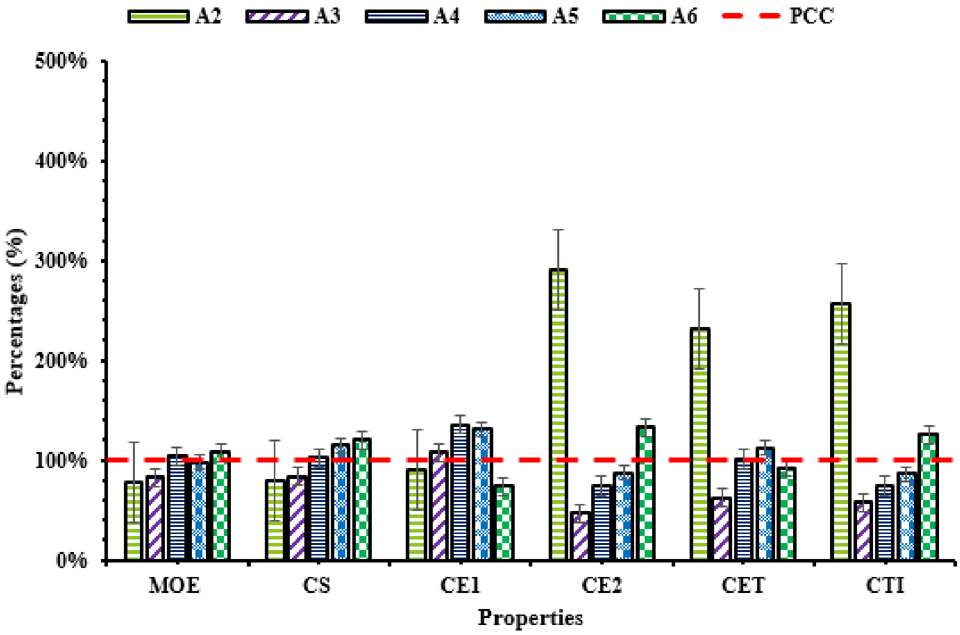

FIGURE 4.6: Comparative Behavior of Compressive Strength Properties Among All FRCs Specimens

4.4.2 Properties under Splitting Tensile Loading

The load-deformation curves, illustrating the relationship between applied load and deformation, are presented in **Figure 4.8** for various concrete mixtures, including Portland Cement (PC), A2 (JG-FRC1), A3 (JG-FRC2), A4 (JG-FRC3), A5 (JG-FRC4), and A6. Notably, **Figure 4.8** clearly demonstrates that A6 (JG-FRC5) exhibits the highest load-carrying capacity among these formulations [129]. This superior load-bearing capability can be primarily attributed to the bridging effect generated by the inclusion of both jute and glass fibers within the JG-FRC matrix [123]. **Table 4.4** provides a comprehensive analysis of various splitting tensile properties, which include Splitting Tensile Strength (STS), Splitting Tensile Pre-crack Absorbed Energy (SE1), Splitting Tensile Post-crack Absorbed Energy (SE2), Splitting Tensile Total Absorbed Energy (STE), and Splitting Tensile Toughness Index (STI).

Table 4.4: Splitting Tensile Loading Variation of PCC and HNS-FRCs

Specimens	**STS (MPa)**	**SE1 (MJ/m^3)**	**SE2 (MJ/m^3)**	**STE (MJ/m^3)**	**STI**
A1	2.2	11.33	0	11.33	1
A2	2.1	35.81	29.2	64.94	1.82
A3	2.033	15.53	33.43	48.96	3.2
A4	2.045	13.12	20.12	33.24	2.54
A5	2.896	21.044	10.694	31.74	1.51
A6	1.88	30.81	20.74	51.54	1.68

Comparative analysis reveals substantial reduction in JG-FRCs except A5 in the STS value for A5, as 34% when compared to the baseline PC. It is worth noting that A5 (JG-FRC5) stands out with the highest STS values, and this notable performance can be attributed to its carefully optimized jute fiber content [100]. The observed reduction in STS across all JG-FRC formulations can predominantly be attributed to the reinforcing influence imparted by the incorporated fibers [132]. In particular, SE1 experiences a remarkable 216% increase in the case of A2, 37% in A3, 16% in A4, 86% in A5, 172% in A6 when contrasted with PC. Conversely, PC demonstrates no post-crack energy absorption characteristics, invariably fracturing into two separate pieces under peak loading conditions. The JG-FRCs consistently display the capacity for post-crack energy absorption, to the presence of both agricultural and commercial fibers (JF and GF) embedded within the concrete matrix [120, 121]. Moreover, it can be reasonably inferred that the JG-FRCs demonstrate superior resistance to tensile loading when jute fiber with PC. This enhanced resistance primarily stems from the crack-retarding attributes of the incorporated fibers, which actively impede the propagation of cracks [12].

Notably, JG-FRC5, characterized by its optimal combination of 50mm jute fibers and 25mm glass fibers, exhibits the highest energy absorption capacity among all formulations. Additionally, the toughness indexes of JG-FRC1 through JG-FRC5 consistently surpass those of PC. Visual representations of typical splitting tensile failure modes for both PC and JG-FRC are provided in **Figure 4.9**. The JG-FRC2 exhibits the highest toughness index because it possesses the maximum pre-crack and post-crack energies [19]. The comparison of splitting tensile strength with plain cement concrete (PCC) reveals that JG-FRC2 exhibits superior toughness. This superiority is attributed to its remarkable pre-crack and post-crack energy levels. This could potentially be attributed to the inclusion of longer jute fibers, which effectively halted crack propagation following tensile loading. **Figure 4.10** illustrate that the comparison behavior of splitting tensile strength compares to PCC. The JG-FRC2 demonstrates superior toughness due to its exceptional pre-crack and post-crack energy levels, resulting in the highest toughness index among the materials tested.

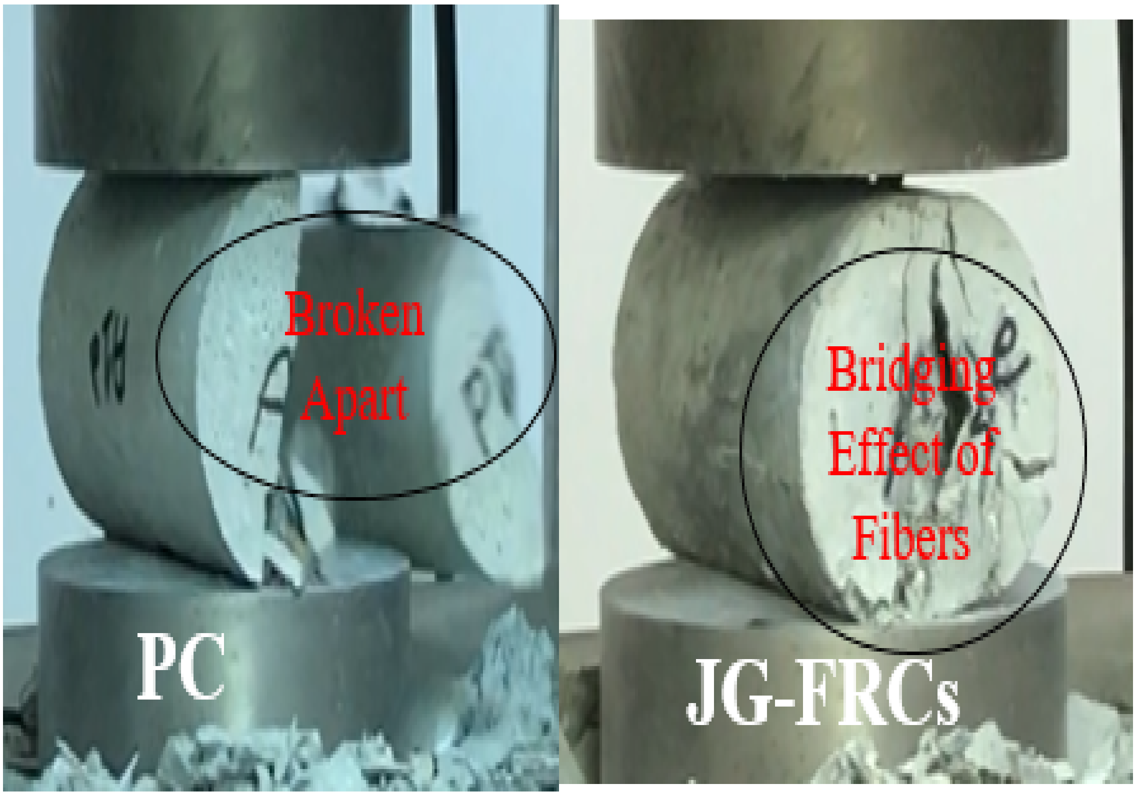

FIGURE 4.7: Typical Failure of Splitting Tensile Strength

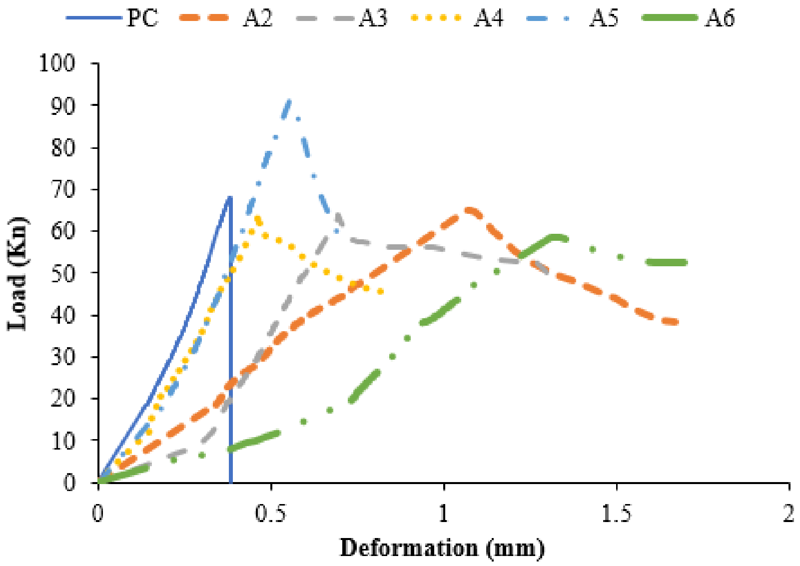

FIGURE 4.8: Splitting Tensile response of PCC and JG-FRCs

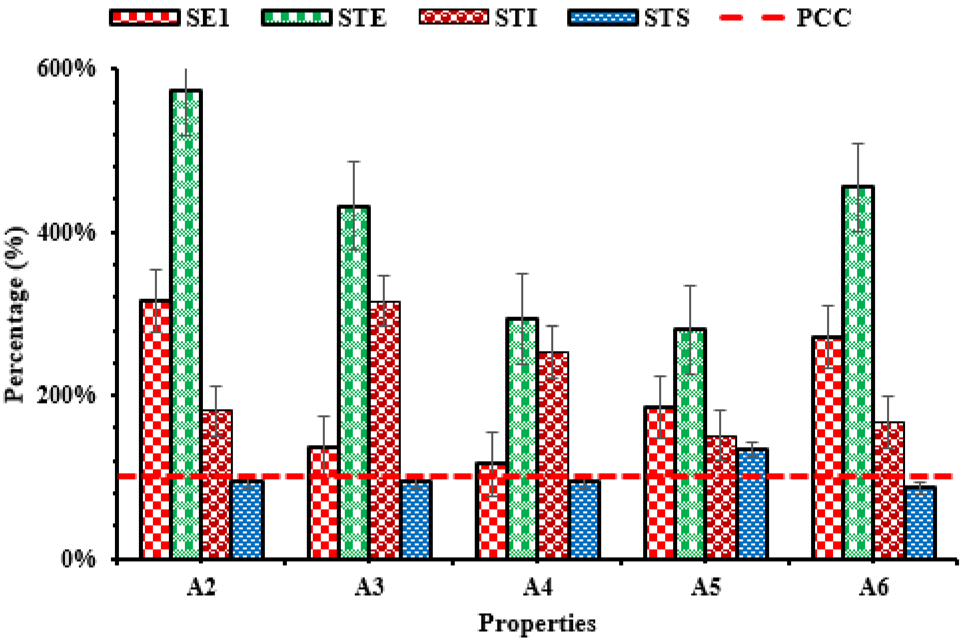

FIGURE 4.9: Splitting Tensile Properties Among PC and All HNS-FRCs Specimens

4.4.3 Properties under Flexural Loading

The load-deformation curves for a variety of materials, including Portland Cement (PC), A2 (JG-FRC1), A3 (JG-FRC2), A4 (JG-FRC3), A5 (JG-FRC4), and A6

(JG-FRC5), are depicted in **Figure 4.11**, offering a visual representation of how these materials respond to applied loads. While ASTM standard C78 recommends a loading rate of 1.03 MPa/min for testing, our study employs a loading rate of 1 kN/sec to assess their dynamic performance under flexural loading conditions [111]. Notably, in **Figure 4.11**, JG-FRC4 exhibits the highest load-carrying capacity, indicating exceptional resistance to flexural loading, likely owing to the reinforcing effect of jute and glass fibers within the JG-FRCs [7 8]. Detailed flexural properties, encompassing flexural strength (F-S), flexural pre-crack absorbed energy (FE1), flexural post-crack absorbed energy (FE2), flexural total absorbed energy (FTE), and flexural toughness index (FTI), are concisely summarized in **Table 4.5**, providing comprehensive insights into the mechanical behavior of these materials. In comparison to PC, the various JG-FRCs demonstrate significant improvements in F-S except A3, with JG-FRC4 standing out due to its highest F-S, potentially attributed to its optimized blend of jute and glass fibers [44]. This overall enhancement in F-S across all JG-FRCs can be attributed to the fiber bridging effect, where fibers effectively reinforce the concrete matrix. Offering thorough insights into the mechanical characteristics of these materials, the diverse Jute and Glass Fiber-Reinforced Concretes (JG-FRCs) exhibit notable enhancements in flexural strength (F-S) when compared to plain concrete (PC). Notably, JG-FRC4 distinguishes itself with the highest F-S, potentially owing to its optimized combination of jute and glass fibers.

Furthermore, FE1 for A2, A3, A4, A5, A6 as 90%, 14%, 69%, 79% and 42% respectively increase compared to PC, emphasizing its substantial energy absorption capacity. In contrast, PC exhibits no flexural post-crack energy dissipation due to its inherent brittle behavior, while JG-FRCs display post-crack absorbed energies, primarily due to the presence of agricul-tural and commercial waste fibers that act as effective crack arrestors [48]. The toughness indices of JG-FRC1, JG-FRC2, JG-FRC3, JG-FRC4, and JG-FRC5 consistently surpass those of PC, with JG-FRC4 having the highest toughness index to its significant pre-crack and post-crack energy absorption capabilities, possibly attributed to the presence of jute fibers, known for their superior crack arrest properties [58]. The non-linear pre-crack behavior observed in concrete can be attributed to the uniform length of natural fibers, leading to an incremental increase in load-bearing capacity as deflection increases [48]. The toughness indices of JG-FRC1, JG-FRC2, JG-FRC3, JG-FRC4, and JG-FRC5 consistently exceed those of plain concrete (PC). In regions characterized by robust fiber bridging effects and strong fiber-matrix bonding, specimens exhibit superior load-bearing capacity and delayed crack propagation, highlighting the impact of fiber reinforcement on crack resistance. **Figure 4.12** illustrates typical flexural failure modes observed in both PC and JG-FRC specimens. The toughness indices of JG-FRC1, JG-FRC2, JG-FRC3, JG-FRC4, and JG-FRC5 consistently outperform those of plain concrete (PC). Notably, this superiority becomes evident in regions marked by robust fiber bridging effects and strong fiber-matrix bonding.

Table 4.5: Flexural Loading Variation of PCC and HNS-FRCs

Specimens	**FS (MPa)**	**FE1 (MJ/m^3)**	**FE2 (MJ/m^3)**	**FTE (MJ/m^3)**	**FTI**
A1	2.54	3.39	0	3.386	1
A2	3.5	6.5	0.46	6.88	1.07
A3	2.5	3.88	1.5	5.4	1.38
A4	3.85	5.72	2.23	7.95	1.4
A5	4.3	6.1	0.67	6.73	1.109
A6	3.0855	4.821	1.94	6.76	1.41

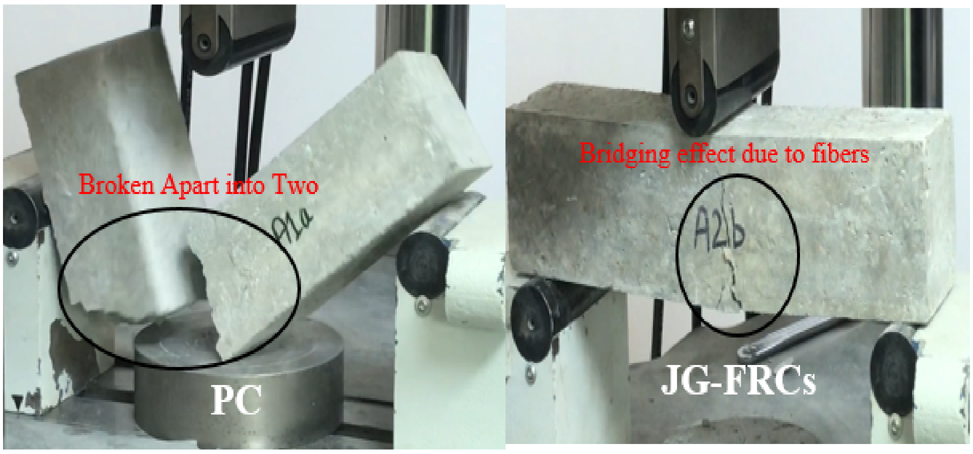

Figure 4.10: Typical Failure of Flexural Strength

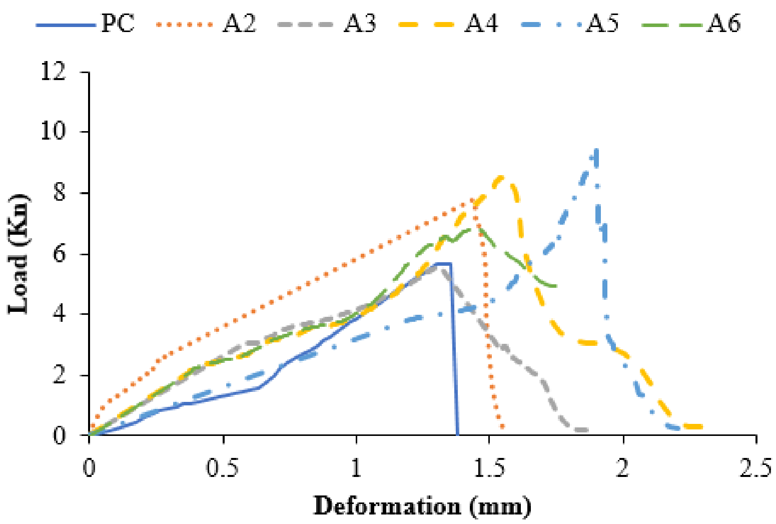

FIGURE 4.11: Flexural response of PCC and JG-FRCs

Provides the diverse properties, specifically observed under controlled and uniform flexural loading conditions. This graphical representation succinctly presents a thorough overview of the performance characteristics exhibited by the investigated materials. Significantly, precise measurements of strength parameters were undertaken, unveiling a substantial and consistent enhancement in the flexural loading capabilities across all tested HNS-FRC specimens. **Figure 4.13** offers a detailed visual comparison of various properties, specifically observed under controlled and consistent flexural loading conditions. This graphical representation serves as a concise yet comprehensive overview of the performance characteristics exhibited by the materials being investigated. Notably, precise measurements of strength parameters were conducted, revealing a substantial and consistent enhancement in the flexural loading capabilities of all tested HNS-FRCs specimens [70]. The superior mechanical properties of the A4 and A6 mixes can be attributed to optimized fiber combinations, uniform dispersion, strong fiber-matrix bonding, and synergistic effects between jute and glass fibers. These factors collectively enhance reinforcement within the concrete matrix, improve load transfer mechanisms, and resist crack propagation, resulting in higher strength and toughness compared to other formulations. This visual depiction effectively highlights the superior flexural performance of these materials within the context of the study's controlled testing conditions.

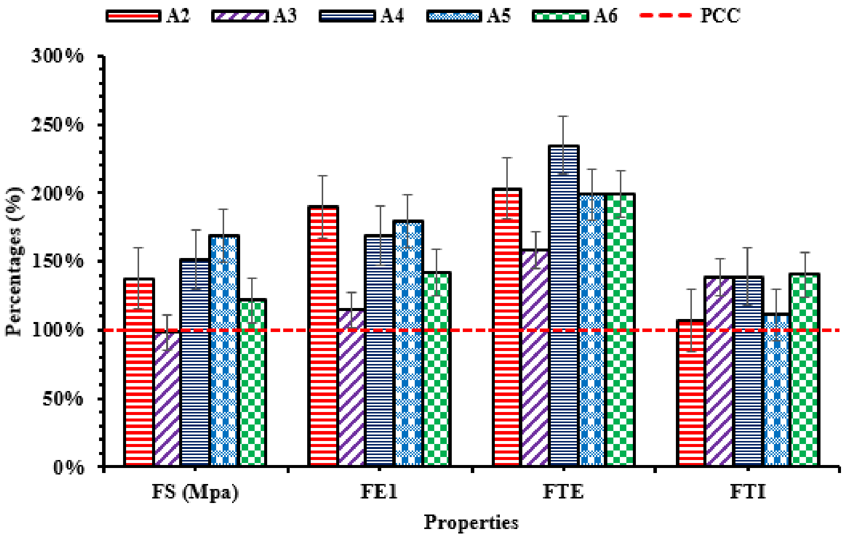

FIGURE 4.12: Flexural Properties Among All PC FRCs Specimens

4.5 Micro structure analysis Tests

4.5.1 Scanning Electron Microscopic Test (SEM)

SEM analysis of the A4 sample, which contains equal quantities of jute and glass fibers (i.e. 2.5% each), provides insights into its superior strength compared to other samples. The SEM images reveal a denser and more homogeneous microstructure in the A4 sample, with both types of fibers evenly distributed throughout the concrete matrix. This uniform dispersion of fibers ensures efficient load transfer mechanism and enhances the bond between the fibers and the surrounding matrix. As a result, the A4 sample exhibits improved resistance to crack initiation and propagation, leading to higher compressive strength. Additionally, SEM analysis also indicate the absence of voids and defects within the microstructure of the A4 sample, further contributing to its enhanced strength. Overall, the SEM results highlight the role of uniform fiber distribution and strong fiber-matrix interaction in enhancing the mechanical properties of the A4 sample. SEM analysis of optimized mix design is performed to examine the pull-out behavior of fibers. In **Figure 4.14**, beginning from the top-left corner of glass fiber and jute fibers are visible exhibiting the balling effect of GF with JF [150]. This might have happened due to the improper mixing of fibers leading to an uneven distribution in the mixture [149]. The image in the middle shows the extraction of fibers, with glass fiber having a bridging effect due to its extended length compared to jute fibers [25]. 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 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. **Figure 4.14** illustrates the micro-structure analysis of fiber-reinforced composite. In hybrid composites, the flexural properties are significantly influenced by the presence of glass fibers [129]. These fibers predominantly bear the load, and upon their failure, the residual load is shifted to the jute fibers. Examining the provided image, it becomes apparent that irregularities in the results stem from factors such as voids, inadequate bonding between the fibers and matrix, and improper blending.

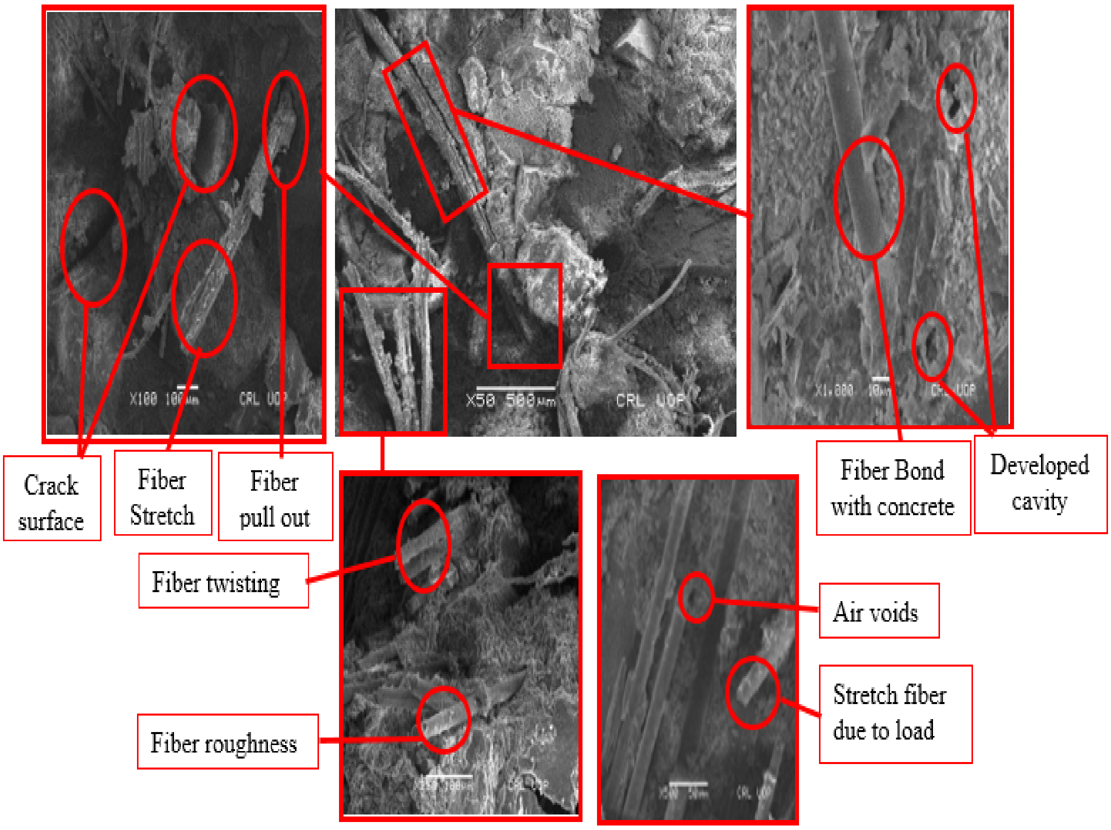

FIGURE 4.13: Scanning Electron microscopic Analysis (SEM)

4.5.2 X-ray Diffraction Analysis Test (XRD)

X-ray diffraction (XRD) analysis was meticulously conducted on a concrete specimen incorporating 2.5% jute fiber and 2.5% glass fiber to interrogate its crystalline structure and mineral composition. The XRD pattern clearly exhibited diffraction peaks that correlated with well-established crystalline phases inherent to concrete, notably including calcium silicate hydrates (C-S-H), calcium hydroxide (CH), and calcium carbonate ($C_a\mathrm{CO}_3$) [81, 83, 86]. These phases are fundamental constituents intricately linked to the cement hydration mechanism [92]. Significantly, it was observed that the inclusion of both jute and glass fibers did not introduce novel crystalline phases nor substantially modify the mineral composition of the concrete specimen [88].

This observation strongly implies that the fibers primarily played a mechanical role, augmenting the concrete's mechanical attributes without inducing significant alterations in its mineralogical constitu-tion [103].These stages are essential components intricately interconnected with the process of cement hydration. **Figure 4.15** illustrate the XRD analysis of the concrete specimen, featuring 2.5% jute and 2.5% glass fiber, yielded valuable insights into its crystalline framework, confirming the presence of customary con-crete phases. Simultaneously, it underscored the fibers' mechanical enhancement without materially affecting the mineral composition. The XRD analysis revealed that the inclusion of both jute and glass fibers in the concrete specimen did not introduce novel crystalline phases or substantially modify the mineral composition. This finding aligns with the mechanical and dynamic testing results, which demonstrated significant improvements in mechanical properties such as compressive strength, modulus of rupture, and fracture toughness due to the addition of HNS-FRCs. The absence of significant changes in mineral composition indicates that the fibers primarily played a mechanical role in augmenting the concrete's performance, confirming the correlation between the XRD findings and the observed enhancements in mechanical properties. **Figure 4.15** presents the XRD analysis of the concrete specimen, incorporating 2.5% jute and 2.5% glass fiber. This analysis provides valuable insights into the crystalline framework.

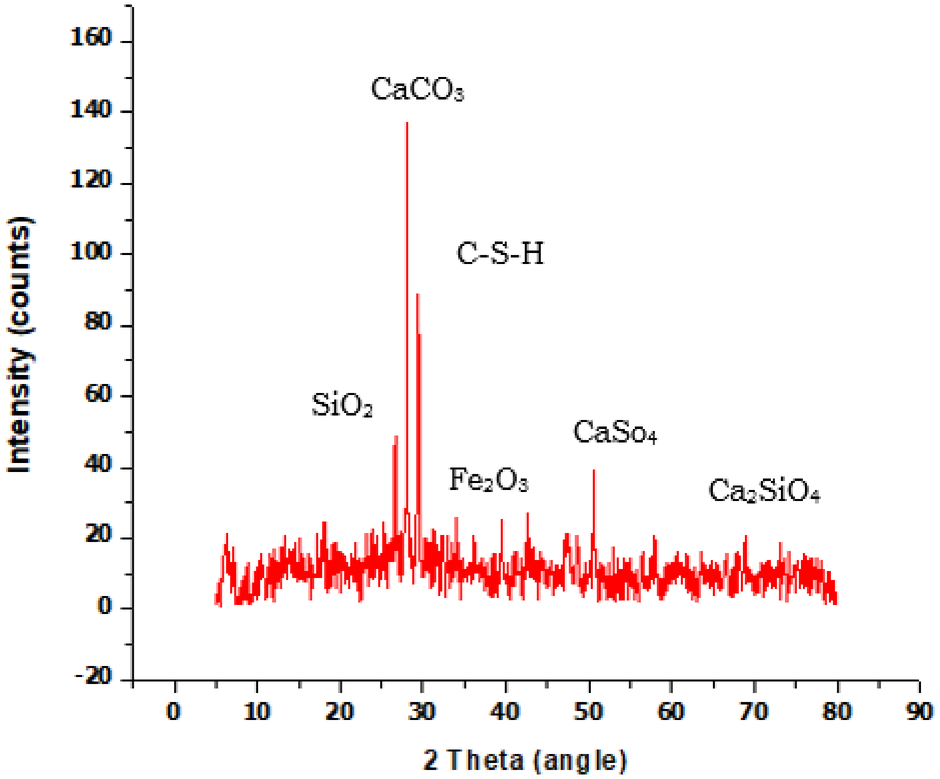

FIGURE 4.14: X-ray Diffraction Analysis (XRD)

4.6 Summary

Comprehensive testing was conducted on a range of concrete specimens, including plain concrete and HNS-FRCs. These tests encompassed evaluation of mechanical, dynamic, slump cone, and various mechanical properties, providing a comprehensive analysis of the material behaviors. The mix design employed a precise ratio of 1:2:3 for aggregates, cement, and sand, with a targeted water cement (w/c) ratio of 0.45. Additionally, superplasticizers were thoughtfully incorporated to enhance workability and performance. The addition of HNS-FRCs significantly improves various mechanical properties, such as energy absorption, toughness index, and overall strength, thereby enhancing structural performance. The observed enhancements in mechanical properties of specimen A4, having equal quantities of fiber i.e. 2.5% jute+2.5% glass, compared to PC reflect the effective reinforcement provided by hybrid natural and synthetic fibers. Despite an apparent deviation between mix design and results, these improvements underscore the adaptability and resilience of concrete mixtures, wherein variations in material properties can lead to unexpected enhancements in structural performance. Moreover, the SEM analysis supports these findings by revealing a denser microstructure with improved fiber-matrix bonding in A4, further supporting its superior mechanical properties. Thus, while probable deviations from mix design may occur, the significant improvements observed in A4 highlight the potential for optimizing concrete mixtures through careful consideration of material interactions and structural performance. In terms of compressive strength, A2, A3, and A5 experience a decrease of 22%, 17.46%, and 2% compared to PC, while A4 and A6 show an increase of 8.5% and 7.5%, respectively, due to fiber content. MOE decreases by 23.6%, 17.46%, and 2.6% in A2, A3, and A5, but increases by 3% in A4 and 7% in A6. CE1 values decrease by 8%, 35%, and 30% in A3, A4, A5 and A6 exhibits an increase in HNS-FRCs, CTE in A2, A4, and A5 is observed at 131%, 1%, and 12%, respectively, compared to PC, CTI increased by the same percentages relative to PC. STS value increases by 34% in A5 compared to PC, and STI an increase 81%, 215%, 153%, 51%, and 67% in A2, A3, A4, A5, and A6, respectively, in HNS-FRCs relative to PC.

Modulus of Rupture (MOR) demonstrates an increase of 38%, 51%, 69%, and 21% in A2, A4, A5, and A6 compared to PC, while FTE increases by 103%, 58%, 135%, 99%, and 100%, respectively. FTI exhibits an increase of 7%, 38%, 39%, 11%, and 40%, respectively, in HNS-FRCs compared to PC. The damping ratio in HNS-FRC cylinders increases by 125%, 75%, 35%, 128%, and 108% compared to PC. In a previous study, adding 50mm jute fiber to concrete with a mix of 1:3:1.5 resulted in a significant 36% reduction in compressive strength [168]. Similarly, a decrease in compressive strength was observed in recycled aggregate concrete as the jute fiber content exceeded 0.5%, attributed to inadequate dispersion and bonding between fibers and the matrix [169]. Whereas, current investigation reveals a contrasting outcome, with the optimized mix showing an 8.5% increase in compressive strength through the utilization of hybrid fibers. Previous research utilizing 50mm glass fibers in concrete with a composition of 1:3.33:1.67 showed a 5% increase in MoR [170], while another study reported a 20% increase in MoR with a 1% glass fiber content compared to plain concrete [171]. In contrast, this study demonstrates a considerable increase of 51% in MoR with the optimized mix employing hybrid fibers. This divergence highlights the effectiveness of hybrid fiber reinforcement in enhancing mechanical properties compared to single fiber. Moreover, glass fibers especially show greater resistance to tensile forces than jute fibers as represented in SEM test. The superior mechanical properties of the A4 and A6 mixes can be attributed to optimized fiber combinations, uniform dispersion, strong fiber-matrix bonding, and synergistic effects between jute and glass fibers. These factors collectively enhance reinforcement within the concrete matrix, improve load transfer mechanisms, and resist crack propagation, resulting in higher strength and toughness compared to other formulations.

Chapter 5

Discussion and Guidelines for Practical Implementation in Rigid Pavements

5.1 Background

The experimental samples utilized in the study yielded quantitative outcomes regarding the impact of length of jute and glass fibers on the characteristics of jute and glass fiber strengthened concrete. The mechanical properties of concrete were demonstrated through stress strain, load deflection, and load deformation curves, which revealed the effect of hybrid jute and glass fibers' lengths. The data required from dynamic and mechanical testing was then employed to establish the most suitable fiber length combinations for jute and glass fibers. Using data from dynamic and mechanical testing, the research identified the most suitable combinations of fiber lengths for both jute and glass fibers in concrete reinforcement. This chapter extensively discusses the practical application of this research and recommends the use of JG-FRC for rigid pavement implementation in real-life.

5.2 Optimized Combinations of Jute and Glass Fibers

This comprehensive study indicates that, in the context of flexural members such as beams and rigid pavements, their behavior closely resembles that of a slab. Initially, A5 and A6 can be supported for optimized mix. Whereas A5 and A6 exhibit zero slump, indicating poor workability of mix. Hence, on careful analysis of testing data reveals that A4 emerges as the optimized mix. Through meticulous examination of mechanical and dynamic properties, it becomes evident that A4 shows superior performance compared to other mixes. Factors such as fiber content, distribution, and matrix-fiber interaction play crucial roles in determining concrete properties. A4 demonstrates an optimal balance, exhibiting enhanced strength, toughness, and energy absorption capabilities, making it the preferred choice for rigid pavement applications. By prioritizing data-driven analysis, A4 emerges as the optimized mix, showcasing the importance of comprehensive evaluation in concrete mix design. **Table 5.1** displays the extreme values obtained from an array of mechanical and dynamic tests. The introduction of hybrid natural and synthetic fibers exerts a positive influence on both splitting tensile and flexural strength [53]. Conversely, the incorporation of hybrid natural and synthetic fibers derived from agricultural and commercial waste has a detrimental impact on the compressive strength of concrete. **Figure 5.1** graphically represents the influence of varying hybrid fiber lengths on the properties of JG-FRCs. From a toughness perspective, A5 (JG-FRC4) emerges as the preferred choice for both compression and tensile loading scenarios due to its superior toughness characteristics. In contrast, for flexural loading applications, A6 (JG-FRC5) takes precedence as it exhibits the highest toughness levels under such loading conditions. The addition of hybrid fibers with varying lengths has significantly improved the CTI , STI , and FTI in JG-FRCs compared to conventional plain concrete. These percentage variations in strengths, absorbed energies, and toughness indices are graphically depicted in **Figure 5.1**. Notably, there is a substantial increase in absorbed energies in the case of JG-FRC5, especially in the context of splitting tensile loading.

Based on the detailed analyzation of the testing data, the overall optimized mix in this study appears to be specimen A4. This specimen exhibited an increase in compressive strength by 8.5% compared toPC, indicating enhanced strength. Additionally, A4 demonstrated an increase in MoE by 3%, MoR by 51%, FTE by 135%, and FTI by 39% compared to PC. These improvements in mechanical properties suggest that the addition of HNS-FRCs in specimen A4 effectively enhances the overall strength of the concrete mix. Furthermore, the damping ratio in A4 cylinders increased by 128% compared to PC, indicating improved dynamic behavior and potential resistance to vibrations, which are crucial for structural integrity. The inclusion of hybrid fibers, combining both natural and synthetic elements, enhances both splitting tensile and flexural strength in concrete. In contrast, the integration of hybrid fibers from agricultural and commercial waste, which encompass both natural and synthetic components, adversely affects the compressive strength of the concrete.

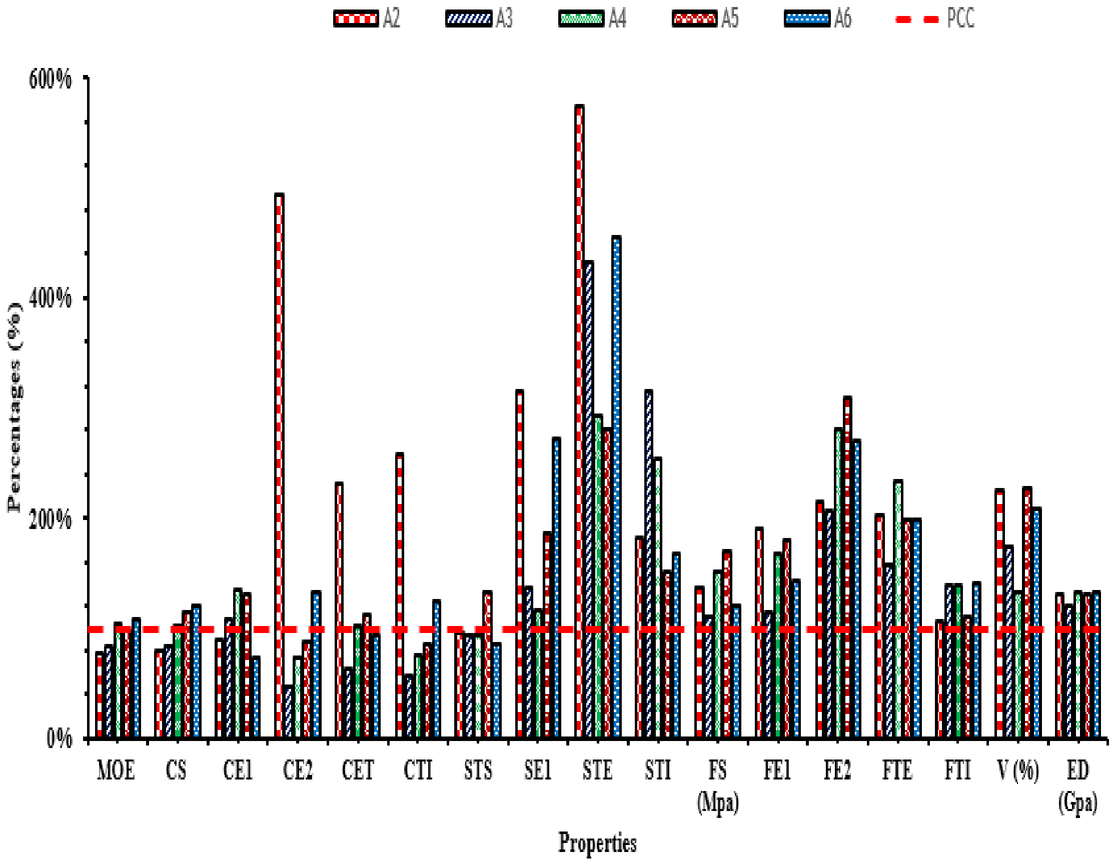

FIGURE 5.1: Optimized Percentage of Hybrid Jute and Glass Fibers

Table 5.1: Optimization of HNS-FRCs Specimens

Specimens	**MOE (GPa)**	**CS (MPa)**	**CTE (MJ/m^3)**	**CTI**	**STS (MPa)**	**STE (MJ/m^3)**	**STI**	**MOR (MPa)**	**FTE (MJ/m^3)**	**FTI**	ζ%	ED (GPa)
A1	30	17.65	0.103	1	2.2	11.33	1	2.5	3.4	1	4	4.75
A2	23.45	14.2	0.24	3.95	2.07	64.9	1.81	3.4	6.87	1.06	9	6.13
A3	24.85	14.74	0.15	2.28	2.03	48.9	3.15	2.49	5.4	1.38	7	5.3
A4	31.2	18.02	0.1521	1.7	2.04	33.2	2.53	3.8	7.9	1.4	5.35	6.24
A5	29.4	20.22	0.17	1.48	2.89	31.7	1.5	4.2	6.7	1.109	9.09	6.19
A6	32.25	21.24	0.17	1.84	1.86	51.5	1.67	3.08	6.8	1.4	8.33	6.29

5.3 Design and Operational Strategies of Rigid Pavement

In the domain of rigid pavement design, the determination of concrete thickness hinges upon two fundamental factors the modulus of elasticity and the modulus of rigidity [63]. These critical parameters find extensive use in pavement design through software systems such as AASHTO and American Concrete Pavement Association (ACPA) Street Pave [70]. Modifying the parameters of elasticity modulus and rupture modulus, while holding all other variables same, presents an opportunity to strategically reduce the necessary thickness of the concrete pavement [109]. As emphasized by Delatte [110], AASHTO recommends deriving the modulus of elasticity derived from the compressive durability of samples of concrete, given its limited influence on pavement thickness. Consequently, this modulus can be determined through testing the crushing strength for concrete specimens. The data table, **Table 5.2**, provides computed thickness values for HNS-FRC specimens in comparison to PCC. Notably, the values of the MOR and MOE exhibit variations depending on the specific concrete mix under consideration. The manual calculation of concrete pavement thickness employs the AASHTO pavement equation where Ec denotes the Elastic Modulus of Concrete (in psi), Sc represents the Flexural Strength of Concrete (in psi, determined empirically), W18 signifies the Traffic Load in Equivalent Standard Axle Loads (5.1 X 10^6 ESALs), Z_R is standard normal variation, S_0 is overall Standard deviation, W_18 is predicted number of load 18kips ESAL, D is the thickness of concrete pavement, E_c is elastic modulus of concrete, S_C id modulus of rupture, J is load transfer coefficient, C_d is a drainage Coefficient. In the domain of rigid pavement construction, it is imperative to note that specimens A2, A3, A4, A5, and A6 exhibit significantly reduced thickness values in comparison to conventional Portland cement (PC) pavement. Among these specimens, A5 and A4 stand out for achieving the most substantial reduction in thickness while simultaneously demonstrating superior mechanical and dynamic performance characteristics. It is essential to emphasize that A2, A3, and A6 also display reduced thickness profiles relative to PC, albeit slightly higher than those observed in A4 and A5. This discrepancy can be explained by the elevated jute fiber content incorporated into these specific specimens, resulting in an increase in the Modulus of Rupture (MOR). The variation can be accounted for by the higher presence of jute fibers in these particular samples, which leads to an elevation in the Modulus of Rupture (MOR).

$$\begin{aligned} log_{10}W_{18} = Z_R S_o + 7.35 log_{10}(D+1) - 0.06 + \frac{log_{10}[\delta PSI/(4.5-1.5)]}{1+[(1.624\times 10^7)/(D+1)^{8.46}]} \\ +(4.22-0.32P_t)log_{10}\left\{ \ \tfrac{S'cCd}{215.63J} \ \ D^{.75} - 1.132D^{.75} - [18.42/(E_c/k)^{.25}] \ \Big) \ \right\} \end{aligned} \tag{5.1}$$

Equation 5.1 shows the AASHTO design equation for rigid pavements. The AASHTO design equation for rigid pavement, outlined in the AASHTO Guide for Design of Pavement Structures, provides a systematic approach for determining the required thickness of rigid pavements based on various design parameters such as traffic loading, material properties, and environmental conditions. The equation incorporates empirical factors and structural analysis principles to ensure pavement performance and durability under anticipated traffic loads and environmental stresses. It considers factors such as traffic volume, axle loads, sub-grade strength, concrete properties, and climatic conditions to calculate the required thickness of the pavement section. The equation provides comprehensive approach to pavement design by extensive research and empirical data, making it a widely accepted and reliable methodology for designing rigid pavements that meet safety, performance, and longevity requirements in transportation infrastructure projects. **Figure 5.2** illustrate that the comparison of hybrid fiber with reference PCC specimens. Thus, the heightened jute fiber content within the concrete matrix definitively improves the performance characteristics of solid road surfaces, including both cost-effectiveness and structural durability. This imperative to advance pavement engineering is particularly salient in the context of developing nations. Improving the performance characteristics of solid road surfaces holds a critical role in creating more sustainable transportation infrastructure. This enhancement, which focuses on aspects such as cost-effectiveness and structural durability. The pivotal role played by MOR in thickness reduction is substantiated by the empirical evidence presented in **Table 5.2**. The augmented jute fiber content within the concrete matrix definitively enhances the performance characteristics of rigid road surfaces, encompassing both cost-effectiveness and structural durability. This imperative holds heightened significance in the context of developing nations, emphasizing the critical role of pavement engineering advancement. Elevating the performance of solid road surfaces plays a pivotal role in establishing more sustainable transportation infrastructure. The empirical evidence presented in this context substantiates the crucial influence of Modulus of Rupture (MOR) in thickness reduction.

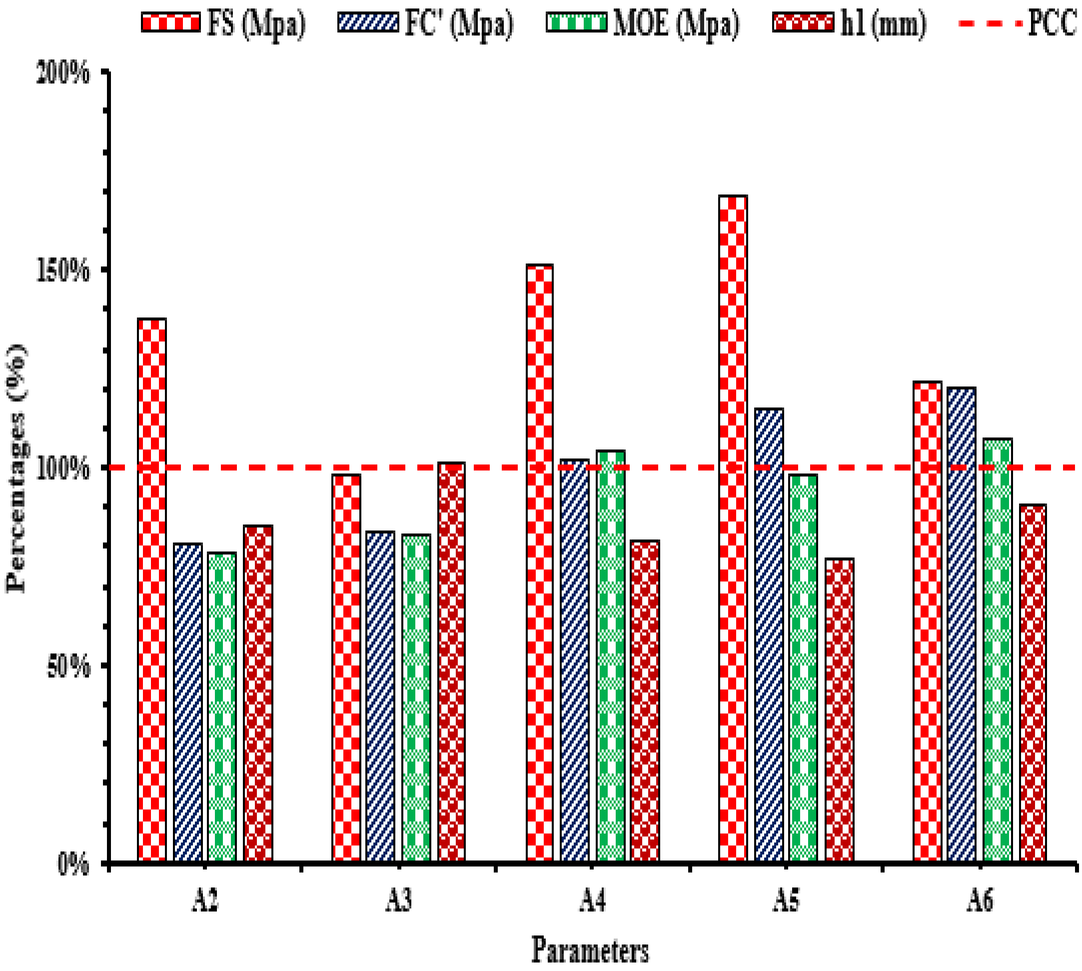

Figure 5.2: Improvement in Performance of Rigid Pavement with Utilization of Hybrid Fiber

Table 5.2: Pavement thickness design of rigid pavement using AASHTO equation

Material	**Flexural Strength FS (MPa)**	**Compressive Strength CS (MPa)**	**Modulus of Elasticity MOE (MPa)**	**Thickness from AASHTO equation (h1) (mm)**	**increase (%)**	**Decrease (%)**
A1	2.5407	17.65	30	217.4	-	-
A2	3.4974	14.2	23.5	185.23	37	-
A3	2.4918	14.74	24.9	219.11	-	2
A4	3.8442	18.02	31.2	176.8	51	-
A5	4.2915	20.22	29.4	167	68	-
A6	3.0855	21.244	32.3	197.2	21	-

5.4 Practical Implementations

In various civil engineering applications, concrete structures are subjected to a range of loads, encompassing both dynamic and mechanical forces. These burdens place considerable pressure on the effectiveness and functionality of concrete, with factors such as tensile and compressive strengths playing pivotal roles. Within the domain of rigid pavement applications, the genesis of cracks predominantly arises from factors including linear shrinkage, water absorption, and tensile strength. Conventionally, the strategy for mitigating concrete cracking involves harnessing the tensile and flexural properties of concrete [111]. Effective control of concrete cracking necessitates ensuring that induced stresses remain below the concrete's tensile strength threshold [112].

Furthermore, cracking stemming from differen-tial settlement can be addressed through augmentations in the flexural strength of the concrete. Hence, it is imperative to meticulously consider both mechani-cal and dynamic loading scenarios to safeguard concrete structures [104]. In this study, we conducted a comprehensive assessment of the performance character-istics of Portland Cement (PC) and High-Performance Natural Fiber-Reinforced Concretes (HNS-FRCs), incorporating varying proportions of jute and glass fibers. Our findings reveal that specimens labeled A2, A3, A4, A5, and A6 exhibit su-perior performance attributes suitable for pavement applications, as they enhance the mechanical properties of concrete in comparison to traditional PC. Notably, specimens A4 and A5 outperform other HNS-FRC variants. Furthermore, specimens A2, A3, A4, A5, and A6 demonstrate the potential to reduce crack formation due to their heightened flexural and tensile strength properties. This observation is further substantiated through an analysis of the relationship between Values for the coefficient of damping and values for the dissipation of energy, obtained from experimental data. Given that resonant responses during seismic events can precipitate structural failures, the augmented damping ratios observed in HNS-FRCs underscore their capacity to mitigate oscillations, owing to their superior energy absorption characteristics compared to PC. The improved properties of HNS-FRCs in crack reduction imply that the practical adoption of this investigated material can lead to elevated functionality, longevity, and efficiency of pavements. It is worth noting that Farooqi and Ali[28] pioneered the integration of wheat straw fiber in concrete, resulting in the development of the first fiber-reinforced rigid pavement, thus confirming its practical viability and performance. Additionally, researchers such as K. Arooj and M. Ali [128] have explored the use of hybrid natural fibers in concrete to drive enhancements in the performance of rigid pavements.

Figure 5.3 provides a comprehensive visual representation, meticulously detailing the process of placing and constructing FRC. The successful realization of rigid pavement empirically validates the effectiveness of integrating fibers within this application, substantiating their profound impact on critical structural properties. In today's construction landscape, fibers have garnered unparalleled attention and are widely utilized as essential additives in concrete formulations. This preeminence is due to their ubiquitous availability, easy handling characteristics, and their demonstrable capacity to significantly enhance the mechanical and durability attributes of concrete.


Surface preparation
Concrete lying
Concrete leveling
Prepared pavement

FIGURE 5.3: Wheat straw fiber reinforced concrete pavement [28]

However, the primary obstacle to their widespread practical deployment remains their limited availability in forms suitable for large-scale implementation, emphasizing the pressing need for readily processed fiber materials. Facilitating the accessibility of these processed fibers to the construction sector, along with a robust educational campaign, has the potential to effect substantial reductions in the utilization of various natural resources [89]. The concomitant reduction in resource consumption would invariably lead to a commensurate decrease in the overall costs associated with construction projects, while concurrently engendering significant enhancements in structural performance and longevity. This salutary effect is particularly conspicuous in the domain of rigid pavements, where the synergistic benefits of fiber reinforcement can be optimally harnessed.

5.5 Summary

The test specimens employed in the investigation produced measurable results concerning how the length of jute and glass fibers affects the properties of concrete reinforced with these fibers. The mechanical characteristics of the concrete were illustrated using stress-strain, load-deflection, and load-deformation curves, providing insights into the influence of the lengths of both jute and glass fibers. The information gathered from dynamic and mechanical tests was subsequently used to determine the most optimal combinations of fiber lengths for both jute and glass fibers. In this chapter, there is an in-depth exploration of the practical applications of this research, along with a recommendation for utilizing JG-FRC for the construction of rigid pavements in real-world scenarios.

Chapter 6

Conclusions and Future Recommendations

6.1 Conclusions

The present study investigates the mechanical behavior of Hybrid Natural and Synthetic Fiber Reinforced Concretes (HNS-FRCs) featuring diverse fiber content compositions, which combine jute and glass fibers. These variations in fiber content serve as parameters for evaluating the optimal fiber-to-cement ratio with the aim of mitigating crack propagation within rigid pavements. Plain cement concrete (PCC) properties are employed as the benchmark for comparative analysis. To produce the HNS-FRC specimens, we systematically introduced fiber contents of 1%, 2%, 2.5%, 3%, and 4% by mass of cement. Jute fibers, measuring 50 mm in length, and glass fibers, measuring 25 mm in length, were selected for inclusion in the mix. A consistent mix design ratio of 1:2:3 was applied for both PCC and HNS-FRCs, ensuring uniformity in testing conditions. The following conclusions emerge from the study's findings:

- The incorporation of fibers within hybrid natural and synthetic fiber-reinforced concrete (HNS-FRC) significantly enhances various mechanical properties, including energy absorption, the toughness index, and overall strength, thereby improving structural performance.

- Compressive strength (CS) experiences a decrease of 22%, 17.46%, and 2% in A2, A3, and A5 when compared to plain concrete (PC).
- A4 and A6 demonstrate an increase of 4% and 7.5% in compressive strength, respectively, due to optimal fiber content.
- Modulus of elasticity (MOE) registers a reduction of 23.6%, 17.46%, and 2.6% in A2, A3, and A5 but an increase of 3% in A4 and 7% in A6.
- CE1 values decrease by 8%, 35%, 30%, in A3, A4, and A5 due to the use of less dense fibers, whereas A6 exhibits an increase owing to the higher strength of the fibers.
- CTE in HNS-FRCs A2, A4, and A5 is observed at 131%, 1%, 12%, respectively, compared to PC. Concurrently, the CTI increases by the same percentages relative to PC.
- STS increases by 34% in A5 compared to PC.
- STI experiences an increase of 81%, 215%, 153%, 51%, and 67% in A2, A3, A4, A5, and A6, respectively in HNS-FRCs relative to PC.
- Modulus of Rupture (MOR) demonstrates an increase of 38%, 51%, 69%, and 21%, in A2, A4, A5, and A6 compared to PC, while Fiber FTE increases by 103%, 58%, 135%, 99%, and 100%, respectively.
- FTI exhibits an increase of 7%, 38%, 39%, 11%, and 40%, respectively in HNS-FRCs compared to PC.
- The damping ratio in HNS-FRC cylinders increases by 125%, 75%, 35%, 128%, and 108% compared to PC.
- Glass fibers exhibit greater resistance to pull-out forces than jute fibers due to their extended embedded length and increased frictional surface area.

The presence of fibers in HNS-FRCs leads to an increase in voids and the formation of air bubbles within concrete specimens.

- A2, A3, A4, A5, and A6 specimens demonstrate a reduction in rigid pavement thickness due to an enhanced modulus of rupture.
- The improved properties of HNS-FRCs specimens make them economically and durably suitable for practical applications, particularly in developing countries.
- Among the various HNS-FRC compositions investigated, A2, A3, A4, A5, and A6 exhibit enhanced efficiency in controlling cracking within rigid pavements, possibly due to the optimized bonding between fibers and specific concrete content.

6.2 Future Recommendations

Therefore, jute and glass, when combined in hybrid configurations within fiber-reinforced concrete, hold promise for improving concrete properties by adjusting their proportions in the concrete mix. The following tasks should be taken into account for future research efforts aimed at gaining a more comprehensive understanding of the behavior of Hybrid Natural-Synthetic Fiber-Reinforced Concretes (HNS-FRCs):

- It is essential to investigate HNS-FRCs using various fiber lengths while maintaining a constant fiber content.
- The enhancement of rigid pavement performance involves the utilization of wheat straw fiber, combined with the hybridizing effect of glass fibers.
- To improve the performance of rigid pavement, researchers have incorporated alternative filler materials such as ceramic waste, marble waste, etc., by partially replacing cement in HNS-FRCs.

- The introduction of additive filler materials like fly ash into HNS-FRCs has been explored to enhance rigid pavement performance.
- There is a need to explore the long-term durability of jute and glass fibers in concrete under various environmental conditions.
- One strategy for improving rigid pavement performance is to employ a hybrid effect by combining poly-propylene fiber with glass fiber.
- Research efforts should encompass empirical studies and the development of finite element models using HNS-FRC specimens.
- Investigating fiber decay within concrete mixtures is crucial for assessing performance under varying environmental conditions over time.
- It is advisable to conduct a Life Cycle Cost Analysis (LCCA) of agricultural and commercial waste materials, such as glass fibers and jute fiber reinforced concrete, including processing and construction costs. This analysis will shed light on the economic aspects of their utilization as products.

Bibliography

[1] Omar Faruqe Hamim, Saidis Salekin Aninda, Md Shamsul Hoque, and Md Hadiuzzaman. Suitability of pavement type for developing countries from an economic perspective using life cycle cost analysis. International Journal of Pavement Research and Technology, 14:259–266, 2021.

[2] Barnali Debnath and Partha Pratim Sarkar. Pervious concrete as an alternative pavement strategy: A state-of-the-art review. International Journal of Pavement Engineering, 21(12):1516–1531, 2020.

[3] Guilherme Alencar, Abílio MP de Jesus, Rui AB Calçada, and José Guilherme S da Silva. Fatigue life evaluation of a composite steel-concrete roadway bridge through the hot-spot stress method considering progressive pavement deterioration. Engineering Structures, 166:46–61, 2018.

[4] Muhammad Faheem Mohd Tahir, Mohd Mustafa Al Bakri Abdullah, Shayfull Zamree Abd Rahim, Mohd Rosli Mohd Hasan, Mohamed Saafi, Ramadhansyah Putra Jaya, and Rosnita Mohamed. Potential of industrial by-products based geopolymer for rigid concrete pavement application. Construction and Building Materials, 344:128190, 2022.

[5] Chidozie Maduabuchukwu Nwakaire, Soon Poh Yap, Chiu Chuen Onn, Choon Wah Yuen, and Hussein Adebayo Ibrahim. Utilisation of recycled concrete aggregates for sustainable highway pavement applications; a review. Construction and Building Materials, 235:117444, 2020.

[6] Waqas Latif Baloch, Hocine Siad, Mohamed Lachemi, and Mustafa Sahmaran. A review on the durability of concrete-to-concrete bond in recent rehabilitated structures. Journal of Building Engineering, 44:103315, 2021.

[7] Abid A Shah and Yuri Ribakov. Recent trends in steel fibered high-strength concrete. Materials Design, 32(8-9):4122–4151, 2011.

[8] Paolino Caputo, Michele Porto, Ruggero Angelico, Valeria Loise, Pietro Calandra, and Cesare Oliviero Rossi. Bitumen and asphalt concrete modified by nanometer-sized particles: Basic concepts, the state of the art and future perspectives of the nanoscale approach. Advances in Colloid and Interface Science, 285:102283, 2020.

[9] Xu Yang, Zhanping You, Jacob E Hiller, Mohd Rosli Mohd Hasan, Aboelkasim Diab, and Sang Luo. Sensitivity of rigid pavement performance predictions to individual climate variables using pavement me design. Journal of Transportation Engineering, Part B: Pavements, 146(3):04020028, 2020.

[10] Solomon Emeka Orji, Drc Ngwu, and Engr Dr Uc Anya. Models for predicting the structural properties and cost of concrete using laterite and quarry dust as fine aggregate. Unpublished Ph. D. Thesis Submitted to the Department of Quantity Surveying, Enugu State University of science and technology, Enugu State, Nigeria, 2021.

[11] Sukanta Kumer Shill. Cementitious Composites to Mitigate Surface Scaling of Concrete at Military Airbases. PhD thesis, UNSW Sydney, 2020.

[12] Joaqu´ın Liaudat. Experimental and numerical study of the effect of stress on asr expansions in concrete. 2018.

[13] Srishti Banerji. Behavior of ultra-high performance concrete beams under fire conditions. Michigan State University, 2021.

[14] Kaynat Arooj and M Ali. Mechanical, dynamic and absorption properties of hybrid fiber reinforced concrete for rigid pavements application. Masters in Civil Engineering, Capital University of Science technology, 2021.

[15] Mostafa Batouli, Michael Bienvenu, and Ali Mostafavi. Putting sustainability theory into roadway design practice: Implementation of lca and lcca analysis for pavement type selection in real world decision making. Transportation Research Part D: Transport and Environment, 52:289–302, 2017.

[16] Jovan Tatar and Sandra Milev. Durability of externally bonded fiberreinforced polymer composites in concrete structures: A critical review. Polymers, 13(5):765, 2021.

[17] Ahmed Hilal Farhan, Andrew Robert Dawson, and Nicholas Howard Thom. Recycled hybrid fiber-reinforced cement-stabilized pavement mixtures: Tensile properties and cracking characterization. Construction and Building Materials, 179:488–499, 2018.

[18] Yurdakul Ayg¨ormez, Orhan Canpolat, Mukhallad M Al-mashhadani, and Mucteba Uysal. Elevated temperature, freezing-thawing and wetting-drying effects on polypropylene fiber reinforced metakaolin based geopolymer composites. Construction and Building Materials, 235:117502, 2020.

[19] Bin Zhang, Waqas Ahmad, Ayaz Ahmad, Fahid Aslam, and Panuwat Joyklad. A scientometric analysis approach to analyze the present research on recycled aggregate concrete. Journal of Building Engineering, 46:103679, 2022.

[20] Mehran Khan, Abdul Rehman, and Majid Ali. Efficiency of silica-fume content in plain and natural fiber reinforced concrete for concrete road. Construction and Building Materials, 244:118382, 2020.

[21] Sarah Hansen and Pedram Sadeghian. Recycled gypsum powder from waste drywalls combined with fly ash for partial cement replacement in concrete. Journal of Cleaner Production, 274:122785, 2020.

[22] Iman Sadrinejad, Rahmat Madandoust, and Malek Mohammad Ranjbar. The mechanical and durability properties of concrete containing hybrid synthetic fibers. Construction and Building Materials, 178:72–82, 2018.

[23] Giuseppe Cantisani, Paola Di Mascio, and Laura Moretti. Comparative life cycle assessment of lighting systems and road pavements in an italian twin-tube road tunnel. Sustainability, 10(11):4165, 2018.

[24] Giuseppe Cantisani, Paola Di Mascio, and Laura Moretti. Comparative life cycle assessment of lighting systems and road pavements in an italian twin-tube road tunnel. Sustainability, 10(11):4165, 2018.

[25] Walter Nsengiyumva, Shuncong Zhong, Jiewen Lin, Qiukun Zhang, Jianfeng Zhong, and Yuexin Huang. Advances, limitations and prospects of nondestructive testing and evaluation of thick composites and sandwich structures: A state-of-the-art review. Composite Structures, 256:112951, 2021.

[26] Aimin Sha, Biao Ma, Hainian Wang, Liqun Hu, Xuesong Mao, Xilan Zhi, Huaxin Chen, Yu Liu, Feng Ma, Zhuangzhuang Liu, et al. Highway constructions on the qinghai-tibet plateau: Challenge, research and practice. Journal of Road Engineering, 2(1):1–60, 2022.

[27] Evan L Schmidt, Mariapaola Riggio, Andre R Barbosa, and Ignace Mugabo. Environmental response of a clt floor panel: Lessons for moisture management and monitoring of mass timber buildings. Building and Environment, 148:609–622, 2019.

[28] MZ Naser, RA Hawileh, and JA Abdalla. Fiber-reinforced polymer composites in strengthening reinforced concrete structures: A critical review. Engineering Structures, 198:109542, 2019.

[29] Renato Pereira, Antonio Lopes Batista, Luis Canhoto Neves, and Jos´e V Lemos. Deduction of ultimate equilibrium limit states for concrete gravity dams keyed into rock mass foundations based on large displacement analysis. In Structures, volume 38, pages 1180–1190. Elsevier, 2022.

[30] Baoguo Han, Liqing Zhang, and Jinping Ou. Smart and multifunctional concrete toward sustainable infrastructures. Springer, 2017.

[31] Mattia Francesco Bado and Joan R Casas. A review of recent distributed optical fiber sensors applications for civil engineering structural health monitoring. Sensors, 21(5):1818, 2021.

[32] Shuo Feng, Huigang Xiao, Rui Liu, and Min Liu. The bond properties between ultra-high-performance concrete and normal strength concrete substrate: Bond macro-performance and overlay transition zone microstructure. Cement and Concrete Composites, 128:104436, 2022.

[33] Khashayar Ebrahimi, Mohammad Javad Daiezadeh, Mohammad Zakertabrizi, Farhad Zahmatkesh, and Asghar Habibnejad Korayem. A review of the impact of micro-and nanoparticles on freeze-thaw durability of hardened concrete: Mechanism perspective. Construction and Building Materials, 186: 1105–1113, 2018.

[34] Rui Guo, Tengfei Nian, Ping Li, Jiangtao Fu, and Hong Guo. Anti-erosion performance of asphalt pavement with a sub-base of cement-treated mixtures. Construction and Building Materials, 223:278–287, 2019.

[35] Narges Kheradmandi and Vida Mehranfar. A critical review and comparative study on image segmentation-based techniques for pavement crack detection. Construction and Building Materials, 321:126162, 2022.

[36] Yue Chen, Guoping Cen, and Yunhua Cui. Comparative analysis on the anti-wheel impact performance of steel fiber and reticular polypropylene synthetic fiber reinforced airport pavement concrete under elevated temperature aging environment. Construction and Building Materials, 192:818–835, 2018.

[37] M Selvam, Solomon Debbarma, Surender Singh, and Xijun Shi. Utilization of alternative aggregates for roller compacted concrete pavements–a stateof-the-art review. Construction and building materials, 317:125838, 2022.

[38] Muhammad Usman Farooqi and Majid Ali. A study on natural fibre reinforced concrete from materials to structural applications. Arabian Journal for Science and Engineering, 48(4):4471–4491, 2023.

[39] Abdulaziz Alsaif and Yousef R Alharbi. Strength, durability and shrinkage behaviours of steel fiber reinforced rubberized concrete. Construction and Building Materials, 345:128295, 2022.

[40] Thamer Alomayri and Babar Ali. Investigating the load-deflection behaviour and drying shrinkage resistance of hpc reinforced using different cellulose fibres. Journal of Building Engineering, 73:106714, 2023.

[41] Sadegh Kazemi and Adam S Lubell. Influence of specimen size and fiber content on mechanical properties of ultra-high-performance fiber-reinforced concrete. ACI materials Journal, 109(6), 2012

[42] Jihui Qin, Jueshi Qian, Zhen Li, Chao You, Xiaobing Dai, Yanfei Yue, and Yingru Fan. Mechanical properties of basalt fiber reinforced magnesium phosphate cement composites. Construction and Building Materials, 188: 946–955, 2018.

[43] Vahid Afroughsabet and Togay Ozbakkaloglu. Mechanical and durability properties of high-strength concrete containing steel and polypropylene fibers. Construction and building materials, 94:73–82, 2015.

[44] FS Khalid, JM Irwan, MH Wan Ibrahim, N Othman, and S Shahidan. Splitting tensile and pullout behavior of synthetic wastes as fiber-reinforced concrete. Construction and Building Materials, 171:54–64, 2018.

[45] Mahmoud Abo El-Wafa. Fiber incorporation and crack control: A synergistic approach to improving serviceability of rc concrete. Global Journal of Engineering and Technology Advances, 15(02):001–010, 2023.

[46] M Ramesh, K Palanikumar, and K Hemachandra Reddy. Plant fibre based bio-composites: Sustainable and renewable green materials. Renewable and Sustainable Energy Reviews, 79:558–584, 2017.

[47] YL Xu, XH Zhang, S Zhan, XJ Hong, LD Zhu, Yong Xia, and Songye Zhu. Structural health monitoring of long suspension bridges: a test-bed. In Proceeding of 8th International Conference on Structural Dynamics, 2011.

[48] Donatas Sikarskas, Valentin Antonoviˇc, Jurgita Malaiˇskien˙e, Renata Boris, Rimvydas Stonys, and Genadijs Sahmenko. Effect of polyvinil alcohol fiber ˇ on the microstructure and properties of cement composite with expanded glass aggregates. In WMCAUS 2020-5 th World Multidisciplinary Civil Engineering Architecture-Urban Planning Symposium, 1-5 September, Prague, Czech Republic: abstract book, volume 1. IOP Publishing Ltd, 2020.

[49] Saptarshi Maiti, Md Rashedul Islam, Mohammad Abbas Uddin, Shaila Afroj, Stephen J Eichhorn, and Nazmul Karim. Sustainable fiber-reinforced composites: A review. Advanced Sustainable Systems, 6(11):2200258, 2022.

[50] Nithesh Naik, B Shivamurthy, BHS Thimmappa, Aman Gupta, John Zhanhu Guo, and Ilwoo Seok. A review on processing methods and characterization techniques of green composites. Engineered Science, 20: 80–99, 2022.

[51] S Dey, VV Praveen Kumar, KR Goud, and SKJ Basha. State of art review on self compacting concrete using mineral admixtures. Journal of Building Pathology and Rehabilitation, 6(1):18, 2021.

[52] Mihai-Paul Todor, Imre Kiss, and Vasile George Cioata. Development of fabric-reinforced polymer matrix composites using bio-based components from post-consumer textile waste. Materials Today: Proceedings, 45:4150– 4156, 2021.

[53] Hassan Ziari, Hassan Fazaeli, Seyed Javad Vaziri Kang Olyaei, and Mohammad Ali Ziari. Evaluation of effects of temperature, relative humidity, and wind speed on practical characteristics of plastic shrinkage cracking distress in concrete pavement using a digital monitoring approach. International Journal of Pavement Research and Technology, 15(1):138–158, 2022.

[54] Lucia Mancini, B Vidal Legaz, Matteo Vizzarri, Dominic Wittmer, Giacomo Grassi, and David Pennington. Mapping the role of raw materials in sustainable development goals. A Preliminary Analysis of Links, Monitoring Indicators, and Related Policy Initiatives, 3:1–9, 2019.

[55] Guipeng Chen, Yanlei Wang, Tao Yu, Baolin Wan, Bing Zhang, and Qing Liu. Behavior and design-oriented model for elliptical frp-confined concrete under axial compression. Engineering Structures, 249:113387, 2021.

[56] Jawad Ahmad and Zhiguang Zhou. Mechanical properties of natural as well as synthetic fiber reinforced concrete: a review. Construction and Building Materials, 333:127353, 2022.

[57] Nima Mohamadian, Hamzeh Ghorbani, Hamid Bazrkar, and David A Wood. Carbon-nanotube-polymer nanocomposites enable wellbore cements to better inhibit gas migration and enhance sustainability of natural gas reservoirs. In Sustainable Natural Gas Reservoir and Production Engineering, pages 243–268. Elsevier, 2022.

[58] Simon Gallagher. Mechanical Resistance of cracked dam mass concrete repaired by grouting: an experimental study. PhD thesis, École Polytechnique de Montréal, 2012.

[59] Sandeep Kumar, Lalta Prasad, and Vinay Kumar Patel. Effect of hybridization of glass/kevlar fiber on mechanical properties of bast reinforced polymer composites: a review. Am. J. Polym. Sci. Eng, 5(13-23), 2017.

[60] Reinhard Krüger and Jürgen Groll. Fiber reinforced calcium phosphate cements–on the way to degradable load bearing bone substitutes? Biomaterials, 33(25):5887–5900, 2012.

[61] Noah Thibodeaux, Daniel E Guerrero, Jose L Lopez, Matthew J Bandelt, and Matthew P Adams. Effect of cold plasma treatment of polymer fibers on the mechanical behavior of fiber-reinforced cementitious composites. Fibers, 9(10):62, 2021.

[62] Natt Makul. Advanced smart concrete-a review of current progress, benefits and challenges. Journal of Cleaner Production, 274:122899, 2020.

[63] Michael D Meyer and Brent Weigel. Climate change and transportation engineering: Preparing for a sustainable future. Journal of Transportation Engineering, 137(6):393–403, 2011.

[64] Kirti Mishra, Nishu Devi, Samarjeet Singh Siwal, Qibo Zhang, Walaa F Alsanie, Fabrizio Scarpa, and Vijay Kumar Thakur. Ionic liquid-based polymer nanocomposites for sensors, energy, biomedicine, and environmental applications: Roadmap to the future. Advanced Science, 9(26):2202187, 2022.

[65] Xiuling Wang, Feifei Fan, Jinxing Lai, and Yongli Xie. Steel fiber reinforced concrete: A review of its material properties and usage in tunnel lining. In Structures, volume 34, pages 1080–1098. Elsevier, 2021.

[66] Sunkuk Kim, Seunghyun Son, and Donghoon Lee. Development of sustainable production technology of free-form concrete panels using a multi-point press cnc machine. Sustainability, 13(4):1990, 2021.

[67] Saroj Gupta, VVL Kanta Rao, and Jayabrata Sengupta. Evaluation of polyester fiber reinforced concrete for use in cement concrete pavement works. Road materials and pavement design, 9(3):441–461, 2008.

[68] Fabiola Vilaseca, Romina Del Rey, Ramon Serrat, Jesus Alba, Pere Mutje, and Francesc X Espinach. Macro and micro-mechanics behavior of stifness in alkaline treated hemp core fibres polypropylene-based composites. Composites Part B: Engineering, 144:118–125, 2018.

[69] PS Song, Sungmoon Hwang, and BC Sheu. Strength properties of nylon- and polypropylene-fiber-reinforced concretes. Cement and concrete research, 35 (8):1546–1550, 2005.

[70] Kin-tak Lau, Pui-yan Hung, Min-Hao Zhu, and David Hui. Properties of natural fibre composites for structural engineering applications. Composites Part B: Engineering, 136:222–233, 2018.

[71] Fabio Iucolano, Luca Boccarusso, and Antonio Langella. Hemp as ecofriendly substitute of glass fibres for gypsum reinforcement: Impact and flexural behaviour. Composites Part B: Engineering, 175:107073, 2019.

[72] Wisal Ahmed and CW Lim. Coupling effect assessment of vacuum based pozzolana slurry encrusted recycled aggregate and basalt fiber on mechanical performance of fiber reinforced concrete. Construction and Building Materials, 300:124032, 2021.

[73] Md Jihad Miah, Junjie Pei, Hyeju Kim, and Jeong Gook Jang. Flexural behavior, porosity, and water absorption of co2-cured amorphous metallicfiber-reinforced belite-rich cement composites. Construction and Building Materials, 387:131668, 2023.

[74] Onur Ozturk and Nilufer Ozyurt. Sustainability and cost-effectiveness of steel and polypropylene fiber reinforced concrete pavement mixtures. Journal of Cleaner Production, 363:132582, 2022.

[75] Nghia P Tran, Chamila Gunasekara, David W Law, Shadi Houshyar, Sujeeva Setunge, and Andrzej Cwirzen. A critical review on drying shrinkage mitigation strategies in cement-based materials. Journal of Building Engineering, 38:102210, 2021.

[76] Robert Haigh, Malindu Sandanayake, Yanni Bouras, and Zora Vrcelj. A review of the mechanical and durability performance of kraft-fibre reinforced mortar and concrete. Construction and Building Materials, 297:123759, 2021.

[77] Satheeskumar Navaratnam, Kajanan Selvaranjan, Darshana Jayasooriya, Pathmanathan Rajeev, and Jay Sanjayan. Applications of natural and synthetic fiber reinforced polymer in infrastructure: a suitability assessment. Journal of Building Engineering, page 105835, 2023.

[78] M Cao, C Xie, L Li, and M Khan. Effect of different pva and steel fiber length and content on mechanical properties of caco 3 whisker reinforced cementitious composites. Materiales de Construcci´on, 69(336):e200–e200, 2019.

[79] Hui Zhong and Mingzhong Zhang. Experimental study on engineering properties of concrete reinforced with hybrid recycled tyre steel and polypropylene fibres. Journal of Cleaner Production, 259:120914, 2020.

[80] Muhammad Yasir Khalid, Zia Ullah Arif, Waqas Ahmed, and Hassan Arshad. Recent trends in recycling and reusing techniques of different plastic polymers and their composite materials. Sustainable Materials and Technologies, 31:e00382, 2022.

[81] Kaijian Huang, Xijun Shi, Dan Zollinger, MirMilad Mirsayar, Aiguo Wang, and Liwu Mo. Use of mgo expansion agent to compensate concrete shrinkage in jointed reinforced concrete pavement under high-altitude environmental conditions. Construction and Building Materials, 202:528–536, 2019.

[82] Christina Plati. Sustainability factors in pavement materials, design, and preservation strategies: A literature review. Construction and Building Materials, 211:539–555, 2019.

[83] Abhilash Mukherjee, Prateek Srivastava, Jasminder Kaur Sandhu, et al. Application of smart materials in civil engineering: A review. Materials Today: Proceedings, 2021.

[84] Supasit Srivaranun, Mitsuyoshi Akiyama, Taiki Yamada, Dan M Frangopol, and Jiyu Xin. A novel combined experimental-machine learning approach to estimate the probabilistic capacity of rc beams with spatially correlated rebar corrosion in transverse and longitudinal directions. Engineering Structures, 279:115588, 2023.

[85] Phuong Ngoc Pham, Yan Zhuge, Anaclet Turatsinze, Ahmed Toumi, and Rafat Siddique. Application of rubberized cement-based composites in pavements: Suitability and considerations. Construction and Building Materials, 223:1182–1195, 2019.

[86] Chanmi Moon, Jung Yun Won, Kijung Lee, Jinwoo Lee, Sung-Woong Kim, and Myoung-Gyu Lee. Mechanical behavior and interfacial damage of carbon

steel-stainless steel corrosion resisted-alloy (cra) cladded plate: Hybrid analysis based on experiment and finite element modeling. Materials Science and Engineering: A, 852:143697, 2022.

[87] Michelle Daarol, Marl Jun Pepito, Rhona Fe Sambong, et al. Properties of fiber cement board affected by afplf (abaca fiber and pineapple leaf fiber). In E3S Web of Conferences, volume 405, page 04004. EDP Sciences, 2023.

[88] Muhammad Usman Farooqi and Majid Ali. Contribution of plant fibers in improving the behavior and capacity of reinforced concrete for structural applications. Construction and Building Materials, 182:94–107, 2018.

[89] Aaron Costin, Alireza Adibfar, Hanjin Hu, and Stuart S Chen. Building information modeling (bim) for transportation infrastructure–literature review, applications, challenges, and recommendations. Automation in construction, 94:257–281, 2018.

[90] Omniya el Baghdadi. Exploring the economic business case for incorporating biophilic urbanism. PhD thesis, Queensland University of Technology, 2016.

[91] Kerstin M¨uller, Elodie Bugnicourt, Marcos Latorre, Maria Jorda, Yolanda Echegoyen Sanz, Jos´e M Lagaron, Oliver Miesbauer, Alvise Bianchin, Steve Hankin, Uwe B¨olz, et al. Review on the processing and properties of polymer nanocomposites and nanocoatings and their applications in the packaging, automotive and solar energy fields. Nanomaterials, 7(4):74, 2017.

[92] Yahya R Atewi, Mustafa F Hasan, and Erhan G¨uneyisi. Fracture and permeability properties of glass fiber reinforced self-compacting concrete with and without nanosilica. Construction and Building Materials, 226:993–1005, 2019.

[93] Waheed Uddin et al. A synthesis study of noncontact nondestructive evaluation of top-down cracking in asphalt pavements. 2013.

[94] Shruti Singh et al. Design of Crack Attenuating Mix using Waste Plastic. PhD thesis, 2022.

[95] Usama Ebead, Denvid Lau, Federica Lollini, Antonio Nanni, Prannoy Suraneni, and Tao Yu. A review of recent advances in the science and technology of seawater-mixed concrete. Cement and concrete research, 152:106666, 2022.

[96] Ali Amin. Post cracking behaviour of steel fibre reinforced concrete: from material to structure. PhD thesis, UNSW Sydney, 2015.

[97] Tracy Leh Xin Wong, Mohd Rosli Mohd Hasan, and Leo Choe Peng. Recent development, utilization, treatment and performance of solid wastes additives in asphaltic concrete worldwide: A review. Journal of Traffic and Transportation Engineering (English Edition), 2022.

[98] Karena Ka Wai Hui, Man Sing Wong, Coco Yin Tung Kwok, Hon Li, Sawaid Abbas, and Janet E Nichol. Unveiling falling urban trees before and during typhoon higos (2020): Empirical case study of potential structural failure using tilt sensor. Forests, 13(2):359, 2022.

[99] Victor C Li, Freek P Bos, Kequan Yu, Wes McGee, Tsz Yan Ng, Stefan Chaves Figueiredo, Karsten Nefs, Viktor Mechtcherine, Venkatesh Naidu Nerella, Jinlong Pan, et al. On the emergence of 3d printable engineered, strain hardening cementitious composites (ecc/shcc). Cement and Concrete Research, 132:106038, 2020.

[100] Denise Ziegler. I experience as i experiment–i experiment as i experience. experience and experimentality in artistic work and research. 2019.

[101] Avishreshth Singh, Prasanna Venkatesh Sampath, and Krishna Prapoorna Biligiri. A review of sustainable pervious concrete systems: Emphasis on clogging, material characterization, and environmental aspects. Construction and Building Materials, 261:120491, 2020.

[102] SZ Qian, VC Li, H Zhang, and GA Keoleian. Life cycle analysis of pavement overlays made with engineered cementitious composites. Cement and Concrete Composites, 35(1):78–88, 2013.

[103] Sadia Sajid Khan. Effect of Pine Needles and Glass Fibers on Concrete Performance. PhD thesis, CAPITAL UNIVERSITY, 2023.

[104] Hemn Unis Ahmed, Ahmed S Mohammed, and Azad A Mohammed. Fresh and mechanical performances of recycled plastic aggregate geopolymer concrete modified with nano-silica: Experimental and computational investigation. Construction and Building Materials, 394:132266, 2023.

[105] Rowan Arundel, Ang Li, Emma Baker, and Rebecca Bentley. Housing unaffordability and mental health: dynamics across age and tenure. International Journal of Housing Policy, pages 1–31, 2022.

[106] Industry Agenda. Shaping the future of construction a breakthrough in mindset and technology. In World Economic Forum, 2016

[107] Daquan Sun, Guoqiang Sun, Xingyi Zhu, Alvaro Guarin, Bin Li, Ziwei Dai, and Jianming Ling. A comprehensive review on self-healing of asphalt materials: Mechanism, model, characterization and enhancement. Advances in colloid and interface science, 256:65–93, 2018.

[108] Natt Makul. Modern sustainable cement and concrete composites: Review of current status, challenges and guidelines. Sustainable Materials and Technologies, 25:e00155, 2020.

[109] Ugo De Corato, Isabella De Bari, Egidio Viola, and Massimo Pugliese. Assessing the main opportunities of integrated biorefining from agro-bioenergy co/by-products and agroindustrial residues into high-value added products associated to some emerging markets: A review. Renewable and Sustainable Energy Reviews, 88:326–346, 2018.

[110] Tasneem Abbasi and SA Abbasi. Biomass energy and the environmental impacts associated with its production and utilization. Renewable and sustainable energy reviews, 14(3):919–937, 2010.

[111] George Z Kyzas. Green adsorbents. Bentham Science Publishers, 2015.

[112] Brenda S Tubana, Tapasya Babu, and Lawrence E Datnoff. A review of silicon in soils and plants and its role in us agriculture: history and future perspectives. Soil science, 181(9/10):393–411, 2016.

[113] B Sangmesh, Nagraj Patil, Krishna Kumar Jaiswal, TP Gowrishankar, K Karthik Selvakumar, MS Jyothi, R Jyothilakshmi, and Santosh Kumar. Development of sustainable alternative materials for the construction of green buildings using agricultural residues: A review. Construction and Building Materials, 368:130457, 2023.

[114] Ali Razmi and MM Mirsayar. On the mixed mode i/ii fracture properties of jute fiber-reinforced concrete. Construction and Building Materials, 148: 512–520, 2017.

[115] Ramanaiah Kandula, Srinivas Prasad Sanaka, Ratna Prasad AV, and Hemachandra Reddy. K. Thermo-physical and fire properties of natural fiber composites for energy saving applications. Journal of Natural Fibers, 19(15):11845–11857, 2022.

[116] M Shadheer Ahamed, P Ravichandran, and AR Krishnaraja. Natural fibers in concrete–a review. In IOP Conference Series: Materials Science and Engineering, volume 1055, page 012038. IOP Publishing, 2021.

[117] GB Ramesh Kumar and V Kesavan. Study of structural properties evaluation on coconut fiber ash mixed concrete. Materials Today: Proceedings, 22: 811–816, 2020.

[118] Akhila Padanattil, Jayanarayanan Karingamanna, and KM Mini. Novel hybrid composites based on glass and sisal fiber for retrofitting of reinforced concrete structures. Construction and Building Materials, 133:146– 153, 2017.

[119] Ismail Shah, Li Jing, Zhang Ming Fei, Yang Sheng Yuan, Muhammad Umar Farooq, and Nipapan Kanjana. A review on chemical modification by using sodium hydroxide (naoh) to investigate the mechanical properties of sisal, coir and hemp fiber reinforced concrete composites. Journal of Natural Fibers, 19(13):5133–5151, 2022.

[120] Musa Adamu, Mohammad Louay Marouf, Yasser E Ibrahim, Omar Shabbir Ahmed, Hani Alanazi, and Abdulrahman Louay Marouf. Modeling and optimization of the mechanical properties of date fiber reinforced concrete containing silica fume using response surface methodology. Case Studies in Construction Materials, 17:e01633, 2022.

[121] TES Lima, LUD Tambara J´unior, LFC Nascimento, LCC Demosthenes, SN Monteiro, and ARG Azevedo. Evaluation of the feasibility application of malva fibers in cement-based composites. Journal of Materials Research and Technology, 23:6274–6286, 2023.

[122] Supriya Mishra, Amar K Mohanty, Lawrence T Drzal, Manjusri Misra, and Georg Hinrichsen. A review on pineapple leaf fibers, sisal fibers and their biocomposites. Macromolecular Materials and Engineering, 289(11):955– 974, 2004.

[123] Elie Awwad, Mounir Mabsout, Bilal Hamad, Mohamad Talal Farran, and Helmi Khatib. Studies on fiber-reinforced concrete using industrial hemp fibers. Construction and Building Materials, 35:710–717, 2012.

[124] Gunti Rajesh, AV Ratna Prasad, and AVSSKS Gupta. Mechanical and degradation properties of successive alkali treated completely biodegradable sisal fiber reinforced poly lactic acid composites. Journal of Reinforced Plastics and Composites, 34(12):951–961, 2015.

[125] Ismail Luhar, Salmabanu Luhar, Mohd Mustafa Al Bakri Abdullah, Rafiza Abdul Razak, Petrica Vizureanu, Andrei Victor Sandu, and PetreDaniel Matasaru. A state-of-the-art review on innovative geopolymer composites designed for water and wastewater treatment. Materials, 14(23): 7456, 2021.

[126] Mahmoud H Akeed, Shaker Qaidi, Hemn U Ahmed, Rabar H Faraj, Ahmed S Mohammed, Wael Emad, Bassam A Tayeh, and Afonso RG Azevedo. Ultrahigh-performance fiber-reinforced concrete. part iv: Durability properties, cost assessment, applications, and challenges. Case Studies in Construction Materials, 17:e01271, 2022.

[127] Muhammad Irfan. Partial Replacement of Cement with Eggshell and Marble Dust Powder in Pine-Needle Fiber Reinforced Concrete. PhD thesis, CAPITAL UNIVERSITY, 2023.

[128] Al Emran Ismail, SNA Khalid, and Nik Hisyamudin Muhd Nor. A review on the perforated impact energy absorption of kenaf fibres reinforced composites. In Journal of Physics: Conference Series, volume 914, page 012044. IOP Publishing, 2017.

[129] Srikanth Koniki and D Ravi Prasad. Influence of hybrid fibres on strength and stress-strain behaviour of concrete under uni-axial stresses. Construction and Building Materials, 207:238–248, 2019.

[130] David B Dittenber and Hota VS GangaRao. Critical review of recent publications on use of natural composites in infrastructure. Composites Part A: applied science and manufacturing, 43(8):1419–1429, 2012.

[131] Varun Mittal and Shishir Sinha. Mechanical, thermal, and water absorption properties of wheat straw/bagasse-reinforced epoxy blended composites. Advances in Polymer Technology, 37(7):2497–2503, 2018.

[132] Min Li, Shou Xi Chai, Hu Yuan Zhang, Hong Pu Du, and Li Wei. Feasibility of saline soil reinforced with treated wheat straw and lime. Soils and foundations, 52(2):228–238, 2012.

[133] K Palanikumar, M Ramesh, and K Hemachandra Reddy. Experimental investigation on the mechanical properties of green hybrid sisal and glass fiber reinforced polymer composites. Journal of Natural Fibers, 13(3):321– 331, 2016.

[134] NM Nurazzi, MRM Asyraf, A Khalina, N Abdullah, HA Aisyah, S Ayu Rafiqah, FA Sabaruddin, SH Kamarudin, MNF Norrrahim, RA Ilyas, et al. A review on natural fiber reinforced polymer composite for bullet proof and ballistic applications. Polymers, 13(4):646, 2021.

[135] Francesco Canestrari and Lorenzo Paolo Ingrassia. A review of top-down cracking in asphalt pavements: Causes, models, experimental tools and future challenges. Journal of Traffic and Transportation Engineering (English Edition), 7(5):541–572, 2020.

[136] Kevin J Edgar, Charles M Buchanan, John S Debenham, Paul A Rundquist, Brian D Seiler, Michael C Shelton, and Debra Tindall. Advances in cellulose ester performance and application. Progress in polymer science, 26(9):1605–1688, 2001.

[137] Muhammad Basit Khan, Ahsan Waqar, Naraindas Bheel, Nasir Shafiq, Nadhim Hamah Sor, Dorin Radu, and Omrane Benjeddou. Optimization of fresh and mechanical characteristics of carbon fiber-reinforced concrete composites using response surface technique. Buildings, 13(4):852, 2023.

[138] Mohammad Zakaria, Mashud Ahmed, Mozammel Hoque, and Abu Shaid. A comparative study of the mechanical properties of jute fiber and yarn reinforced concrete composites. Journal of Natural Fibers, 2018.

[139] Pappu Asokan, Mohamed Osmani, and Andrew DF Price. Improvement of the mechanical properties of glass fibre reinforced plastic waste powder filled concrete. Construction and Building Materials, 24(4):448–460, 2010.

[140] Li, Shuai, Tengteng Zheng, Qi Li, Yingcheng Hu, and Bing Wang. "Flexural and energy absorption properties of natural-fiber reinforced composites with a novel fabrication technique." Composites Communications 16 (2019): 124-131.

[141] Ruben, Nerella, Chava Venkatesh, Chereddy Sonali Sri Durga, and Madduru Sri Rama Chand. "Comprehensive study on performance of glass fibers-based concrete." Innovative Infrastructure Solutions 6, no. 2 (2021): 112.

[142] Khalid, Muhammad Yasir Arif, Zia Ullah Sheikh, Muhammad Nasir, Muhammad Ali. (2021). Mechanical characterization of glass and jute fiber-based hybrid composites fabricated through compression molding technique. International Journal of Material Forming. 14. 1-11. 10.1007/s12289-021-01624-w.

[143] Abbas, Yassir M., and M. Iqbal Khan. ”Fiber–matrix interactions in fiber-reinforced concrete: A review.” Arabian Journal for Science and Engineering 41, no. 4 (2016): 1183-1198.

[144] Memon, Imtiaz Ahmed, Ashfaque Ahmed Jhatial, Samiullah Sohu, Muhammad Tahir Lakhiar, and Zahid Hussain. ”Influence of fibre length on the behaviour of polypropylene fibre reinforced cement concrete.” Civil Engineering Journal 4, no. 9 (2018): 2124-2131.

[145] Shaikh, Mohd Afsar, A. Razzaq, G. Selvarani, and Faizan Mujahid. ”Comparative study between fibre reinforced concrete (Glass, Jute, Steel Fibre) with traditional concrete.” Int J Eng Res Technol. ISSN (Online) (2021): 2278-0181.

[146] Chen, Lin, Zhonghao Chen, Zhuolin Xie, Lilong Wei, Jianmin Hua, Lepeng Huang, and Pow-Seng Yap. ”Recent developments on natural fiber concrete: A review of properties, sustainability, applications, barriers, and opportunities.” Developments in the Built Environment 16 (2023): 100255.

[147] Anas, Muhammad, Majid Khan, Hazrat Bilal, Shantul Jadoon, and Muhammad Nadeem Khan. ”Fiber Reinforced Concrete: A Review.” Engineering Proceedings 22, no. 1 (2022): p3.

[148] Ali, Babar, Hawreen Ahmed, Hisham Hafez, Ameni Brahmia, Mohamed Hechmi El Ouni, and Ali Raza. ”Life cycle impact assessment (cradle-to-gate) of fiber-reinforced concrete application for pavement use: A case study of Islamabad City.” International Journal of Pavement Research and Technology 16, no. 2 (2023): 247-263.

[149] Hait, P. R. I. T. A. M., R. Karthik, Rituparna Mitra, and Ritwik Haldar. ”Natural and Artificial Fibre Reinforced Concrete: A State-of-art Review.” International Journal of Engineering 37, no. 3 (2024): 503-510.

[150] Khan, Muhammad Basit, Nasir Shafiq, Ahsan Waqar, Dorin Radu, Ciprian Cismaș, Muhammad Imran, Hamad Al-mujibah, and Omrane Benjeddou. ”Effects of jute fiber on fresh and hardened characteristics of concrete with environmental assessment.” Buildings 13, no. 7 (2023): 1691.

[151] Begum, Hosne Ara, Tanima Rahman Tanni, and Md Abul Shahid. "Analysis of water absorption of different natural fibers." Journal of Textile Science and Technology 7, no. 4 (2021): 152-160.

[152] Alsadey, Salahaldein, and Saieed Mohamed. "Evaluation of the superplasticizer effect on the workability and strength of concrete." International Journal of Engineering Technology 9, no. 1 (2020): 198-201.

[153] Jaini, Zainorizuan Mohd, Rahmat Hidayat Mohammed Rum, Nor Hayati Abd Ghaffar, Mohammad Shahrul Aizat Misbah, and Mohd Shaffiq Md Desa. "Experimental study on vibration responses and energy dissipation of foamed concrete composite slabs." Malaysian Construction Research Journal 4, no. 2 (2018): 193-207.

[154] Xie, Liyu, Li Zhang, Chao Pan, Ruifu Zhang, and Tianli Chen. "Uniform damping ratio-based design method for seismic retrofitting of elastoplastic RC structures using viscoelastic dampers." Soil Dynamics and Earthquake Engineering 128 (2020): 105866.

[155] Georgiou, Antroula V., and Stavroula J. Pantazopoulou. "Effect of fiber length and surface characteristics on the mechanical properties of cementitious composites. "Construction and Building Materials 125 (2016): 1216-1228.

[156] Wang, Lei, Tingshu He, Yongxiang Zhou, Shengwen Tang, Jianjun Tan, Zhentao Liu, and Jianwen Su. "The influence of fiber type and length on the cracking resistance, durability and pore structure of face slab concrete." Construction and building materials 282 (2021): 122706.

[157] Tripathy, S. S., L. Di Landro, D. Fontanelli, A. Marchetti, and Giovanni Levita. "Mechanical properties of jute fibers and interface strength with an epoxy resin." Journal of applied polymer science 75, no. 13 (2000): 1585-1596.

[158] Hossain, Mohammad K., Mohammad W. Dewan, Mahesh Hosur, and Shaik Jeelani. "Mechanical performances of surface modified jute fiber reinforced biopol nanophased green composites." Composites Part B: Engineering 42, no. 6 (2011): 1701-1707.

[159] Nagaraj, Chetty, Debashis Mishra, and J. Durga Prasad Reddy. ”Estimation of tensile properties of fabricated multi layered natural jute fiber reinforced E-glass composite material.” Materials today: proceedings 27 (2020): 1443-1448.

[160] Sharafeddin, F., A. A. Alavi, and Z. Talei. ”Flexural strength of glass and polyethylene fiber combined with three different composites.” Journal of Dentistry 14, no. 1 (2013): 13.

[161] Ou, Yunfu, and Deju Zhu. ”Tensile behavior of glass fiber reinforced composite at different strain rates and temperatures.” Construction and Building Materials 96 (2015): 648-656.

[162] Ou, Yunfu, Deju Zhu, Huaian Zhang, Liang Huang, Yiming Yao, Gaosheng Li, and Barzin Mobasher. ”Mechanical characterization of the tensile properties of glass fiber and its reinforced polymer (GFRP) composite under varying strain rates and temperatures. ” Polymers 8, no. 5 (2016): 196.

[163] Abdelrazik, Ahmed T., and Kamal H. Khayat. ”Effect of fiber characteristics on fresh properties of fiber-reinforced concrete with adapted rheology.” Construction and Building Materials 230 (2020): 116852.

[164] Figueiredo, Antonio Domingues de, and Marcos Roberto Ceccato. ”Workability analysis of steel fiber reinforced concrete using slump and Ve-Be test.” Materials Research 18 (2015): 1284-1290.

[165] Braga, R. A., and P. A. A. Magalhaes Jr. ”Analysis of the mechanical and thermal properties of jute and glass fiber as reinforcement epoxy hybrid composites.” Materials science and engineering: C 56 (2015): 269-273.

[166] Sun, Wei, Huisu Chen, Xin Luo, and Hongpin Qian. ”The effect of hybrid fibers and expansive agent on the shrinkage and permeability of high-performance concrete.” Cement and concrete research 31, no. 4 (2001): 595-601.

[167] He, Fengzhen, Luigi Biolzi, and Valter Carvelli. ”Effect of fiber hybridization on mechanical properties of concrete.” Materials and Structures 55, no. 7 (2022): 195.

[168] Zia, Asad, and Majid Ali. ”Behavior of fiber reinforced concrete for controlling the rate of cracking in canal-lining.” Construction and Building Materials 155 (2017): 726-739.

[169] Jamil, Kamran, Faisal Shabbir, and Ali Raza. ”Performance evaluation of jute fiber-reinforced recycled aggregate concrete: Strength and durability aspects.” Structural Concrete (2023).

[170] Khan, Mehran, and Majid Ali. ”Use of glass and nylon fibers in concrete for controlling early age micro cracking in bridge decks.” Construction and Building Materials 125 (2016): 800-808.

[171] Hilles, Mahmoud Mazen, and Mohammed M. Ziara. ”Mechanical behavior of high strength concrete reinforced with glass fiber.” Engineering Science and Technology, an International Journal 22, no. 3 (2019): 920-928.

[172] Nasir, Syed, Muhammad Ayoub, Syed Zafar, Ahmed Bilal, Anwaar Hazoor, Ehsanullah Kakar, and Aamir Mehmood. ”Experimental study on comparison of strength properties of natural waste fiber (coir and jute) reinforced concrete.” Journal of Applied and Emerging Sciences 7, no. 2 (2018): pp105-110.

[173] Guru, Bal Gopal, Sangeeta Swain, Swapna Seth, and Madhusudan Sahu. ”Analysis of Workability and Compressive Strength of the Fiber Reinforced Concrete by using Jute Fiber.” (2018).

[174] C. ASTM, Standard test method for density, absorption and voids in hardened concrete, pp. 1-3, ed, 2013