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Mechanistic-Empirical Performance Prediction of Fiber-Reinforced Concrete for Rigid Pavement Design

by

Qazi Muhammad Tariq

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

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(Qazi Muhammad Tariq)

Abstract

Rigid pavements are widely used in transportation infrastructure because of their high load-carrying capacity and long service life. However, conventional Portland cement concrete (PCC) has limited flexural performance and may develop cracking under repeated traffic and environmental stresses. This study investigated jute fiber-reinforced concrete (JFRC) for rigid pavement applications and identified the optimum fiber content. Four mixtures, including PCC and JFRC containing 1%, 2%, and 3% jute fiber by mass of wet concrete, were evaluated experimentally for slump, compressive strength, modulus of rupture, and elastic modulus. Increasing jute fiber content reduced workability, compressive strength, and elastic modulus, while improving flexural performance. Compared with PCC, modulus of rupture increased by 7.2%, 31.4%, and 29.7% for JFRC-1, JFRC-2, and JFRC-3, respectively, while compressive strength decreased by 9.7%, 13.1%, and 19.2%. JFRC-2 was identified as the optimum mixture, achieving the highest modulus of rupture of 3.10 MPa. AASHTOWare Pavement ME Design reduced the required slab thickness from 380 mm for PCC to 360, 265, and 265 mm for JFRC-1, JFRC-2, and JFRC-3, respectively, with a maximum reduction of 30.3%. An independent AASHTO (1993) calculation showed thicknesses of 325, 313, 282, and 284 mm, respectively, with a maximum reduction of 13.2% for JFRC-2. All MEPD alternatives satisfied the specified distress criteria over the 20-year design period. Overall, JFRC-2 provided the most favorable balance of mechanical performance and pavement design efficiency. Field validation is recommended for practical implementation.

Key Words: AASHTOWare Pavement ME Design, International Roughness Index (IRI), jute fiber-reinforced concrete, joint faulting, mechanistic-empirical analysis.

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Abbreviations

AADT	Average Annual Daily Traffic
AADTT	Average Annual Daily Truck Traffic
AASHTO	American Association of State Highway and Transportation Officials
ASTM	American Society for Testing and Materials
CTE	Coefficient of Thermal Expansion
E	Modulus of Elasticity
EICM	Enhanced Integrated Climatic Model
FRC	Fiber-Reinforced Concrete
IRI	International Roughness Index
JFRC	Jute Fiber-Reinforced Concrete
JPCP	Jointed Plain Concrete Pavement
kg	Kilogram
m	Meter
M-E	Mechanistic-Empirical
MEPD	Mechanistic-Empirical Pavement Design
mm	Millimeter
MPa	Megapascal
PCC	Portland Cement Concrete
PMD	Pakistan Meteorological Department
SDG	Sustainable Development Goal
UTM	Universal Testing Machine
w/c	Water-to-Cement Ratio

Symbols

%	Percentage
°C	Degree Celsius
A	Area
α	Coefficient of thermal expansion
Cd	Drainage coefficient
D	Concrete slab thickness
Δ PSI	Allowable serviceability loss
Ec	Modulus of elasticity of concrete
ε	Strain
fc	Compressive strength of concrete
GPa	Gigapascal
J	Load-transfer coefficient
k	Modulus of subgrade reaction
kg	Kilogram
kg/m ³	Kilograms per cubic meter
km	Kilometer
kN	Kilonewton
L	Slab/joint length
M	Mass
m	Meter
m/km	Meters per kilometer
mm	Millimeter
MPa	Megapascal
MPa/m	Megapascals per meter

μ	Poisson's ratio
P	Load
Po	Initial serviceability index
Pt	Terminal serviceability index
r	Pearson correlation coefficient
R	Reliability
Sc	Modulus of rupture of concrete
σ	Stress
So	Overall standard deviation
t	Thickness
t	Ton
V	Volume
W18	Predicted number of 18-kip equivalent single-axle loads
ZR	Standard normal deviate corresponding to selected reliability

Chapter 1

Introduction

Rigid pavements form a critical component of highway infrastructure due to their ability to carry heavy traffic loads and provide a long service life. These pavements distribute wheel loads over a wide area through a stiff concrete slab. However, their performance depends not only on strength but also on how the pavement responds to repeated traffic loading and environmental conditions over time [1]. In practice, rigid pavements often experience distresses such as transverse cracking, joint faulting, and increased surface roughness, which directly affect ride quality and serviceability. Therefore, understanding pavement behavior at the structural level is more important than focusing solely on material strength [2].

To improve pavement performance, modifications in concrete materials have been widely explored, including the use of fiber-reinforced concrete (FRC). The addition of fibers is not only intended to enhance material properties but also to control crack development and improve load transfer efficiency within the slab [3]. In pavement systems, cracking is one of the primary causes of failure, and any improvement that delays crack initiation or reduces crack width can significantly enhance pavement life. Jute fiber, as a natural and sustainable material, is considered in this study due to its potential to improve crack resistance and overall pavement behavior under service conditions [4].

The mechanistic-empirical (M-E) pavement design approach provides a comprehensive framework for performance evaluation. Implemented through AASHTO-Ware Pavement ME Design (MEPD), this method integrates traffic loading, climatic conditions, and material properties to simulate pavement responses such as stresses, strains, and deflections. These responses are then used to predict long-term performance indicators, including cracking, faulting, and roughness [5]. Compared to traditional empirical methods, this approach enables a more realistic assessment of pavement behavior. It allows engineers to evaluate how changes in material properties and design parameters influence long-term pavement performance rather than only short-term strength [6].

This study focuses on mechanistic-empirical simulations to analyze how variations in material properties influence pavement distress development and service life. A comparative analysis is conducted between conventional plain cement concrete (PCC) and jute fiber-reinforced concrete (JFRC) pavements. Additionally, a parametric study is performed to evaluate the effects of slab thickness, flexural strength, and fiber content on pavement performance. The findings aim to determine whether the inclusion of jute fibers can enhance pavement durability and enable design optimization, such as reduced slab thickness or extended service life. Flexural strength is particularly critical in rigid pavement design because the concrete slab is subjected to bending under wheel loading. A higher modulus of rupture enables the slab to resist greater tensile bending stresses and can reduce the required slab thickness for a given traffic, environmental, and support condition, provided that the allowable pavement distress criteria are satisfied.

Overall, this research integrates experimental data with advanced pavement design software to provide a realistic and practical evaluation of rigid pavement performance, contributing to the development of more sustainable and efficient pavement systems.

However, durability refers to the ability of the pavement to resist traffic and environmental deterioration over its service life, whereas sustainability additionally considers environmental and economic impacts. The use of JFRC has potential

sustainability benefits because improved flexural performance can allow a reduction in slab thickness and consequently reduce concrete consumption and associated material impacts.

1.1 Research Motivation and Problem Statement

Advancing sustainable and resilient highways motivates the use of innovative construction materials. Natural fibers offer an eco-friendly reinforcement alternative that can enhance rigid pavement performance, reduce maintenance, and extend service life. This study explores the potential of jute fiber-reinforced concrete to improve predicted pavement performance using mechanistic-empirical simulations, linking laboratory material characterization with computational pavement analysis for sustainable and durable pavement solutions.

Rigid pavements are susceptible to premature distresses like cracking, joint faulting, and surface roughness due to the brittle behavior and low tensile strength of conventional concrete, which limits their structural performance and service life. While fiber reinforcement has shown promise in improving concrete performance, the effect of jute fibers on rigid pavement structural behavior remains largely unexplored. There is a need to determine how jute fiber-reinforced concrete influences mechanical properties relevant to pavement performance, particularly compressive and flexural strength, and to identify an optimal fiber content. These laboratory-scale results can then be incorporated into mechanistic-empirical simulations using AASHTOWare Pavement ME Design to predict the performance of rigid pavement, without the need for full-scale pavement construction.

1.1.1 Research Questions

The research questions are:

- i. How do different percentages of jute fiber 1%, 2%, and 3% influence the mechanical properties of concrete?

- ii. How can AASHTOWare Pavement ME Design be used to evaluate the long-term performance of jute fiber-reinforced concrete rigid pavements under identical traffic and climatic conditions?
- iii. How does the variation in jute fiber content affect the predicted pavement distresses, including transverse cracking, joint faulting, and the International Roughness Index (IRI), and what is the optimum fiber content for rigid pavement applications?

1.2 Overall Aim and Specific Goal of this Study

The overall aim of this study is to develop durable and sustainable rigid pavements using jute fiber-reinforced concrete for improved pavement performance and economic benefits in developing countries.

The specific goal of this study is to evaluate the mechanical strength of jute fiber-reinforced concrete and predict its performance in rigid pavements using a mechanistic-empirical approach.

1.3 Scope of Work and Study Limitations

This study investigates the suitability of jute fiber-reinforced concrete (JFRC) for rigid pavement applications by integrating laboratory material characterization with mechanistic-empirical pavement performance analysis. Four concrete mixes will be prepared, including one control mix and three mixes containing 1%, 2%, and 3% jute fibers (25 mm length) by mass of wet concrete. Laboratory testing will be conducted to determine key mechanical properties relevant to rigid pavement performance, primarily compressive strength, elastic modulus, and flexural strength (modulus of rupture). The experimentally obtained mechanical properties will be used to develop pavement material input parameters for rigid pavement analysis. These parameters will then be incorporated into AASHTOWare Pavement ME Design to simulate the structural behavior and long-term performance

of plain concrete pavements constructed with both conventional concrete and jute fiber-reinforced concrete. Using identical pavement structures, traffic loading conditions, and climatic inputs, the software will be used to evaluate key pavement performance indicators including:

- i. Transverse cracking
- ii. Joint faulting
- iii. Pavement roughness (IRI)
- iv. Predicted pavement service life

A comparative mechanistic-empirical analysis will be conducted to assess how the incorporation of jute fibers influences pavement distress development and long-term structural performance. Additionally, a parametric analysis will be performed to examine whether improvements in flexural strength due to fiber reinforcement may allow reduction in slab thickness or extension of pavement service life, thereby highlighting the potential structural and economic benefits of jute fiber-reinforced concrete in pavement applications.

This research is limited to laboratory-scale material characterization and computational pavement performance evaluation. Only one type of natural fiber (jute) with a fixed length of 25 mm and fiber contents of 1%, 2%, and 3% will be investigated. The study focuses on the mechanical strength of jute fiber-reinforced concrete. Other performance characteristics, such as energy absorption, crack resistance, crack initiation, and crack propagation, were not considered. Field-scale pavement construction, prototype slab testing, and long-term monitoring of in-service pavements are beyond the scope of this study. Instead, the influence of jute fiber reinforcement on pavement performance will be evaluated through mechanistic-empirical simulations using AASHTOWare Pavement ME Design, assuming standardized pavement structures, traffic levels, and climatic conditions.

1.3.1 Rationale Behind the Variable Selection

- i. The jute fiber contents of 1%, 2%, and 3% were selected based on previous studies that identified this range as suitable for evaluating the effect of fiber dosage on concrete performance [4, 6].
- ii. AASHTOWare Pavement ME Design was selected because it is a widely accepted mechanistic-empirical software for predicting the long-term performance of rigid pavements [7].
- iii. Transverse cracking, joint faulting, and the International Roughness Index (IRI) were selected because they are the primary mechanistic-empirical performance indicators used to assess the structural and functional performance of rigid pavements [8].

1.4 Brief Methodology

The methodology of this study is based on the design and performance evaluation of rigid pavements using AASHTOWare Pavement ME Design (MEPD). The main focus is on using the software to analyze how different types of concrete behave in pavement structures under the same conditions. In the first step, rigid pavement sections are designed in the (MEPD) software. This includes defining basic project information such as design life, traffic data, and environmental conditions. After that, the required material input parameters are entered. In this study, the key inputs for the concrete layer are compressive strength and flexural strength (modulus of rupture), as these are the primary parameters required by MEPD for rigid pavement analysis. The values for these parameters are found out from experimental work.

Four different material cases are considered in the analysis. These include conventional plain cement concrete (0% fiber) and jute fiber-reinforced concrete with 1%, 2%, and 3% fiber content. Each case is defined separately in the software by assigning the corresponding strength values. Apart from material properties,

other pavement design inputs such as slab thickness, base layer properties, traffic loading, and climate data are kept consistent so that a fair comparison can be made. Once all inputs are defined, the software performs

mechanistic analysis. In this step, the program calculates critical responses of the pavement, such as stresses, strains, and deflections in the concrete slab under applied traffic loads. These responses represent the structural behavior of the pavement and form the basis for further performance prediction. After the mechanistic analysis, the software uses embedded empirical models to predict pavement performance over the design period. In this stage, key performance indicators are obtained, including transverse cracking, joint faulting, pavement roughness, and overall service life. These outputs help in understanding how the pavement will perform over time under real traffic and environmental conditions. In the next step, a comparative analysis is carried out between conventional concrete pavement and jute fiber-reinforced concrete pavement. The purpose of this comparison is to evaluate whether the inclusion of fibers improves pavement performance in terms of reduced distress and increased service life. Following this, a parametric study is conducted to further analyze the effect of important design variables. In this study, parameters such as slab thickness, flexural strength, and fiber content are varied within practical ranges. Each variation is modeled separately in the software, and its impact on pavement performance is observed. This helps in identifying the most influential factors affecting pavement behavior and in understanding how changes in design inputs can improve performance.

1.5 Research Significance

1.5.1 Industrial and Academic Collaborator Roles

This research was carried out under academic guidance using standard laboratory testing and mechanistic-empirical pavement analysis. Laboratory experiments were performed to determine the mechanical properties of conventional concrete and jute fiber-reinforced concrete. The experimental results were integrated into

AASHTOWare Pavement ME Design for long-term performance evaluation. Although no direct industrial collaboration was involved, the study addresses practical challenges associated with rigid pavement design. The findings are intended to support future engineering applications and research.

1.5.2 Research Novelty and Uniqueness

This research presents an integrated approach by combining laboratory testing with mechanistic-empirical pavement performance analysis. The experimentally determined properties of jute fiber-reinforced concrete were directly incorporated into AASHTOWare Pavement ME Design to evaluate long-term pavement behavior. The study also identifies the optimum jute fiber content for rigid pavement applications. This approach provides a comprehensive assessment beyond conventional material testing.

1.5.3 Research Significance and Benefits

The research demonstrates the potential of jute fiber as a sustainable reinforcement material for rigid pavements. Improved flexural performance and optimized slab thickness contribute to efficient pavement design without compromising long-term performance. The study encourages the use of renewable materials in pavement engineering and provides valuable information for future research and practical applications. The findings also support sustainable infrastructure development.

1.5.4 Practical Implementation

The findings of this study can assist engineers in evaluating the use of jute fiber-reinforced concrete for rigid pavement construction. The identified optimum fiber content provides guidance for concrete mix selection and pavement design. The

study also demonstrates the application of mechanistic-empirical analysis for assessing alternative pavement materials. These outcomes may support future field implementation after further validation.

1.5.5 National and Global Impact with Emphasis on SDGs relevance

The use of jute fiber promotes sustainable construction through the utilization of renewable and environmentally friendly materials. Improved pavement performance and reduced slab thickness contribute to efficient resource utilization and sustainable infrastructure development. The research supports environmentally responsible engineering practices and aligns with the objectives of SDG 9 (Industry, Innovation and Infrastructure) and SDG 11 (Sustainable Cities and Communities).

1.5.6 Ethical and Management Considerations including Risk Management

The research was conducted by following standard laboratory procedures and accepted engineering practices. Experimental data were recorded, analyzed, and reported objectively to ensure research integrity. Safety measures were maintained during specimen preparation and testing activities. Proper planning and management of laboratory resources helped ensure the successful completion of the study.

1.5.7 Research Deliverables, Sales and Marketing Potential

The research provides experimentally determined mechanical properties of jute fiber-reinforced concrete together with their mechanistic-empirical pavement performance evaluation. It also identifies the optimum jute fiber content for rigid

pavement applications and offers recommendations for sustainable pavement design. Although the study is academic in nature, its findings may support the future adoption of jute fiber-reinforced concrete in pavement engineering and encourage further industry-based research.

1.6 Thesis Structure

This thesis is organized into five main chapters, each addressing a specific aspect of the research work.

Chapter 1: This chapter described, the overview and background of the research, research motivation, problem statement, research questions, Overall Goal of the research program and specific aim of this particular study, scope of work and study limitation, research impact on industry and brief methodology.

Chapter 2: This chapter presents a critical review of rigid pavement performance, common distresses, influencing factors, and the role of fiber-reinforced concrete, particularly jute fiber, in improving pavement durability. It also discusses the mechanistic-empirical design approach using AASHTOWare Pavement ME Design (MEPD) and identifies the research gap for the present study.

Chapter 3: A detailed methodology of research work is explained in this chapter. The selection and adoption of tools, techniques, and parameters are incorporated into the AASHTOWare Pavement ME Design software, along with the modeling approach, input variables, and simulation procedures used for pavement performance evaluation.

Chapter 4: This chapter describes the results obtained and also covers the discussion on the achieved results.

Chapter 5: This chapter covers the conclusion of the research and future recommendation.

Bibliography

Chapter 2

Literature Review

2.1 Background

Rigid pavements are widely recognized for their high structural capacity and long service life, making them suitable for highways subjected to heavy traffic loading. Unlike flexible pavements, rigid pavements rely on the flexural strength of the concrete slab to distribute loads over a wider area, thereby reducing stresses on the subgrade. However, recent studies have highlighted that pavement performance is not solely dependent on strength but is also influenced by traffic loading patterns, environmental conditions, and long-term material behavior [1, 2]. The interaction of these factors leads to stress development within the slab, which eventually contributes to different types of pavement distresses as shown in Figure 2.1.

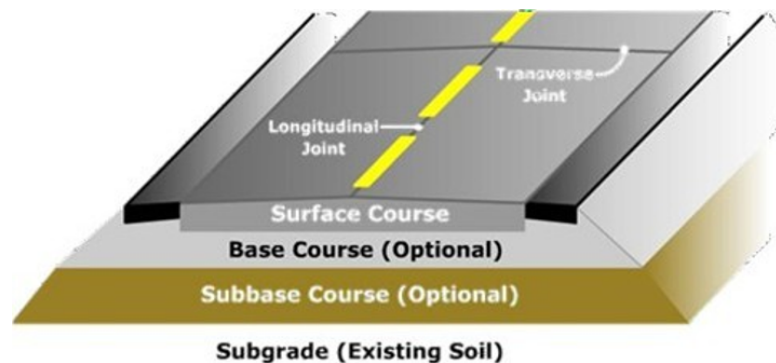


FIGURE 2.1: Cross-Sectional View of a Typical Rigid Pavements [6]

In recent years, researchers have focused on improving rigid pavement performance through material modification techniques. Fiber-reinforced concrete has gained significant attention due to its ability to enhance tensile strength, ductility, and crack resistance [3, 9]. Among various fibers, natural fibers such as jute have been explored due to their environmental benefits and cost-effectiveness. Studies have shown that the inclusion of fibers can effectively control crack propagation and improve the durability of concrete under repeated loading conditions [4, 10]. This has opened new possibilities for sustainable pavement construction. Simultaneously, advancements in pavement design methodologies have led to the adoption of the mechanistic-empirical (M-E) approach. This approach integrates material properties, traffic loading, and climatic conditions to predict pavement performance more accurately [5, 6]. Tools such as AASHTOWare Pavement ME Design (MEPD) have been developed to simulate real-world pavement behavior and predict long-term distresses such as cracking, faulting, and roughness. The integration of advanced materials with modern design approaches forms the basis of current research in rigid pavement engineering [8, 11].

2.2 Rigid Pavement Distresses, Performance Factors and Remedial Measures

2.2.1 Common Distresses in JPCP

Rigid pavements are subjected to several recurring distresses during their service life due to the combined effects of traffic loading, environmental conditions, material properties, construction quality, and support conditions as shown in Figure 2.2. Transverse cracking is one of the most common structural distresses, developing perpendicular to the direction of traffic as a result of temperature-induced stresses, drying shrinkage, and repeated axle loading [12]. Temperature fluctuations cause concrete slabs to expand and contract, generating tensile stresses that may exceed the tensile strength of concrete, while early-age shrinkage produces microcracks that gradually propagate under continuous traffic loading [13].

The severity of transverse cracking is influenced by slab thickness, joint spacing, material properties, subgrade support, construction quality, and curing practices, whereas the incorporation of fiber reinforcement has been reported to reduce crack width, delay crack propagation, and improve pavement durability [14]. Longitudinal cracking develops parallel to the direction of traffic and is generally associated with poor load transfer, differential settlement of the subgrade, improper lane construction, and fatigue stresses under repeated heavy axle loads, allowing water infiltration that accelerates deterioration of the pavement structure [15]. Studies have shown that improved joint design, adequate support conditions, and the use of dowel bars, tie bars, and fiber-reinforced concrete can effectively reduce longitudinal cracking by enhancing load transfer and increasing the tensile capacity of concrete [16]. Joint faulting is characterized by a difference in elevation between adjacent slabs due to erosion of the base or subgrade, pumping of water and fine materials, loss of support, repeated traffic loading, and inadequate drainage conditions [17]. The use of stabilized base layers, efficient drainage systems, and dowel bars has been recommended to minimize erosion and improve load transfer across pavement joints, thereby reducing joint faulting [18] as shown in table 2.1. Pavement roughness, commonly measured using the International Roughness Index (IRI), represents the functional condition and ride quality of rigid pavements and increases progressively as distresses such as cracking, faulting, and surface irregularities accumulate under traffic and environmental effects [19].

TABLE 2.1: Comparative Evaluation of Rigid Pavement Distresses

MEPDG Indicators	Mechanical Property	Research Finding	References
Transverse Cracking	Flexural Strength (MOR)	Higher MOR → greater resistance to tensile stresses → less cracking	[4, 7]
Joint Faulting	Elastic Modulus + MOR	Mechanical properties influence slab response → affect joint faulting	[20–22]
IRI	Elastic Modulus + MOR	Mechanical properties influence slab response and deterioration → affect pavement roughness	[2, 23]

Higher IRI values reduce ride com-fort, increase vehicle operating costs and fuel consumption, and lower pavement serviceability, making roughness prediction an essential component of mechanistic-empirical pavement design [24]. In addition, corner breaks occur when high stress concentrations at slab corners combine with inadequate support and repeated traffic loading, producing triangular cracks that reduce the structural capacity of the slab [20]. Surface deterioration, including scaling, spalling, and material degradation, develops primarily because of temperature fluctuations, moisture toughness, control crack formation, and enhance the long-term durability of rigid pavements. infiltration, chemical exposure, poor material quality, and inadequate construction practices, while fiber reinforcement has been shown to improve.

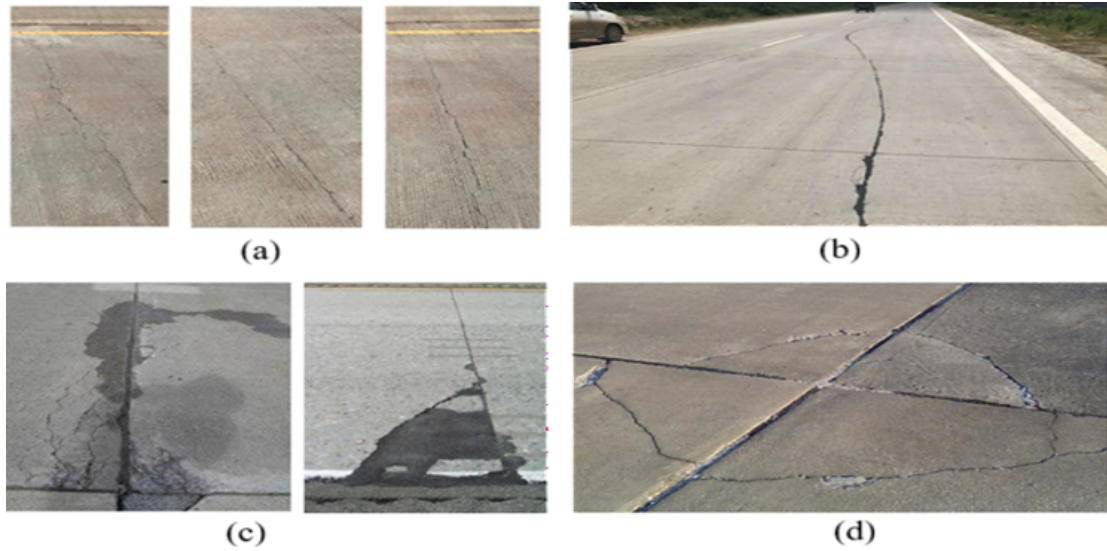


FIGURE 2.2: Common Distresses in Rigid Pavements: (a) Transverse Cracks [8], (b) Longitudinal Cracks [8], (c) Joint Deterioration [17], and (d) Corner Breaks [20]

2.2.2 Performance Factor

The performance of rigid pavements is governed by several interrelated factors, including traffic loading, environmental conditions, support layers, material properties, and slab thickness. Traffic loading is one of the most critical factors affecting pavement performance, as the magnitude, frequency, and configuration of axle loads generate tensile stresses within the concrete slab, leading to fatigue

cracking and cumulative structural damage under repeated loading, particularly with high traffic volumes and heavy axle loads [25]. The type and distribution of traffic, including mixed traffic conditions, varying axle configurations, dynamic loading, overloading, and future traffic growth, further influence stress distribution and pavement service life, while the use of fiber-reinforced concrete improves resistance to fatigue loading and enhances durability [26].

Environmental and climatic conditions also have a significant influence on rigid pavement performance because temperature variations cause expansion and contraction of concrete slabs, producing thermal and warping stresses that may result in cracking, whereas moisture variations contribute to volume changes and increased internal stresses [27]. Climatic factors such as rainfall, humidity, and freeze-thaw cycles promote water infiltration through joints and cracks, weaken the base and subgrade, and cause erosion, scaling, and cracking; therefore, proper drainage, durable materials, and consideration of climatic conditions in pavement design are essential for improving long-term performance [28]. The subgrade and base layers provide the structural support required for rigid pavements, and a strong, uniformly compacted subgrade ensures effective load distribution, whereas weak support increases slab deflection and accelerates distresses such as cracking and joint faulting [29].

Similarly, the base layer improves load distribution, minimizes erosion, enhances drainage, and reduces pumping and faulting, making proper material selection, stabilization, and compaction essential for long-term pavement durability [30]. Material properties also play a fundamental role in pavement performance, as flexural strength, modulus of elasticity, thermal expansion coefficient, water-cement ratio, aggregate quality, and curing conditions determine the ability of concrete to resist stresses and maintain durability, while fiber reinforcement further improves these properties and enhances pavement performance [31]. Flexural stresses are induced when wheel loads cause the concrete pavement slab to bend. The bending creates tensile stresses, mainly at the bottom of the slab, which may lead to cracking when they exceed the concrete's flexural strength (modulus of rupture). In addition, slab thickness directly affects stress distribution within the pavement,

with thicker slabs reducing stress concentrations and cracking risk by distributing loads over a larger area; however, increasing slab thickness raises construction costs, making it necessary to achieve an optimum balance between structural performance and economy, which can be facilitated through the use of fiber-reinforced concrete [32]. Collectively, these factors contribute to the progressive reduction of pavement serviceability by increasing structural and functional distresses such as transverse cracking, joint faulting, and surface roughness, which are therefore considered important indicators in mechanistic-empirical pavement performance evaluation. Proper construction practices are essential for achieving the required structural and functional performance of rigid pavements. From an engineering perspective, these include adequate subgrade and base preparation, proper concrete mixing and placement, compaction, surface finishing, joint construction, and curing. Proper control of these activities helps achieve the required strength, load transfer, durability, and serviceability of the pavement.

2.2.3 Role of Fiber as a Remedial Measure

Several remedial measures have been developed to restore the structural and functional performance of rigid pavements, including conventional repair techniques and the use of fiber reinforcement. Conventional maintenance methods such as joint resealing, slab replacement, crack repair, surface grinding, and overlay application are commonly employed to repair existing distresses and improve pavement serviceability by preventing water infiltration, restoring ride quality, increasing structural capacity, and replacing severely damaged slabs [33]. However, these techniques are generally reactive in nature, often fail to address the root causes of pavement deterioration, and can result in increased maintenance costs over the pavement life cycle, highlighting the need for more durable and preventive solutions [21]. Fiber reinforcement has emerged as an effective approach for improving the mechanical performance and durability of rigid pavements because synthetic fibers, such as polypropylene, steel, and glass, as well as natural fibers, including jute, coir, and sisal, bridge microcracks, reduce crack propagation, distribute tensile stresses more uniformly, and enhance flexural strength, toughness,

and fatigue resistance under repeated traffic loading [34]. By controlling crack initiation and propagation, fiber-reinforced concrete improves load transfer across slabs, reduces joint faulting, minimizes surface deterioration, and extends pavement service life. Natural fibers have attracted considerable attention because they are biodegradable, renewable, environmentally friendly, cost-effective, and locally available, while also providing adequate tensile strength and elasticity for crack control [35]. Previous studies have demonstrated that natural fibers such as coir, sisal, bamboo, and jute improve the modulus of rupture, ductility, and fracture energy of concrete, whereas their low density helps maintain workability and reduces the overall weight of the pavement [5, 6, 8, 10, 11]. Among these natural fibers, jute is particularly suitable for rigid pavement applications because of its abundant availability, low cost, high tensile strength, good elongation characteristics, biodegradability, and compatibility with sustainable construction practices [36]. Research has further shown that incorporating jute fibers into concrete enhances flexural strength, toughness, crack resistance, durability, and resistance to micro-cracking, scaling, and spalling without significantly increasing construction costs. Based on these characteristics and the findings of previous studies, the present research selects jute fiber for evaluating its suitability in rigid pavements by investigating concrete mixtures containing 1%, 2%, and 3% jute fiber to determine the optimum performance [4, 6, 19].

2.3 Jute Fiber - Reinforced Concrete for Pavement Applications

The performance of rigid pavements largely depends on the mechanical and durability properties of the concrete slab, and jute fiber contributes significantly to these characteristics. Studies have shown that incorporating jute fibers improves flexural strength, modulus of rupture, and toughness, enabling concrete to resist higher tensile and bending stresses before cracking [7, 37, 38]. The elastic modulus is an important property of concrete because it represents the stiffness of the material and influences the way stresses and strains develop within a pavement slab.

The incorporation of natural fibers can affect the stiffness of concrete depending on the fiber type, content, distribution, and bond with the cement matrix. Since jute fibers are relatively flexible compared with the concrete matrix, increasing their content may reduce the overall stiffness of the composite.

Therefore, the effect of jute fiber on pavement performance should not be assessed from flexural strength alone; both flexural strength and elastic modulus, along with other pavement design parameters, should be considered when evaluating the structural performance of JFRC. [39, 40].

From Table 2.2, it can be observed that all natural fibers improve the mechanical properties of concrete. However, jute fiber demonstrates a significant enhancement in flexural strength up to 15 to 35% at a very low dosage of 0.25% [2]. Coir and sisal require higher dosages of 2% to 4% to achieve comparable improvements [3], [16].

TABLE 2.2: Comparative Evaluation of Natural Fiber-Reinforced Concrete Reported in Previous Studies

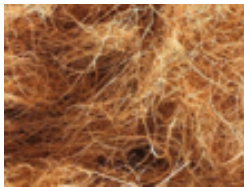
Natural Fiber	Image	Mechanical Properties	Obtained Values	Ref
Jute		Flexural Strength (MPa)	+15 to 35% at (0.25%)	[2, 12, 39]
		Compressive Strength (MPa)	+11.61% at (0.50%)	
		Modulus of Elasticity (GPa)	+14.91% at (1.0%)	
Coir		Flexural Strength (MPa)	+10.62% at (2%)	[41–43]
		Compressive Strength (MPa)	+10.34% at (2%)	
		Modulus of Elasticity (GPa)	+12.04% at (4%)	

Table 2.2 continued from previous page

Natural Fiber	Image	Mechanical Properties	Obtained Values	Ref
Sisal		Flexural Strength (MPa)	+13.79% at (2%)	[5, 44]
		Compressive Strength (MPa)	+14.18% at (2%)	
		Modulus of Elasticity (GPa)	+26.18% at (1%)	
Wheat Straw		Flexural Strength (MPa)	+20.56% at (0.1% wheat straw + bamboo fiber)	[2, 24]
			+14.43% at (0.1% wheat straw + treated bamboo fiber)	
		Modulus of Elasticity (GPa)		
Hemp		Flexural Strength (MPa)	+14.0% at (1% hemp + 17.5% FA)	[7, 9]
		Compressive Strength (MPa)	+22.3% at (1% hemp + 17.5% FA)	

Similarly, jute shows improvement in both compressive strength and modulus of elasticity, which are critical parameters for rigid pavement design. Based on the comparative evaluation, Jute fiber can provide significant flexural improvement at relatively low dosages, typically around 0.25%–1.0%, making it more economical and helping to avoid the workability problems that may occur with higher fiber contents required for coir and sisal [5], [11]. This is particularly relevant to rigid pavement applications, where flexural strength and modulus of elasticity are important factors governing pavement performance. Previous studies reported positive effects of jute fiber on these properties. In addition, jute is widely available in Pakistan and South Asia, which makes it a practical, cost-effective, and sustainable natural fiber compared with alternatives such as hemp, which may

require greater dependence on imported material. These characteristics are particularly beneficial for pavements subjected to heavy traffic loading and environmental stresses because they directly influence crack initiation, crack propagation, and overall slab behavior [39, 40]. From a pavement design perspective, the improvement in flexural strength is particularly significant because the modulus of rupture is a direct structural parameter in conventional rigid pavement thickness design. Therefore, improvement in flexural strength can potentially reduce the required concrete slab thickness, provided that the resulting pavement satisfies the specified traffic, serviceability, and distress criteria. In addition to mechanical improvements, jute fibers enhance durability by increasing resistance to fatigue, shrinkage, and microcracking. Experimental studies as shown in table 2.2, have reported that jute fibers act as crack arresters by bridging microcracks before they develop into visible cracks, thereby extending pavement service life [12, 13].



FIGURE 2.3: Jute Fiber

Furthermore, jute fibers as shown in Figure 2.3 improve freeze-thaw resistance, reduce surface scaling, and enhance resistance to environmental deterioration under fluctuating temperature and moisture conditions [14]. The incorporation of jute fibers significantly improves the crack resistance and durability of rigid pavements. Since cracking is one of the most common causes of functional and structural pavement distress, the addition of jute fibers effectively reduces crack width and delays crack propagation, thereby enhancing structural integrity and pavement serviceability [15]. Comparative studies between plain concrete and JFRC have demonstrated that incorporating 1-3% jute fiber by weight improves

resistance to fatigue and repeated loading while reducing joint faulting and surface deterioration over time. The fibers distribute stresses more uniformly throughout the concrete matrix, minimizing localized stress concentrations and improving overall pavement performance [16–19]. In addition, jute fibers reduce shrinkage-related cracking during the early curing stage and limit microcracking caused by thermal expansion and contraction, thereby improving resistance to environmental degradation [20, 24].

As a result, pavements reinforced with jute fibers exhibit longer service life, lower maintenance requirements, and improved ride quality, while the incorporation of these enhanced material properties into mechanistic-empirical simulations enable more accurate prediction of pavement performance and optimization of slab thickness and joint spacing [25].

Determining the optimum jute fiber content is essential to maximize the benefits of fiber reinforcement without adversely affecting workability or increasing construction costs. Previous studies have indicated that fiber contents ranging from 1% to 3% by mass of wet concrete provide an effective balance between mechanical performance and practical feasibility [26–29]. At a dosage of 1%, moderate improvements in flexural strength and crack resistance are achieved, whereas fiber contents of 2% and 3% produce greater improvements in toughness and crack control, although excessive fiber content may slightly reduce workability if the concrete mix is not properly adjusted [30, 31]. Previous studies have reported different optimum jute fiber contents depending on fiber characteristics, mix proportions, curing conditions, and testing methods. Therefore, the optimum fiber content cannot be assumed universally. In the present study, 1%, 2%, and 3% jute fiber contents were evaluated experimentally, and the resulting material properties were subsequently incorporated into pavement performance analysis to identify the most suitable content [4, 6, 19].

However, the selection of the optimum fiber content should not be based solely on the maximum laboratory strength. It should also consider how the resulting material properties affect pavement-level performance, including transverse cracking, joint faulting, IRI, and the required slab thickness. This provides the basis for

integrating the experimental JFRC results with mechanistic-empirical pavement analysis in the present study.

2.4 Mechanistic-Empirical Pavement Analysis

Using AASHTOWare Pavement ME Design

The mechanistic-empirical (M-E) pavement design approach represents a significant advancement over traditional empirical methods by combining principles of mechanics with observed pavement performance data to evaluate pavement behavior under traffic loading and environmental conditions [45]. Unlike conventional empirical methods that rely primarily on historical experience, the M-E approach uses material properties, structural mechanics, and predictive models to calculate stresses, strains, and deflections within pavement layers and predict long-term distresses such as transverse cracking, longitudinal cracking, joint faulting, and surface roughness [46]. This approach provides a reliable framework for evaluating both conventional and fiber-reinforced concrete pavements because it integrates laboratory- and field-measured material properties into performance predictions [47]. The mechanistic component calculates pavement responses using material properties, layer thicknesses, subgrade stiffness, and traffic loading are presented in Table 2.3, whereas the empirical component converts these calculated responses into predictions of pavement distress, service life, and maintenance requirements using calibrated field-performance models. Furthermore, the approach accounts for environmental variability, including temperature fluctuations, moisture changes, freeze-thaw cycles, and repeated axle loading, enabling more realistic prediction of pavement performance and allowing innovative materials such as jute fiber-reinforced concrete (JFRC) to be evaluated using experimentally determined mechanical properties [48]. Compared with traditional empirical methods, the M-E approach provides greater flexibility, improved prediction accuracy, and better optimization of pavement designs, resulting in longer service life and reduced maintenance requirements [17]. AASHTOWare Pavement ME Design (MEPD), developed under the guidance of the American Association of State Highway and

Transportation Officials (AASHTO), is the industry-standard software that implements the mechanistic-empirical design methodology for analyzing and designing flexible, rigid, and composite pavements [49].

TABLE 2.3: Summary of previous studies on mechanistic-empirical pavement design and sensitivity analysis.

Study Focus	Research Approach	Key Findings	Pros	Cons	Ref
Mechanistic-Empirical Pavement design	Literature review	Explained the integration of mechanistic analysis with empirical calibration for improved pavement performance prediction.	Combines theoretical analysis with field-based empirical data for better performance prediction.	Prediction accuracy depends on reliable input data and calibration.	[49]
Application of AASHTOWare Pavement ME	Mechanistic-empirical simulation	Demonstrated that AASHTOWare Pavement ME can effectively evaluate pavement performance under different design conditions.	Predicts multiple pavement distresses under different traffic, material, and climate conditions.	Requires several input parameters and suitable calibration.	[50]
Influence of base and subgrade properties	Sensitivity analysis using MEPD	Reported that base and subgrade properties significantly influence stress response and rigid pavement performance.	Identifies critical parameters affecting pavement performance and design.	Findings can vary with local soil, climate, material, and traffic conditions.	[51]

The software integrates traffic loading, material properties, climatic conditions, pavement geometry, and layer characteristics to simulate long-term pavement performance by combining mechanistic response analysis with empirically calibrated distress prediction models [52].

For rigid pavements, MEPD requires comprehensive input parameters, including axle load spectra, traffic growth, design life, flexural strength, modulus of elasticity, Poisson's ratio, fatigue properties, slab and layer thicknesses, resilient modulus of the supporting layers, drainage characteristics, and climatic data such as temperature, precipitation-, and freeze-thaw cycles, ensuring realistic simulation of field conditions [-].

Using these inputs, the software predicts important pavement performance indicators, including transverse cracking, longitudinal cracking, joint faulting, and International Roughness Index (IRI), by evaluating the effects of traffic loading, environmental conditions, load transfer efficiency, base support, erosion, and accumulated fatigue damage [53].

Previous studies have demonstrated that MEPD provides reliable long-term performance predictions, supports sensitivity and parametric analyses, and enables evaluation of design alternatives involving slab thickness, material properties, climatic conditions, and advanced materials such as fiber-reinforced concrete, thereby facilitating optimized pavement designs with improved durability, serviceability, and reduced life-cycle maintenance costs [1, 14].

2.4.1 AASHTO Rigid Pavement Thickness Design Equation

The conventional AASHTO rigid pavement design procedure provides an important basis for understanding the relationship between concrete material properties and slab thickness.

The 1993 AASHTO rigid pavement design equation relates the allowable number of 18-kip equivalent single-axle loads, $W_{18W_{18}}$, to slab thickness, reliability, serviceability loss, concrete modulus of rupture, elastic modulus, drainage condition, joint load-transfer characteristics, and foundation support. The design equation

is expressed as:

$$\begin{aligned} \log(W_{18}) = & Z_R \times S_0 + 7.35 \log(D + 1) \\ & - 0.06 \frac{\log\left(\frac{\Delta PSI}{4.2 - 1.5}\right)}{1 + \frac{624 \times 10}{(D + 1)^{8.46}}} \\ & + (4.22 - 0.32p_t) \log \left[\frac{S'_c \times C_d (D^{0.75} - 1.132)}{215.63 \times J \left[D^{0.75} - \frac{18.42}{\left(\frac{E_c}{k}\right)^{0.25}} \right]} \right] \end{aligned} \quad (2.1)$$

where ‘W18’ is the design traffic in equivalent single-axle loads, ‘ZR’ is the standard normal deviate corresponding to the selected reliability, ‘So’ is the overall standard deviation, ‘D’ is slab thickness, ‘ΔPSI’ is the allowable serviceability loss, ‘pt’ is terminal serviceability, ‘Sc’ is the concrete modulus of rupture, ‘Cd’ is the drainage coefficient, JJ is the joint load-transfer coefficient, ‘Ec’ is the concrete elastic modulus, and ‘k’ is the modulus of subgrade reaction. The equation is solved for the required slab thickness under the specified design conditions. The equation demonstrates the importance of concrete flexural strength in rigid pavement thickness design. An increase in the modulus of rupture improves the structural capacity of the concrete slab and can reduce the required thickness for a given traffic and support condition.

However, the final pavement thickness must satisfy the combined requirements of traffic, serviceability, reliability, load transfer, drainage, material properties, and foundation support. Load transfer across joints is primarily achieved through dowel action and aggregate interlock, while its effectiveness is influenced by joint opening, joint condition, shoulder configuration, and other structural factors. Load Transfer Efficiency (LTE) is used to quantify the effectiveness of load transfer between adjacent slabs. These factors determine how effectively wheel loads are

transferred from one slab to the adjacent slab and consequently influence slab deflection, joint faulting, and overall pavement performance. In the AASHTO rigid pavement design equation, the effects associated with joint load-transfer characteristics are accounted for through the load-transfer coefficient, J .

In this study, the material properties obtained from the laboratory tests for PCC and JFRC were used in AASHTOWare Pavement ME Design to evaluate pavement performance. The analysis considered transverse cracking, joint faulting, and IRI throughout the design period rather than considering concrete strength alone. This approach helped to assess whether the improved flexural strength of JFRC could allow a reduction in slab thickness while still providing satisfactory pavement performance.

2.5 Summary

The performance of rigid pavements is significantly influenced by traffic loading, environmental conditions, subgrade support, and material properties. Repeated distresses such as transverse and longitudinal cracking, joint faulting, corner breaks, and surface deterioration compromise both structural integrity and ride quality. Conventional repair techniques, while useful, are often reactive and do not prevent crack initiation or long-term deterioration. It has also been observed that fiber reinforcement, particularly using natural fibers like jute, can improve concrete's flexural strength, toughness, and crack resistance. Jute fibers function as micro-reinforcements that bridge microcracks, redistribute tensile stresses, and enhance fatigue resistance under repeated loading. Studies suggest that fiber contents between 1% and 3% by weight optimize mechanical performance while maintaining workability. It has further been seen that mechanistic-empirical (M-E) design approaches, implemented in AASHTOWare Pavement ME Design (MEPD), can predict long-term pavement performance, including cracking, joint faulting, roughness (IRI), and service life, by integrating material, traffic, and climate data. Research confirms that MEPD is effective for evaluating both conventional and fiber-reinforced pavements and for conducting parametric studies to optimize slab

thickness, fiber content, and other design variables. Overall, it has been observed that combining jute fiber reinforcement with MEPD-based analysis provides a sustainable, durable, and cost-effective approach for enhancing rigid pavement performance and extending service life.

Chapter 3

Research Methodology

3.1 Background

This chapter presents the research methodology adopted to investigate the performance of jute fiber-reinforced concrete (JFRC) in rigid pavement applications through laboratory testing and mechanistic-empirical pavement analysis. The methodology was developed to establish a direct relationship between the mechanical properties of JFRC and its long-term structural performance under traffic loading and environmental conditions. The study combines experimental investigation with pavement performance simulation to evaluate the effectiveness of different jute fiber contents in improving rigid pavement behavior.

A mechanistic-empirical (M-E) approach was adopted because it provides a comprehensive framework for integrating pavement material properties, traffic loading, climatic conditions, and structural characteristics into a single analysis platform. Compared with conventional empirical approaches, the M-E method enables more realistic prediction of pavement responses and long-term distress development by considering the interaction between pavement materials and field conditions. Therefore, this approach was considered appropriate for evaluating the influence of JFRC on rigid pavement performance. AASHTOWare Pavement ME Design was selected as the primary analysis tool because it incorporates mechanistic analysis

together with empirically calibrated distress prediction models for rigid pavements. The software predicts pavement performance throughout the selected design life based on traffic loading, environmental conditions, pavement structure, and material properties. The primary performance indicators considered in this study include transverse cracking, joint faulting, and the International Roughness Index (IRI).

The methodology adopted in this research consists of two major stages. The first stage involves the collection and characterization of pavement design inputs, including pavement material properties, traffic data, climatic conditions, and pavement structural information. The laboratory testing to determine the mechanical properties of conventional concrete and jute fiber-reinforced concrete mixtures containing 1%, 2%, and 3% jute fibers by mass of wet concrete. In the second stage, the experimentally determined material properties are incorporated into AASHTOWare Pavement ME Design to simulate rigid pavement performance under identical traffic and environmental conditions. The predicted pavement responses are subsequently compared to evaluate the effectiveness of jute fiber reinforcement in improving the structural and functional performance of rigid pavements.

3.2 Research Methodology Framework

The research methodology adopted in this study was developed to evaluate the performance of jute fiber-reinforced concrete (JFRC) in rigid pavement applications through an integrated experimental and mechanistic-empirical approach. The methodology consists of a systematic sequence of interconnected stages, beginning with the collection of pavement design inputs, followed by laboratory investigation, and concluding with mechanistic-empirical pavement analysis. This integrated framework establishes a direct relationship between the engineering properties of JFRC obtained from laboratory testing and its predicted long-term performance under traffic loading and environmental conditions. The overall research methodology adopted in this study is illustrated in Figure 3.1.

The methodology comprises two principal stages. Stage 1 involved the collection and characterization of all input data required for pavement analysis.

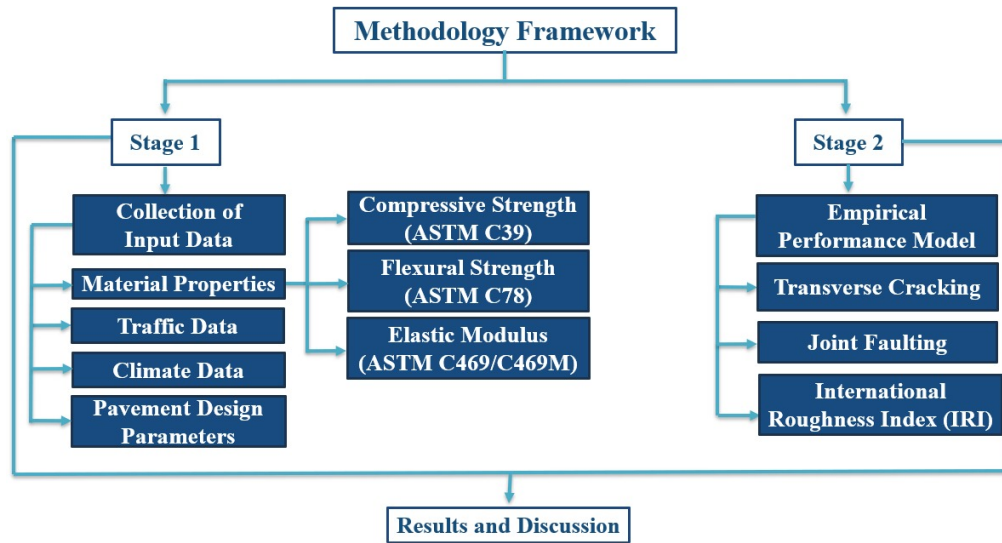


FIGURE 3.1: Research methodology framework

This included pavement material properties, pavement structural configuration, traffic loading characteristics, climatic conditions, and design parameters necessary for developing the rigid pavement models in AASHTOWare Pavement ME Design. The analysis was not associated with a specific existing road or project; representative traffic, structural, and climatic inputs were adopted based on the approach used in previous studies to provide a consistent basis for comparative evaluation of PCC and JFRC pavement models. The experimental investigation carried out to determine the engineering properties of conventional concrete and jute fiber-reinforced concrete mixtures containing 1%, 2%, and 3% jute fibers by mass of wet concrete. Laboratory testing was conducted to determine the compressive strength, flexural strength, and elastic modulus of each concrete mixture. The experimentally determined properties were subsequently used as material inputs for mechanistic-empirical pavement analysis. Stage 2 involved mechanistic-empirical pavement analysis using AASHTOWare Pavement ME Design. The collected traffic, climatic, pavement structural, and material data were incorporated into the software to develop rigid pavement models for conventional concrete and JFRC mixtures. The software was then used to predict long-term pavement performance in terms of transverse cracking, joint faulting, and International Roughness

Index (IRI). Finally, the predicted performance of all pavement models was comparatively evaluated to assess the effectiveness of jute fiber reinforcement and to identify the optimum fiber content for rigid pavement applications.

3.3 Phase-I: Experimental Program

The experimental program was conducted to determine the engineering properties of conventional concrete and jute fiber-reinforced concrete (JFRC) required for mechanistic-empirical pavement analysis. Laboratory testing was performed to evaluate the influence of different jute fiber contents on the mechanical behavior of concrete. The experimentally determined material properties were subsequently incorporated into AASHTOWare Pavement ME Design to simulate the long-term performance of rigid pavements. The laboratory investigation consisted of concrete mix preparation, specimen casting, curing, and testing in accordance with relevant standard procedures. Four concrete mixtures were prepared for the experimental investigation, comprising one control mix without jute fibers and three JFRC mixtures containing 1%, 2%, and 3% jute fibers by mass of wet concrete. A nominal concrete mix proportion of 1:2:3 (cement, sand, coarse aggregate) with a water-cement ratio of 0.46 was adopted for all mixtures to maintain consistency throughout the experimental program.

TABLE 3.1: Mix proportions of control concrete (PCC) and jute fiber reinforced concrete (JFRC) expressed per cubic meter of concrete

Mix ID	Fiber Content (%)	Cement (kg/m ³)	Sand (kg/m ³)	Coarse Aggregate (kg/m ³)	Water (kg/m ³)
Control mix	0	239.80	479.50	719.20	110.40
JFRC-1	1%	237.22	474.34	711.46	110.40
JFRC-2	2%	234.64	469.17	703.71	110.40
JFRC-3	3%	232.05	464.01	695.97	110.40

The quantity of cement, fine aggregate, coarse aggregate, and water remained constant, while only the fiber content was varied to evaluate its influence on the mechanical properties of concrete. The mix proportions adopted in this study are

presented in Table 3.1. A total of twenty-four concrete specimens were prepared for laboratory testing, comprising twelve beam specimens and twelve cylindrical specimens. For each concrete mixture, three beam specimens and three cylinder specimens were cast to ensure consistency and reliability of the experimental results. Concrete ingredients were mixed thoroughly to obtain a uniform mixture before the addition of jute fibers. The fibers were distributed evenly throughout the concrete to minimize fiber balling and achieve uniform reinforcement within the matrix. Fresh concrete was then placed into the prepared moulds and adequately compacted to remove entrapped air and ensure proper consolidation. After casting, all specimens were left undisturbed for 24 hours before being demolded. The specimens were subsequently cured in water under controlled laboratory conditions until the designated testing ages. The complete procedure adopted for specimen preparation and laboratory testing is illustrated in Figure 3.2.

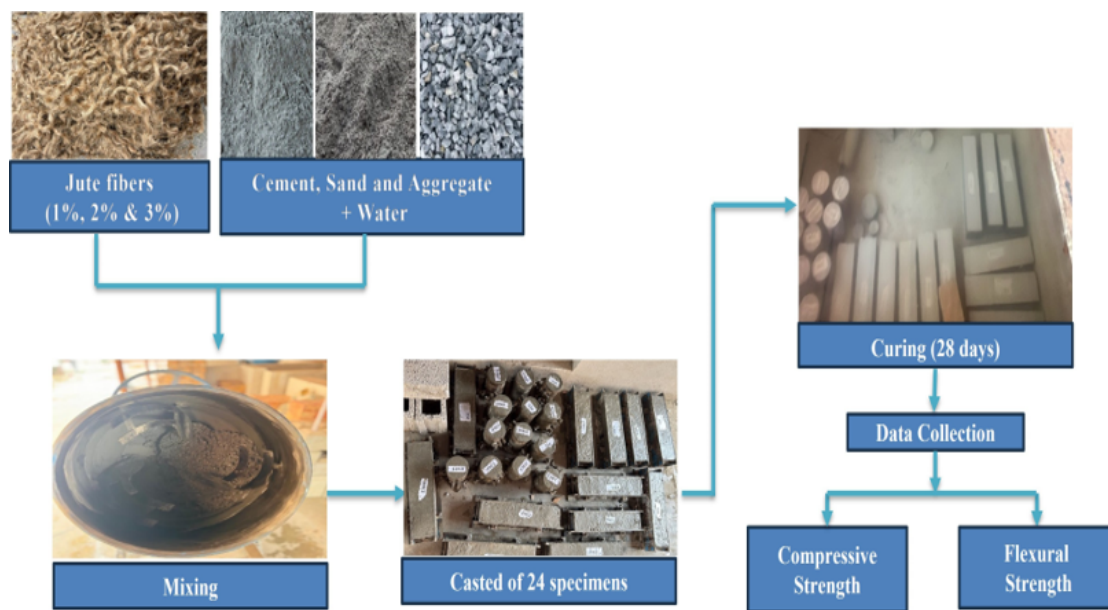


FIGURE 3.2: Experimental methodology for preparing and testing JFRC specimens.

Laboratory testing was carried out to determine the engineering properties of conventional concrete and jute fiber-reinforced concrete mixtures. The principal material properties required for mechanistic-empirical pavement analysis included compressive strength, flexural strength (modulus of rupture), and elastic modulus. These parameters govern the structural response of rigid pavements

and therefore represent essential inputs for AASHTOWare Pavement ME Design. Compressive strength testing was performed using cylindrical specimens after the specified curing period, while flexural strength was determined using beam specimens subjected to flexural loading. The elastic modulus of each concrete mixture was subsequently determined from the measured strength properties using standard relationships. Additional material parameters required by AASHTOWare Pavement ME Design, including Poisson's ratio and the coefficient of thermal expansion (CTE), were adopted from published literature and standard pavement design recommendations because direct laboratory measurement was beyond the scope of this study. A Poisson's ratio of 0.20 was adopted for both PCC and all JFRC mixtures [54, 55]. The same value was used for all mixtures to maintain consistency in the AASHTOWare Pavement ME analysis. The experimental investigation demonstrated that the incorporation of jute fibers influenced the engineering properties of concrete. The measured compressive strength, flexural strength, and elastic modulus for each concrete mixture were used as the primary material inputs in the mechanistic-empirical pavement analysis.

The remaining material properties required by the software, including Poisson's ratio and the coefficient of thermal expansion, were assigned based on published references to ensure consistency among all pavement models. The material properties adopted for conventional concrete (PCC) and jute fiber-reinforced concrete (JFRC) mixtures are presented in Table 3.2.

TABLE 3.2: PCC and JFRC layer material properties used in AASHTOWARE Pavement ME Design

Property	PCC	JFRC-1%	JFRC-2%	JFRC-3%
Compressive strength (MPa)	17.83	16.1	15.5	14.4
Flexural Strength (MPa)	2.36	2.53	3.1	3.06
Elastic Modulus, E ($\times 10^3$ MPa)	19.84	18.50	18.49	17.82
Poisson's Ratio	0.20	0.20	0.20	0.20
CTE ($\times 10^{-6}/^\circ\text{C}$)	9.9	9.9	9.9	9.9

The experimentally determined properties established the direct link between the laboratory investigation and the mechanistic-empirical pavement analysis. These material inputs were subsequently incorporated into AASHTOWare Pavement ME Design to evaluate the influence of different jute fiber contents on the long-term structural and functional performance of rigid pavements. The detailed experimental results and their discussion are presented in Chapter 4.

3.4 Phase-II: Mechanistic - Empirical Pavement Analysis

Following the experimental investigation, the measured material properties of conventional concrete and jute fiber-reinforced concrete (JFRC) were incorporated into AASHTOWare Pavement ME Design to evaluate the long-term performance of rigid pavements. The mechanistic-empirical (M-E) approach combines mechanistic analysis of pavement responses with empirically calibrated distress prediction models to simulate pavement behavior under actual traffic loading and environmental conditions. In this study, separate pavement models were developed for conventional concrete and JFRC mixtures while maintaining identical traffic, climatic, and structural conditions. The analysis focused on predicting transverse cracking, joint faulting, and the International Roughness Index (IRI) throughout the selected design life.

3.4.1 Pavement Material Properties and Characterization

Accurate characterization of pavement materials is essential for reliable mechanistic-empirical pavement analysis. In AASHTOWare Pavement ME Design, each pavement layer must be assigned appropriate engineering properties to simulate its structural response under traffic loading and environmental conditions. The pavement structure analyzed in this study consisted of a concrete surface layer, crushed stone base layer, and subgrade layer. The engineering properties of the PCC and

JFRC surface layers were obtained from laboratory testing, while the remaining material parameters for the concrete, base, and subgrade layers were adopted from published literature, available data, and standard pavement design recommendations. The experimentally determined material properties presented in Table 3.2 were used as the primary material inputs for all pavement models. The base layer was modeled as a 150-mm non-stabilized crushed stone layer that provides uniform support to the concrete slab, assists in load distribution, and improves drainage. The material properties adopted for the base layer are presented in Table 3.3.

TABLE 3.3: Base Layer Material Properties Used in AASHTOWare Pavement ME Design

Layers	Materials	Parameters	Values
Layer 2	Non-stabilized Crushed Stone	Layer thickness (mm)	150
		Gradation	A-1-a
		Resilient Modulus (MPa)	300
		Poisson's Ratio	0.35
		Coeff. of Lateral earth Pressure (k_0)	0.5

The 150-mm layer thickness and resilient modulus of 300 MPa were adopted as design input values based on standard pavement design recommendations and the selected AASHTOWare Pavement ME Design input criteria. The Poisson's ratio of 0.35 and coefficient of lateral earth pressure (k_0) of 0.50 were adopted as representative values for unbound granular materials based on published literature and standard pavement design recommendations [56, 57].

These parameters were kept constant for all pavement models to provide a consistent basis for comparison and to isolate the effect of the concrete material properties on pavement performance. The subgrade forms the foundation of the pavement structure and significantly influences slab deflection and stress distribution. The resilient modulus and soil classification adopted for the subgrade were selected based on available data and standard pavement design recommendations. The adopted subgrade properties are presented in Table 3.4.

TABLE 3.4: Subgrade layer material properties used in AASHTOWARE Pavement ME Design

Layer	Material	Parameter	Value
Layer 3	Subgrade Soil	Soil Type	A-6
		Resilient Modulus (MPa)	100
		Poisson's Ratio	0.40
		Coefficient of Lateral Earth Pressure (k_0)	0.50

3.4.2 Traffic Data Inputs

Traffic loading is one of the most influential inputs in mechanistic-empirical pavement analysis because it governs the magnitude and frequency of pavement loading throughout the design life. The traffic inputs used in this study were based on the predefined Level-3 traffic framework available in AASHTOWare Pavement ME Design rather than on traffic data from a specific road or site-specific traffic survey. The analysis used the FHWA vehicle Classes 4–13 to represent the general truck traffic spectrum considered in pavement design, with a 7% annual compound traffic growth rate over the 20-year design period [58]. The traffic characterization included Average Annual Daily Truck Traffic (AADTT), vehicle class distribution, traffic growth rate, and axle load distributions. Where detailed local traffic information was unavailable, default axle load spectra and traffic characteristics provided by the software were adopted. The summarized traffic data used for pavement modeling are presented in Table 3.5.

TABLE 3.5: Summarized traffic data used in this study

Vehicle Class	AADT	Distribu- tion (%) (Level 3)	Growth Rate (%)	Factor	Growth Factor Function
Class 4	19.3		7		Compound
Class 5	16.9		7		Compound
Class 6	4.8		7		Compound
Class 7	5.1		7		Compound
Class 8	23.2		7		Compound

Table 3.5 continued from previous page

Vehicle Class	AADT	Distribu- tion (%) (Level 3)	Growth Rate (%)	Factor	Growth Factor Function
Class 9	25.3		7		Compound
Class 10	1.7		7		Compound
Class 11	1.2		7		Compound
Class 12	1.2		7		Compound
Class 13	1.3		7		Compound

The same vehicle class distribution and 7% annual growth rate were applied consistently to all pavement models so that the traffic loading remained identical and the effect of the concrete material properties on pavement performance could be evaluated fairly.

3.4.3 Climatic Conditions

Environmental conditions significantly influence the performance of rigid pavements by affecting temperature- and moisture-related stresses, material properties, and pavement deterioration. For the mechanistic-empirical pavement analysis, climatic inputs were required to simulate environmental effects over the 20-year design period. Bahawalpur meteorological station was selected as a representative climatic station for providing the environmental inputs required by AASHTO-Ware Pavement ME Design. Bahawalpur is an established meteorological station in Punjab, and climatic data for the station have been reported based on data obtained from the Pakistan Meteorological Department (PMD) [59]. The climatic data were used solely as environmental inputs for pavement performance simulation and were not intended to define a specific study area. The climatic parameters considered in the analysis included mean annual air temperature, precipitation, freezing index, freeze/thaw cycles, wet days, groundwater table depth, and sunshine hours. The same climatic conditions were applied to PCC and all JFRC pavement alternatives to maintain consistency and enable a fair comparison of

pavement performance. The adopted climatic parameters are presented in Table 3.6.

TABLE 3.6: Climatic inputs adopted for AASHTOWare Pavement ME analysis

Parameters	Values
Mean annual air temperature ($^{\circ}\text{C}$)	27
Mean annual precipitation (mm)	150–180
Freezing index ($^{\circ}\text{C}\text{-day}$)	0
Average annual number of freeze/thaw cycles	0–1
Number of wet days per year	25–30
Ground water table depth (m)	11.93
Percentage (%) of sunshine hours	80–90

3.4.4 Analysis Parameters and Design Reliability

The values presented in Table 3.7 were selected based on the performance criteria and reliability framework used in AASHTOWare Pavement ME Design. The software requires the pavement designer to specify acceptable distress and smoothness threshold values at a selected reliability level for evaluating the adequacy of a trial pavement design. The primary distress criteria considered in this study were transverse cracking, joint faulting, and International Roughness Index (IRI). For JPCP, the adopted values of 2.7 m/km for terminal IRI, 15% transverse cracking, and 3 mm mean joint faulting are consistent with the performance criteria reported in AASHTOWare Pavement ME Design documentation and previous pavement studies [60, 61]. An initial IRI of 1.0 m/km was adopted as the starting pavement smoothness condition, while a 20-year design life was selected to evaluate long-term pavement performance.

A reliability level of 90% was used to provide a consistent reliability basis for comparison of the PCC and JFRC alternatives. Therefore, these values were adopted as the acceptance criteria for evaluating pavement performance and kept constant for all PCC and JFRC alternatives to ensure a fair comparison. Keeping these parameters constant ensured that differences in predicted pavement performance

were primarily associated with the changes in concrete material properties and jute fiber content.

TABLE 3.7: Design Reliability Parameters

Parameter	Selected Value
Design Life	20 years
Reliability	90%
Initial IRI (m/km)	1
Terminal IRI (m/km)	2.7
JPCP Transverse cracking	15%
Mean Joint Faulting (mm)	3

3.4.5 Development of Rigid Pavement Design

A Jointed Plain Concrete Pavement (JPCP) structure was developed in AASHTOWare Pavement ME Design using the representative traffic loading, climatic conditions, and pavement material properties of the selected study area. The pavement structure consisted of a PCC/JFRC surface layer, crushed stone base layer, and subgrade layer. Four separate pavement models were developed representing conventional concrete (PCC), JFRC containing 1% jute fiber, JFRC containing 2% jute fiber, and JFRC containing 3% jute fiber.

All pavement models were analyzed using identical traffic loading, climatic conditions, structural configuration, and reliability level so that the influence of jute fiber reinforcement could be evaluated independently.

3.4.6 AASHTOWare Project Setup

The pavement analysis was carried out by creating a new project in AASHTOWare Pavement ME Design. The project settings were configured to represent the study area and remained identical for all pavement models throughout the analysis. The principal project settings included pavement type, design life, reliability level,

traffic input level, climate station, performance indicators, and distress criteria. These settings are summarized in Table 3.8.

A Jointed Plain Concrete Pavement (JPCP) was selected as the pavement type, while the Bahawalpur climate station was adopted to represent the environmental conditions of the study area.

TABLE 3.8: Summary of the Principal Project Settings Adopted in AASHTOWare Pavement ME Design

Parameters	Selected Values
Pavement type	Joint Plain Concrete Pavement
Design life	20 Years
Reliability Level	90%
Traffic input level	Level 3
Climate station	Bahawalpur
Performance indicators	Transverse Cracking, Joint Faulting and IRI
Distress Criteria	Default AASHTOWare thresholds

3.4.7 AASHTOWare Simulation Run

Following completion of all pavement design inputs, the mechanistic-empirical analysis was performed using AASHTOWare Pavement ME Design. The software calculated pavement responses under combined traffic loading and environmental effects throughout the selected design life.

Separate simulation cases were developed for conventional concrete and each JFRC mixture. Based on the calculated pavement responses, the software predicted the progression of transverse cracking, joint faulting, and International Roughness Index (IRI) at different stages of pavement service life. The overall software input procedure adopted in this study is illustrated in Figure 3.3.

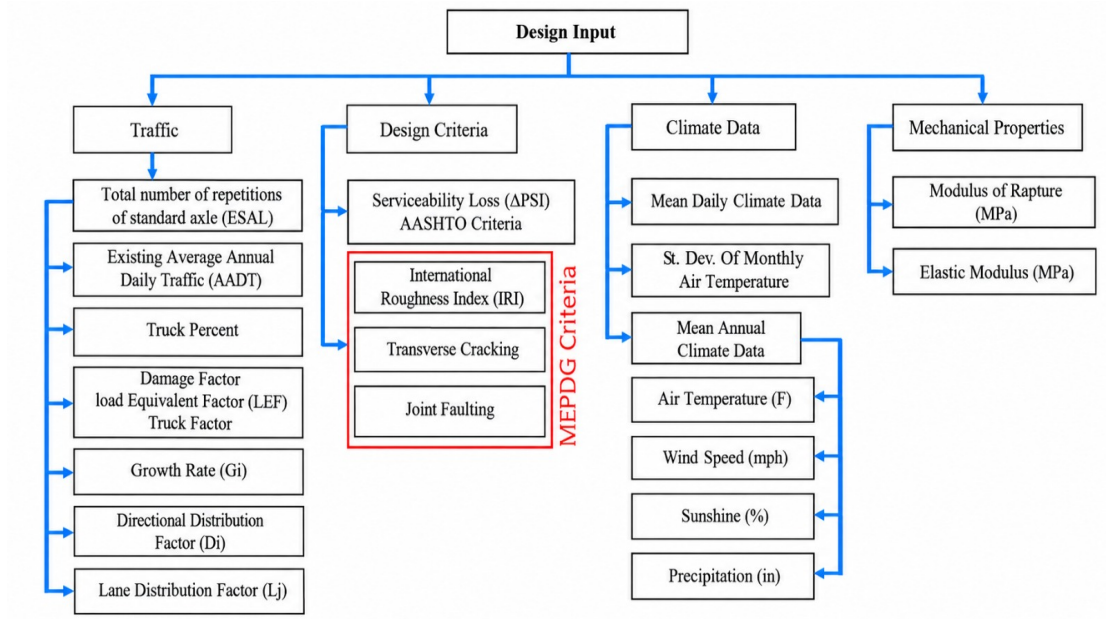


FIGURE 3.3: AASHTOWare Pavement ME input procedure.

3.4.8 Parametric Analysis

Parametric analysis was conducted to investigate the influence of selected pavement and material parameters on the predicted performance of the rigid pavement. The purpose of the parametric analysis was to determine how changes in slab thickness, flexural strength, and jute fiber content affect the predicted pavement distresses and to identify the slab thickness and fiber content combination that satisfies the specified performance criteria. Three parameters were considered in the parametric analysis: slab thickness, flexural strength, and jute fiber content. Slab thickness was varied to determine the minimum concrete slab thickness required to satisfy the allowable pavement distress limits. Flexural strength was investigated because it is an important mechanical property governing the structural response and cracking resistance of concrete pavement. Jute fiber content was varied among 0%, 1%, 2%, and 3% to evaluate the effect of fiber reinforcement on pavement performance. The experimentally determined mechanical properties corresponding to each fiber content were incorporated into the AASHTOWare Pavement ME Design models.

During the parametric analysis, the traffic loading, climatic conditions, base and subgrade properties, pavement configuration, design life, and reliability level were

kept constant for all simulation cases. This ensured that the changes in predicted pavement performance were primarily associated with the parameter being investigated. The analysis was performed for a 20-year design period at 90% reliability. For each simulation case, the predicted transverse cracking, mean joint faulting, and International Roughness Index (IRI) were recorded. The predicted distress values were compared with the adopted performance criteria of 15% transverse cracking, 3 mm mean joint faulting, and 2.70 m/km IRI. The slab thickness was progressively adjusted until the minimum thickness satisfying the applicable distress criteria was identified.

TABLE 3.9: Summary of the Principal Project Settings Adopted in AASHTO-Ware Pavement ME Design

Parameter	Values/Levels	Considered	Output Evaluated	Purpose
Slab thickness	Varied according to pavement performance requirements		• Transverse cracking • Joint faulting • IRI	To determine the minimum slab thickness satisfying the distress criteria.
MOR	PCC = 2.36 MPa; JFRC-1 = 2.53 MPa; JFRC-2 = 3.10 MPa; JFRC-3 = 3.06 MPa			To evaluate the influence of flexural strength and elastic modulus on pavement performance.
Elastic Modulus, E	PCC = 19.84 GPa; JFRC-1 = 18.85 GPa; JFRC-2 = 18.49 GPa; JFRC-3 = 17.82 GPa			
Jute fiber content	0%, 1%, 2%, 3%			To evaluate the effect of fiber reinforcement and identify the optimum fiber content.

Similarly, the performance of the four concrete mixtures was compared to determine the effect of jute fiber content. The parametric analysis therefore consisted of the following three investigations, the concrete slab thickness was varied while

maintaining the material properties, traffic, climate, base, and subgrade conditions constant. The purpose was to determine the minimum slab thickness that could satisfy the pavement performance criteria. Flexural strength was varied to evaluate its influence on predicted transverse cracking, joint faulting, and IRI. This analysis was used to establish the relationship between the mechanical performance of concrete and the predicted pavement response. Four concrete mixtures, namely PCC (0%), JFRC-1 (1%), JFRC-2 (2%), and JFRC-3 (3%), were analyzed using their respective experimentally determined material properties. The predicted pavement distresses were compared to assess the effectiveness of jute fiber reinforcement and to identify the optimum fiber content. The parameters investigated in the parametric analysis are summarized in Table 3.9. All other pavement design inputs were maintained constant during the parametric analysis. The results obtained from these simulations were subsequently compared to determine the influence of the selected parameters and to identify the optimum pavement configuration. The detailed results of the parametric analysis are presented and discussed in Chapter 4.

3.5 Summary

This chapter presented the research methodology adopted to evaluate the performance of jute fiber-reinforced concrete (JFRC) in rigid pavement applications through an integrated experimental and mechanistic-empirical approach. The methodology was organized into three sequential stages. The first stage involved the collection and characterization of pavement design inputs, including pavement material properties, traffic data, climatic conditions, and structural parameters required for pavement modeling. The second stage comprised the experimental investigation, in which conventional concrete and JFRC mixtures containing 1%, 2%, and 3% jute fibers were prepared, cast, cured, and tested to determine their compressive strength, flexural strength, and elastic modulus. The experimentally determined material properties served as the primary inputs for the

mechanistic-empirical pavement analysis. The third stage involved the development and analysis of rigid pavement models using AASHTOWare Pavement ME Design. The experimentally determined material properties, together with traffic loading, climatic conditions, pavement structure, and design reliability parameters, were incorporated into the software to simulate long-term pavement performance. Separate pavement models were developed for conventional concrete and each JFRC mixture while maintaining identical traffic, environmental, and structural conditions to ensure a consistent basis for comparison.

The mechanistic-empirical analysis predicted the progression of key pavement performance indicators, including transverse cracking, joint faulting, and the International Roughness Index (IRI), throughout the selected design life. A comparative analysis was then conducted to evaluate the influence of different jute fiber contents on the structural and functional performance of rigid pavements. In addition, a parametric study was performed by varying slab thickness, flexural strength, and fiber content to assess their influence on pavement behavior. The methodology presented in this chapter establishes the basis for the results and discussion presented in Chapter 4.

Chapter 4

Results and Analysis

4.1 Background

This chapter presents and discusses the results obtained from the two phases of the study: (i) the experimental investigation phase and (ii) the mechanistic-empirical pavement design (MEPD) phase. In Phase 1, laboratory testing was conducted to evaluate the fresh and hardened properties of plain cement concrete (PCC) and jute fiber-reinforced concrete (JFRC), including workability, compressive strength, flexural strength, modulus of elasticity, and stress-strain behavior. In Phase 2, the experimentally determined material properties were incorporated into AASHTO-Ware Pavement ME Design (MEPD) software to assess the long-term performance of rigid pavements in terms of transverse cracking, joint faulting, International Roughness Index (IRI), and service life. The primary objective of this chapter is to evaluate the effectiveness of jute fiber reinforcement in improving concrete performance and to determine its potential benefits for rigid pavement applications.

The experimental phase focuses on the evaluation of fresh and hardened concrete properties for both control mix and fiber-reinforced mixes containing 1%, 2%, and 3% jute fibers. Fresh concrete behavior is assessed through workability (slump

test), while hardened properties include compressive strength, flexural strength, and modulus of elasticity. These parameters are essential for rigid pavement design because they directly influence slab performance under traffic loading and environmental conditions. The results obtained from laboratory testing are used not only to compare the performance of different mixes but also to provide input parameters for pavement modeling in the MEPD software. In addition to experimental analysis, the study incorporates mechanistic-empirical pavement modeling to evaluate the long-term performance of rigid pavements. The MEPD approach is based on the combination of mechanistic principles and empirical calibration, allowing for more realistic prediction of pavement distresses such as transverse cracking, longitudinal cracking, joint faulting, and International Roughness Index (IRI). By incorporating laboratory-derived material properties along with traffic loading and climatic conditions, the software simulates pavement behavior over its design life and provides a comparative assessment between conventional concrete and jute fiber-reinforced concrete pavements.

The integration of both experimental and numerical approaches provides a comprehensive understanding of how jute fiber influences rigid pavement performance. While the experimental results highlight improvements in mechanical properties and crack resistance at material level, the MEPD analysis extends these findings to pavement scale performance, including distress development and service life prediction. This dual approach allows for a more reliable evaluation of JFRC and helps in identifying the optimum fiber content for practical pavement applications.

Furthermore, this chapter is divided into two main phases for clarity. The first phase presents the experimental results and discussion, including fresh concrete behavior, strength development, and failure characteristics. The second phase presents the mechanistic-empirical modeling results obtained from MEPD, followed by a comparative discussion between control and fiber-reinforced pavement systems. The combined analysis of both phases forms the basis for understanding the overall effectiveness of jute fiber reinforcement in improving rigid pavement performance and sustainability.

4.2 Phase I: Experimental Results

4.2.1 Fresh Concrete Properties

The fresh properties of concrete play a crucial role in determining its workability, placing behavior, and ease of compaction during construction. In this study, the fresh concrete characteristics of plain cement concrete (PCC) and jute fiber-reinforced concrete (JFRC) were evaluated to understand the influence of fiber incorporation on mixing and handling behavior. Since the addition of fibers can significantly affect the internal friction and water demand of concrete, it is essential to assess workability before analyzing hardened properties. The slump test was therefore conducted to quantify changes in consistency with varying jute fiber content. The results of the fresh concrete evaluation are presented in the following subsections.

The slump test was conducted to evaluate the workability of fresh concrete mixtures containing different percentages of jute fiber. Workability is an important property that influences the ease of mixing, transportation, placement, and compaction of concrete. The test was performed in accordance with ASTM C143/C143M.

TABLE 4.1: Slump Test Results

Mix ID	Fiber Content (%)	Slump (mm)
PCC	0	81.7
JFRC-1	1	63.8
JFRC-2	2	35.0
JFRC-3	3	18.2

The slump value was determined by filling the standard slump cone with fresh concrete, lifting the cone vertically, and measuring the reduction in height of the concrete in millimeters; the measured height difference was recorded as the slump value. The results obtained for the control mix and jute fiber-reinforced concrete (JFRC) mixes are presented in Table 4.1. The results as shown in Figure 4.1

indicate that the slump value decreased continuously with the increase in jute fiber content. The control mix (PCC) exhibited the highest slump value of 81.7 mm, indicating good workability. The addition of 1% jute fiber reduced the slump to 63.8 mm, representing a decrease in workability.

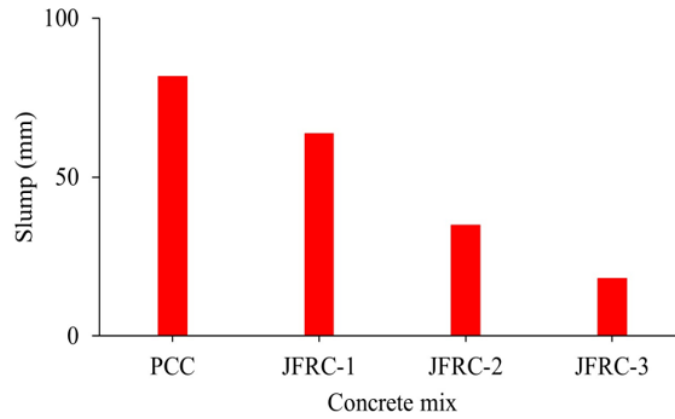


FIGURE 4.1: Effect of Jute Fiber Content on Slump Value

Further increases in fiber content resulted in more significant reductions, with slump values of 35.0 mm and 18.2 mm recorded for the 2% and 3% fiber mixes, respectively. The reduction in slump can be attributed to the ability of jute fibers to absorb part of the mixing water and increase internal friction within the concrete matrix. As the fiber content increased, the fibers created a network that restricted the movement of fresh concrete, resulting in lower workability. Similar behavior has been reported in previous studies on natural fiber-reinforced concrete, where increasing fiber dosage led to a reduction in slump values. Although workability decreased with increasing fiber content, the mixes remained cohesive and showed no signs of segregation. The lowest slump value was observed for the JFRC-3 mix, indicating that higher fiber contents may require the use of admixtures or adjustments in the mix design to maintain adequate workability during construction.

A comparison of the slump values shows that the workability of concrete decreased as the percentage of jute fiber increased. The control mix produced the highest slump value, indicating better flowability and ease of handling. In contrast, all jute fiber-reinforced mixes showed lower slump values, with the lowest value recorded for the 3% fiber mix. The reduction in workability may be attributed to the

presence of jute fibers within the concrete matrix. Jute fibers tend to absorb a portion of the mixing water and create resistance to the movement of fresh concrete. As the fiber content increased, the concrete became stiffer and less workable. This effect was more noticeable in the mixes containing 2% and 3% fiber. During mixing and casting, the 1% fiber mix remained relatively easy to handle, while the 2% and 3% mixes required additional effort for proper compaction. Despite the reduction in slump, no segregation or bleeding was observed in any of the mixes, indicating that the concrete remained stable and uniform. Overall, the demonstrate that the inclusion of jute fiber adversely affects workability. However, the reduction in workability is expected when fibers are added to concrete and may be considered acceptable in view of the improvements achieved in the mechanical performance of the hardened concrete.

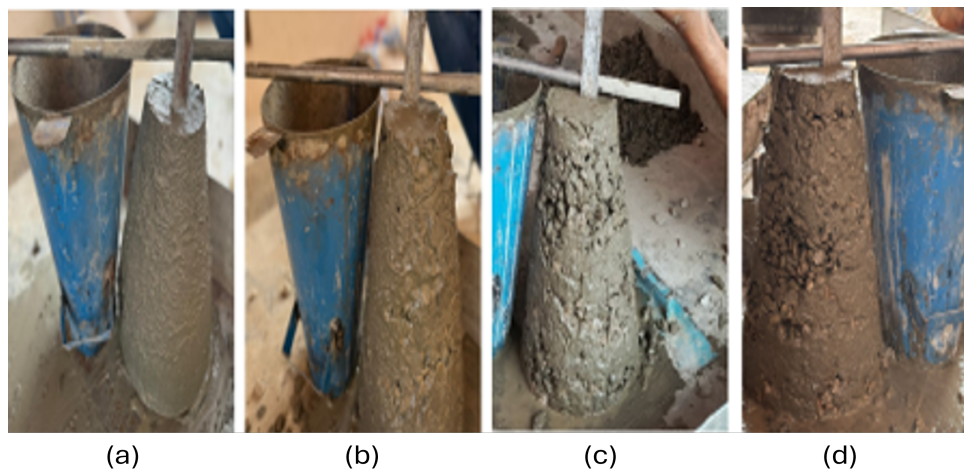


FIGURE 4.2: The slump test conducted on the fresh concrete mixtures (a) PCC, (b) JFRC1, (c) JFRC2, (d) JFRC3

4.2.2 Hardened Concrete Properties

The hardened concrete properties were evaluated to determine the effect of jute fiber incorporation on the mechanical behavior of PCC and JFRC mixtures. The investigated properties included compressive strength, flexural strength, and elastic modulus. These properties were selected because they are important inputs for evaluating the structural response of rigid pavements in the mechanistic-empirical pavement analysis.

4.2.2.1 Compressive Strength

The 28-day compressive strength results indicate that the incorporation of jute fibers resulted in a gradual reduction in compressive strength as shown in Table 4.2. The compressive strength testing was performed in accordance with ASTM C39/C39M - Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens. For each mix, three cylindrical specimens were tested, and the reported mean strength represents the average compressive strength of the three specimens. The $\pm$ values represent the standard deviation of the three test results, which indicates the degree of variation or scatter among the specimens. The control concrete achieved the highest average compressive strength of 17.83 MPa, while the strengths of JFRC-1, JFRC-2, and JFRC-3 were 16.10 MPa, 15.50 MPa, and 14.40 MPa respectively. The reduction in compressive strength can be attributed to the presence of fibers within the concrete matrix. As fiber content increased, additional voids and discontinuities were introduced, reducing the compactness of the concrete. Moreover, the absorption of water by jute fibers may have reduced the amount of free water available for cement hydration, affecting the development of compressive strength.

TABLE 4.2: Compressive Strength Results

Mix ID	Mean Strength (MPa)	Standard Deviation
PCC	17.83	± 1.64
JFRC-1	16.10	± 0.45
JFRC-2	15.50	± 0.32
JFRC-3	14.40	± 0.16

Despite the reduction in compressive strength, the results remained suitable for the pavement analysis conducted in this study. The reduction from PCC to JFRC-3 was approximately 19.2%, indicating that jute fiber addition primarily affected compressive strength, while its major benefit was observed in flexural performance. An important observation is the progressive reduction in standard deviation with increasing fiber content. The PCC specimens exhibited the highest variability (± 1.64 MPa), whereas JFRC-3 showed the lowest variability (± 0.16

MPa). The lower standard deviations observed for the JFRC mixtures indicate lower specimen-to-specimen variation within the tested samples.

The stress-strain curves revealed significant differences between PCC and JFRC specimens. The PCC specimen exhibited a steep ascending branch followed by a sudden drop after reaching peak stress. This behavior is characteristic of brittle concrete, where failure occurs rapidly once the maximum load-carrying capacity is reached. The JFRC specimens displayed a more gradual post-peak response. Although the peak stress decreased slightly with increasing fiber content, the specimens continued to sustain load after crack initiation. This behavior indicates a more gradual post-peak response and improved deformation capacity compared with PCC. The presence of jute fibers restricted crack widening and delayed complete fracture. Fiber bridging across developing cracks enabled stress transfer even after matrix cracking occurred, resulting in a slower reduction in load-carrying capacity. Among all fiber-reinforced mixes, JFRC-2 showed the most balanced behavior, exhibiting reasonable compressive strength together with improved deformation capacity.

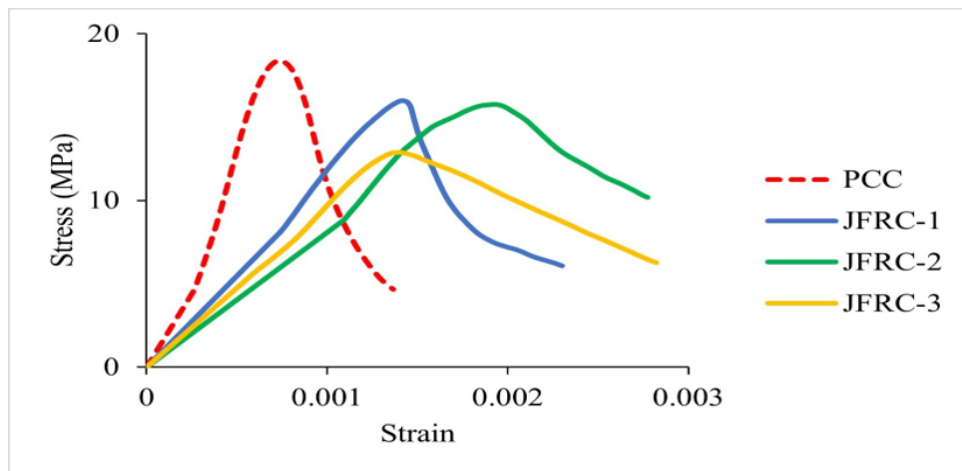


FIGURE 4.3: Stress-strain response of PCC and JFRC specimens under compression.

The experimental results revealed that the compressive strength decreased from 17.83 MPa for conventional PCC to 16.10 MPa, 15.50 MPa, and 14.40 MPa for JFRC containing 1%, 2%, and 3% jute fibers, respectively as shown in Figure 4.3. This indicates that increasing the jute fiber content reduced the compressive

strength of concrete. Similar trends have been reported in previous studies [7, 26–31, 37, 38], where researchers observed that natural fiber reinforcement generally lowers compressive strength because the fibers increase the porosity of the concrete matrix and reduce workability. Therefore, the findings of the present study are consistent with the published literature. The reduction in compressive strength is mainly attributed to the water absorption characteristics of jute fibers, which affect cement hydration, as well as fiber clustering at higher dosages that creates weak zones within the concrete. Although compressive strength decreased, the obtained values remained suitable for rigid pavement analysis, indicating that the addition of jute fibers primarily improves crack resistance rather than compressive load-carrying capacity.

Visual inspection of the failed specimens showed clear differences in the failure patterns of PCC and JFRC. PCC specimens exhibited sudden brittle failure, whereas JFRC specimens retained greater specimen integrity after peak loading. The PCC cylindrical specimens exhibited typical brittle failure characteristics under compressive loading as shown in Figure 4.4. Vertical splitting cracks developed suddenly along the height of the specimen after reaching the maximum load capacity. These cracks propagated rapidly, leading to complete crushing of the specimen with noticeable spalling of concrete fragments from the surface. The failure occurred abruptly with minimal warning, indicating limited post-peak load-carrying capacity. In contrast, the JFRC cylindrical specimens showed a more controlled and gradual failure pattern. Although initial cracking occurred at approximately similar load levels as PCC, the propagation of cracks was significantly restrained by the presence of randomly distributed jute fibers. The fibers acted as internal reinforcement elements, reducing crack width and preventing sudden disintegration of the specimen. Even after peak load was reached, the specimens retained partial integrity.

Overall, the results highlight that fiber reinforcement modifies the failure mechanism of concrete from brittle to more ductile behavior, making it more suitable for rigid pavement applications where crack resistance is a critical requirement. The crack development behavior of plain concrete and jute fiber reinforced concrete

(JFRC) was examined under both compressive and flexural loading conditions. Visual inspection of failed specimens provided clear evidence of the influence of jute fibers on crack initiation, propagation, and final failure mode.

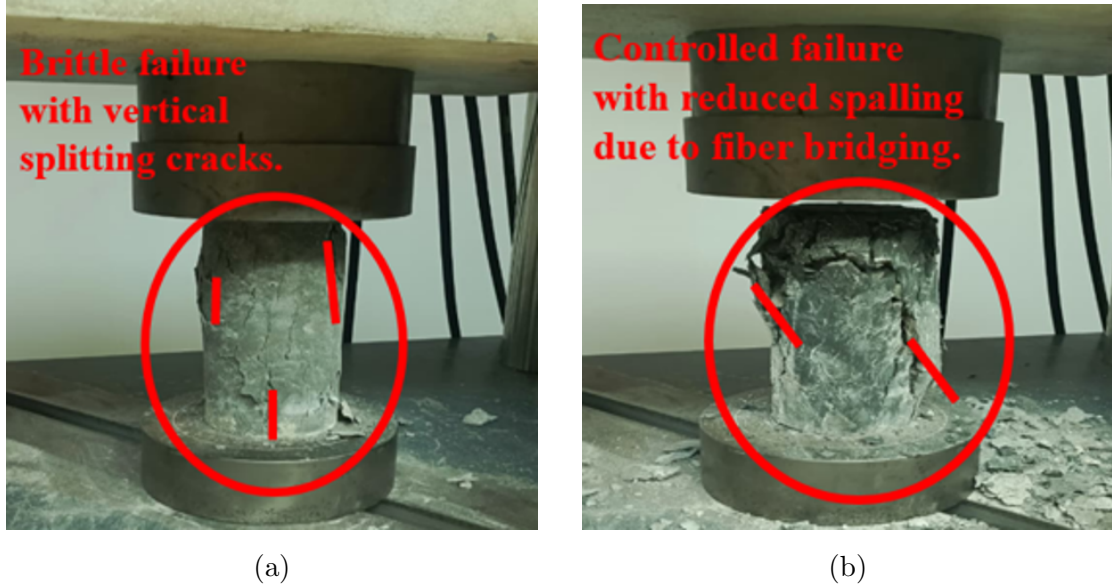


FIGURE 4.4: Crack patterns of (a) PCC and (b) JFRC specimens under compressive loading conditions

The PCC cylindrical specimens exhibited typical brittle failure characteristics under compressive loading. Vertical splitting cracks developed suddenly along the height of the specimen after reaching the maximum load capacity. These cracks propagated rapidly, leading to complete crushing of the specimen with noticeable spalling of concrete fragments from the surface. The failure occurred abruptly with minimal warning, indicating limited post-peak load-carrying capacity. In contrast, the JFRC cylindrical specimens showed a more controlled and gradual failure pattern. Although initial cracking occurred at approximately similar load levels as PCC, the propagation of cracks was significantly restrained by the presence of randomly distributed jute fibers. The fibers acted as internal reinforcement elements, reducing crack width and preventing sudden disintegration of the specimen. Even after peak load was reached, the specimens retained partial integrity due to fiber bridging action, and spalling was considerably reduced compared to PCC. In compression, failure was characterized by the rapid development of vertical splitting cracks accompanied by crushing of the concrete matrix near the loading zone.

4.2.2.2 Elastic Modulus

With the addition of jute fibers, a decreasing trend in elastic modulus was observed. JFRC-1 showed a slight reduction to 18.85 GPa, followed by further decreases in JFRC-2 (18.49 GPa) and JFRC-3 (17.82 GPa) as shown in Table 4.3. This reduction can be attributed to the introduction of natural fibers, which create micro-voids and reduce the overall continuity and stiffness of the cement matrix. Additionally, the hydrophilic nature of jute fibers may absorb part of the mixing water, affecting cement hydration and resulting in a slightly less dense microstructure. Despite the reduction in stiffness, the decrease is gradual and remains within an acceptable range for rigid pavement applications. The lower elastic modulus indicates a reduction in concrete stiffness with increasing jute fiber content. The effect of this reduction on pavement performance was therefore evaluated together with flexural strength, slab thickness, traffic, climate, and foundation conditions through the MEPD analysis. Among all mixes, JFRC-2 shows a balanced performance, maintaining relatively high stiffness while benefiting from fiber-induced toughness improvements observed in other mechanical tests.

TABLE 4.3: Modulus of Elasticity (E) of PCC and JFRC Mixes

Mix ID	Elastic Modulus (GPa)
PCC	19.84
JFRC-1	18.85
JFRC-2	18.49
JFRC-3	17.82

Overall, the results confirm that jute fiber incorporation slightly reduces elastic modulus but enhances the flexibility and crack resistance characteristics of concrete, making it more suitable for pavement applications where long-term structural performance and controlled cracking are important. The modulus of elasticity decreased gradually with increasing jute fiber content, from 19.84 GPa for PCC to 18.85 GPa, 18.49 GPa, and 17.82 GPa for JFRC containing 1%, 2%, and 3% fibers, respectively. A similar reduction has been reported in previous investigations [16–19][26–31], where natural fiber-reinforced concrete exhibited lower

stiffness than conventional concrete due to the comparatively lower elastic modulus of natural fibers. Accordingly, the results of the present study are consistent with the available literature. The decrease in elastic modulus is attributed to the increased deformability of the composite material and the lower stiffness of jute fibers compared with the cement matrix. Although the elastic modulus decreased with increasing fiber content, the combined effects of flexural strength, elastic modulus, slab thickness, traffic, climate, and foundation conditions were considered in the MEPD analysis. The resulting pavement performance remained within the specified design criteria.

The relationship between compressive strength and elastic modulus was evaluated for all concrete mixtures to examine whether changes in concrete strength were accompanied by corresponding changes in stiffness. The results showed a consistent decreasing trend in both properties with increasing jute fiber content. The PCC mixture exhibited the highest compressive strength of 17.83 MPa and elastic modulus of 19,840 MPa, whereas JFRC-3 recorded lower values of 14.40 MPa and 17,820 MPa, respectively. Similarly, JFRC-1 and JFRC-2 showed intermediate reductions in both properties. This consistent trend indicates a strong positive relationship between compressive strength and elastic modulus for the mixtures investigated. The Pearson correlation coefficient was calculated as $r = 0.9998$, indicating an extremely strong positive linear relationship between compressive strength and elastic modulus for the four mixtures investigated. Thus, the decrease in compressive strength with increasing jute fiber content was accompanied by a corresponding decrease in elastic modulus. The experimentally determined elastic modulus was subsequently used as an input parameter in the AASHTOWare Pavement ME Design analysis.

4.2.2.3 Flexural Strength

The flexural strength results demonstrate that jute fiber reinforcement improved the resistance of concrete to bending stresses. The flexural testing was conducted in accordance with ASTM C78/C78M - Standard Test Method for Flexural

Strength of Concrete (Using Simple Beam with Third-Point Loading). For each mix, three beam specimens were tested, and the reported modulus of rupture (MOR) values in Table 4.5 represent the average of the three test results. The control mix exhibited a modulus of rupture of 2.36 MPa. The incorporation of 1% jute fiber increased the value to 2.53 MPa, representing an improvement of approximately 7%. The highest flexural strength was achieved by JFRC-2, which recorded a modulus of rupture of 3.10 MPa.

This corresponds to an increase of approximately 31% compared with PCC. The improvement can be attributed to the crack-bridging action of fibers, which delayed crack propagation and enabled the concrete to sustain higher tensile stresses. Although JFRC-3 contained a greater quantity of fibers, the flexural strength decreased slightly to 3.06 MPa as shown in table 4.4. This reduction may be associated with fiber clustering and reduced workability, which can create localized weak zones within the concrete matrix. The results indicate that 2% fiber content provided the optimum balance between fiber reinforcement and concrete workability, resulting in the highest flexural performance.

The load-deflection curves in Figure 4.5 showed clear differences between PCC and JFRC specimens. The PCC specimen exhibited a nearly linear response up to the peak load, followed by a sudden loss of load-carrying capacity immediately after cracking. This behavior indicates brittle failure and limited post-cracking resistance.

TABLE 4.4: Flexural Strength Results

Mix ID	Modulus of Rupture, MOR (MPa)	Standard Deviation
PCC	2.36	± 0.205
JFRC-1	2.53	± 0.124
JFRC-2	3.10	± 0.163
JFRC-3	3.06	± 0.205

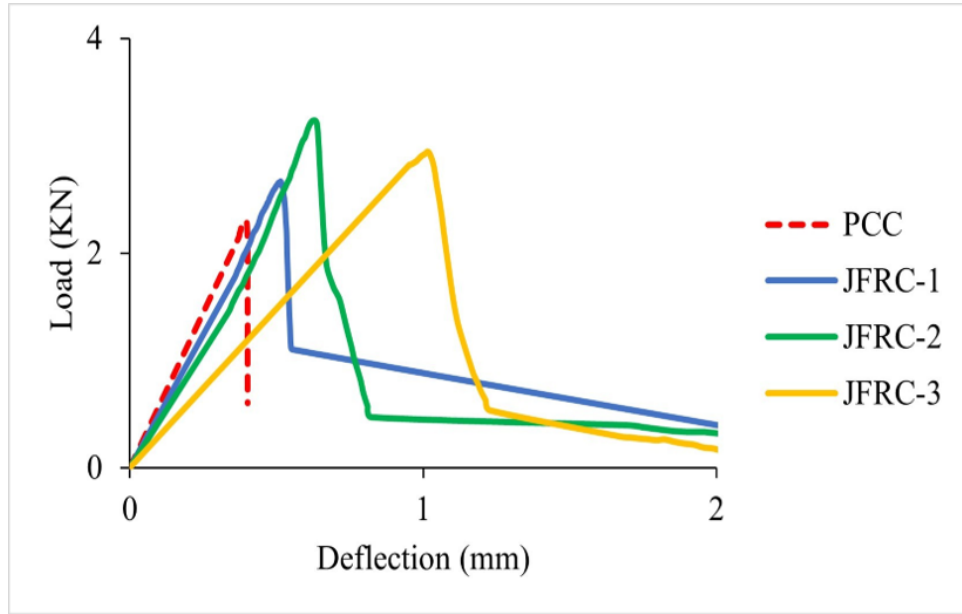


FIGURE 4.5: Modulus of rupture of PCC and JFRC mixes.

The JFRC specimens demonstrated improved post-cracking performance. After the formation of the first crack, the fibers continued to transfer stresses across the sudden collapse. The fiber bridging mechanism played a key role in maintaining load-carrying capacity after cracking. Even at higher deflections, JFRC specimens continued to sustain load, showing improved ductility and toughness compared to plain concrete. Among all mixes, JFRC-2 exhibited the most stable crack pattern with controlled crack propagation and higher resistance to crack widening. The plain cement concrete (PCC) specimens exhibited a sudden and brittle failure mode under both compressive and flexural loading conditions. In compression, failure was characterized by the rapid development of vertical splitting cracks accompanied by crushing of the concrete matrix near the loading zone.

The absence of any post-peak load resistance indicated low energy absorption capacity. Under flexural loading, a single major crack formed at the bottom tensile zone, which propagated rapidly through the depth of the specimen. This crack led to immediate separation of the specimen into two parts, confirming the brittle nature of plain concrete without any reinforcement mechanism to control crack growth. The fiber-reinforced concrete specimens exhibited a noticeably different failure pattern compared to PCC. The presence of jute fibers altered the failure



FIGURE 4.6: Crack patterns of (a) PCC and (b) JFRC specimens under flexural loading conditions

mechanism from sudden fracture to progressive damage development. After initial cracking, the fibers remained engaged within the matrix and provided resistance against further crack opening.

During compression, JFRC specimens showed delayed crack widening and reduced surface spalling. Even after peak load was reached, the specimens retained partial load-carrying capacity, indicating improved post-peak behavior. In flexural loading, instead of a single dominant crack, multiple fine cracks were observed, which is a typical sign of improved stress distribution and ductile response. Visual examination of the fractured surfaces showed the presence of jute fibers bridging across the crack planes. These fibers acted as internal reinforcement elements that connected separated portions of the cement matrix after cracking occurred. This bridging action helped in transferring tensile stresses across the crack, thereby preventing sudden crack opening and catastrophic failure. The effectiveness of this mechanism depends on fiber

distribution, orientation, and bond strength with the cement matrix. In well-dispersed mixes such as JFRC-2, the fractured surfaces showed fibers bridging portions of the cracked matrix, providing a qualitative indication of the fiber-bridging mechanism. This mechanism is primarily responsible for the enhanced flexural strength and improved post-cracking behavior observed in the experimental results.

4.3 Phase 2: Mechanistic-Empirical Results

The mechanistic-empirical pavement analysis was conducted using AASHTOWare Pavement ME Design (MEPD) to evaluate the long-term performance of rigid pavements incorporating jute fiber reinforced concrete (JFRC). The software integrates mechanistic pavement response calculations with empirical distress prediction models to estimate pavement deterioration throughout the design life.

The pavement structure was modeled using the material properties obtained from laboratory testing, including compressive strength, flexural strength, and modulus of elasticity. Traffic loading parameters were defined based on projected axle load repetitions and traffic growth rates, while climatic conditions were incorporated to account for environmental effects such as temperature variations and moisture fluctuations. Subgrade properties and pavement layer characteristics were also included in the model to simulate realistic field conditions.

Separate pavement models were developed for PCC, JFRC-1, JFRC-2, and JFRC-3 mixes. The pavement structure was modeled using the experimentally determined concrete properties required by the MEPD analysis, particularly flexural strength and elastic modulus, together with the specified pavement, traffic, climate, and foundation inputs. These properties directly influence slab stresses, fatigue resistance, and cracking behavior, making them critical inputs for rigid pavement performance prediction.

The performance of PCC and jute fiber-reinforced concrete (JFRC) pavements was evaluated using AASHTOWare Pavement ME Design outputs obtained from the mechanistic-empirical simulations. The analysis focused on comparing predicted pavement distresses and functional performance indicators under identical traffic, climate, and subgrade conditions.

The evaluation framework was based on three primary distress measures: transverse cracking, joint faulting, and International Roughness Index (IRI), which collectively represent structural deterioration and serviceability loss over the pavement design life. To ensure consistency in comparison, all pavement sections were

subjected to the same loading and environmental conditions, while only material properties and slab thickness variations influenced the resulting performance outputs. The results were interpreted in terms of relative improvement of JFRC mixes over conventional PCC in resisting fatigue-related distresses and maintaining ride quality.

The combined influence of compressive strength, flexural strength, and elastic modulus was considered in the AASHTOWare Pavement ME Design analysis. These three mechanical properties collectively characterize the strength and stiffness of the concrete mixtures and were incorporated as material inputs in the pavement performance analysis. With increasing jute fiber content, compressive strength and elastic modulus decreased, while flexural strength increased, with JFRC-2 achieving the highest modulus of rupture.

Therefore, pavement performance was evaluated based on the combined effect of these material properties rather than relying on a single mechanical parameter. The resulting effects on transverse cracking, joint faulting, and International Roughness Index (IRI) are discussed in the following sections.

4.3.1 Transverse Cracking Analysis

Transverse cracking is one of the most critical structural distresses in Jointed Plain Concrete Pavements (JPCP) because it reflects the fatigue performance of the concrete slab under repeated traffic loading and environmental effects. These cracks develop when the tensile stress at the bottom of the slab repeatedly exceeds the fatigue resistance of the concrete. In AASHTOWare Pavement ME Design (MEPD), transverse cracking is predicted using mechanistic-empirical models that consider slab thickness, flexural strength, elastic modulus, axle loading, load transfer efficiency, and temperature-induced stresses.

In this study, the allowable transverse cracking was limited to 15% at the end of the 20-year design period with a design reliability of 90%. The minimum slab

thickness required for each pavement section to satisfy this criterion is presented in Table 4.5.

TABLE 4.5: Minimum slab thickness required to satisfy transverse cracking criterion

Pavement Type	Slab Thickness (mm)	Distress @ Specified Reliability		Reliability (%)		Criterion Satisfied?
		Target	Predicted	Target	Achieved	
PCC	380	15	14.32	90	91.66	Pass
JFRC-1	360	15	14.38	90	91.51	Pass
JFRC-2	265	15	12.32	90	95.57	Pass
JFRC-3	265	15	12.21	90	95.75	Pass

The simulation results show that JFRC-2 and JFRC-3 provided lower predicted transverse cracking than PCC at substantially reduced slab thicknesses. JFRC-1 showed a similar cracking level to PCC despite its reduced slab thickness. The improved transverse cracking performance of JFRC-2 and JFRC-3 is associated with their higher flexural strength, while the MEPD prediction also reflects the combined effects of slab thickness, elastic modulus, traffic, climate, and foundation conditions. The conventional PCC pavement required a slab thickness of 380 mm to satisfy the transverse cracking criterion, whereas the addition of 1% jute fiber reduced the required thickness to 360 mm. A much greater improvement was achieved with 2% jute fiber, where the slab thickness decreased to 265 mm while still meeting the design requirements. The same slab thickness was also adequate for the 3% fiber mixture.

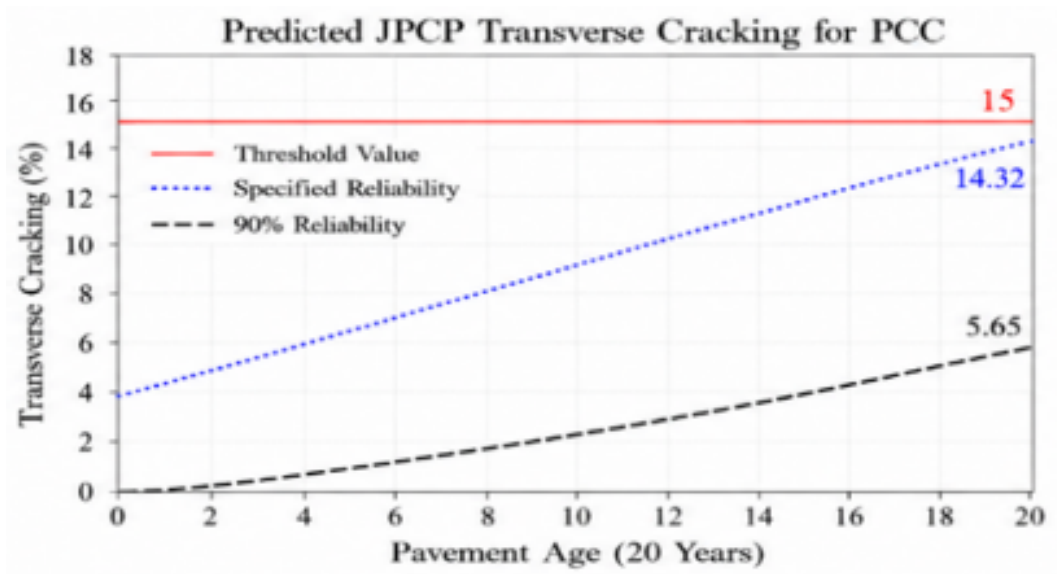
The improved performance of the JFRC pavements is primarily attributed to the increase in flexural strength, which governs fatigue behavior in rigid pavements. Laboratory testing showed that although compressive strength decreased slightly with increasing fiber content, the flexural strength improved considerably, particularly for the 2% fiber mixture. Since fatigue cracking initiates due to repeated tensile stresses at the bottom of the slab, the higher modulus of rupture enabled the JFRC pavements to resist fatigue loading more effectively, thereby reducing the predicted percentage of transverse cracking. The improved flexural behavior

observed in the laboratory can be associated with the crack-bridging action of the jute fibers. Once microcracks begin to form, the randomly distributed fibers bridge the crack surfaces and continue transferring tensile stresses across the cracks. This mechanism delays crack propagation, reduces stress concentration, and preserves the structural integrity of the slab under repeated axle loading. Consequently, JFRC-2 and JFRC-3 showed lower predicted transverse cracking than PCC under the specified design conditions as shown in Figure 4.7.

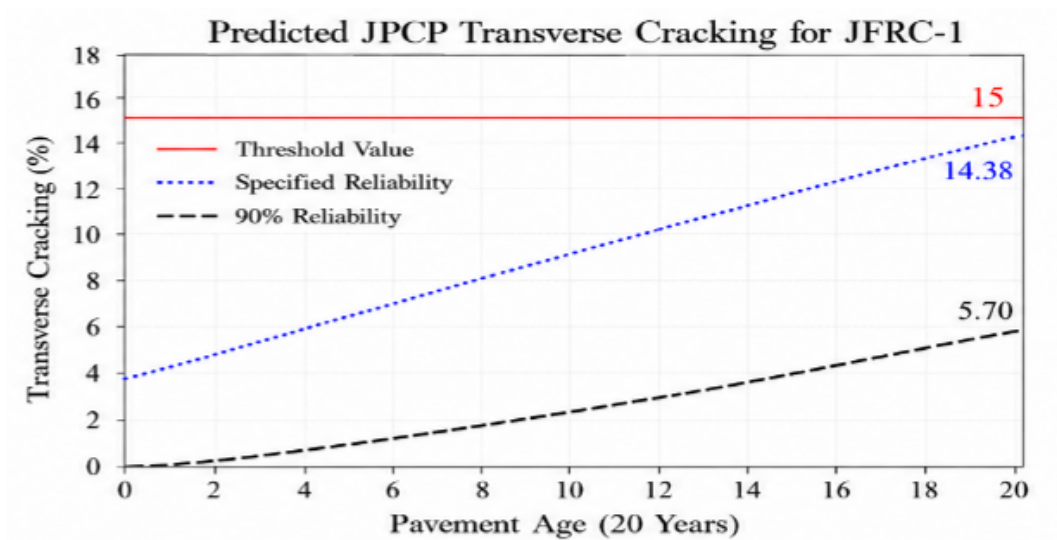
A comparison between JFRC-2 and JFRC-3 indicates that increasing the fiber content beyond 2% provides only a negligible improvement in pavement performance. Although JFRC-3 exhibited a slightly lower predicted cracking value (12.21%) than JFRC-2 (12.32%), both mixtures satisfied the design criterion using the same slab thickness of 265 mm. Considering that the 3% fiber mixture exhibited reduced workability and no significant increase in flexural strength during laboratory testing, the additional fiber content cannot be justified from either a structural or an economic perspective. From an engineering standpoint, the reduction in slab thickness from 380 mm for PCC to 265 mm for JFRC-2 represents a significant improvement in structural efficiency. A thinner pavement section requires less concrete while still maintaining satisfactory fatigue performance, resulting in lower material consumption, reduced construction cost, shorter construction time, and lower environmental impact.

Overall, the transverse cracking analysis indicates that the 2% and 3% jute fiber mixtures provided improved predicted cracking performance compared with PCC under the specified design conditions, while JFRC-1 produced a cracking level comparable to PCC. Among all mixtures evaluated, JFRC containing 2% jute fiber provided the optimum balance between structural performance, slab thickness, workability, and material efficiency, making it the most suitable mixture for the traffic and climatic conditions considered in this study.

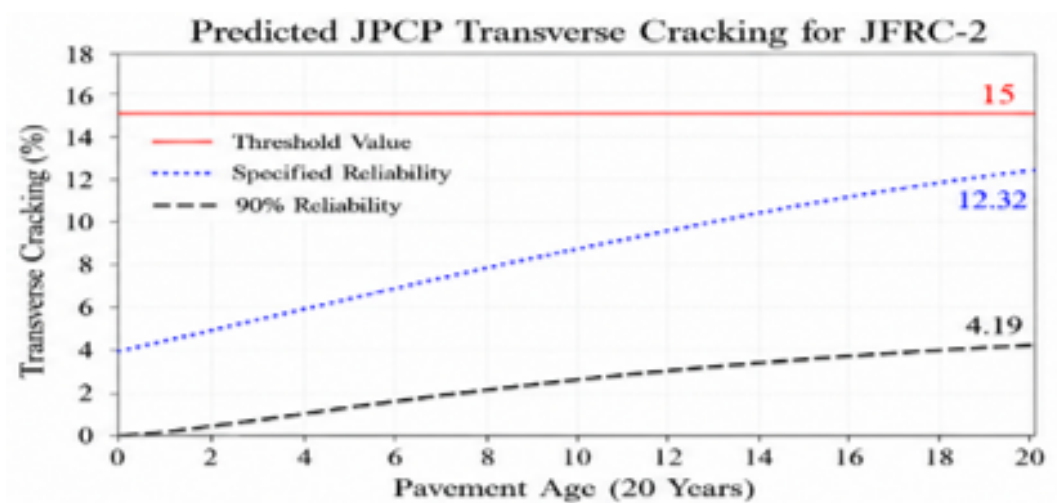
The mechanistic-empirical analysis predicted that the required slab thickness satisfying the allowable transverse cracking criterion decreased from 380 mm for PCC to 360 mm for JFRC-1 and 265 mm for both JFRC-2 and JFRC-3. These results



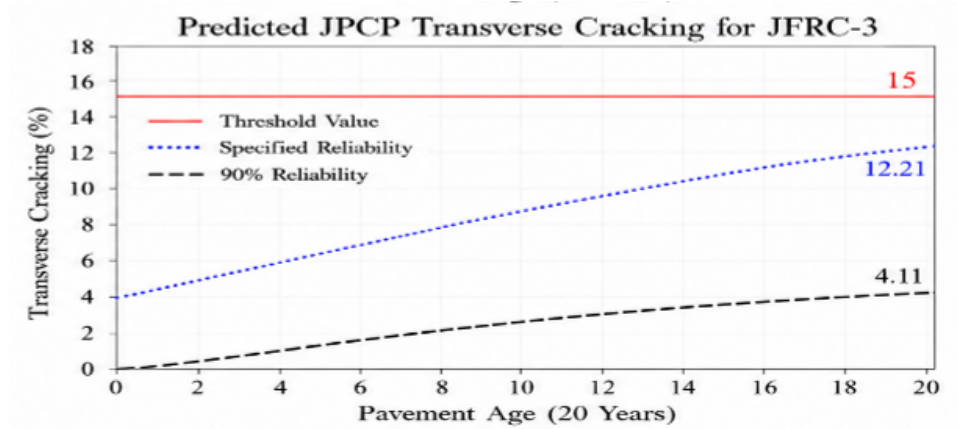
(a)



(b)



(c)



(d)

FIGURE 4.7: Predicted transverse cracking for PCC and JFRC pavements over 20 years.

indicate that the 2% and 3% jute fiber mixtures provided lower predicted transverse cracking than PCC at substantially reduced slab thicknesses. JFRC-1 produced a cracking value comparable to PCC. Similar findings have been reported in previous mechanistic-empirical studies [16–19][32][62], which concluded that increased flexural strength reduces fatigue damage and delays transverse crack development. Therefore, the present results are in agreement with the published literature. The higher flexural strength measured experimentally contributed to the improved pavement response predicted for JFRC-2 and JFRC-3.

The laboratory-observed fiber-bridging mechanism provides a physical explanation for the improvement in flexural performance, while the MEPD analysis evaluates pavement response using the specified material, structural, traffic, and climatic inputs. Although both 2% and 3% fiber contents produced similar pavement performance, the 2% mixture is considered the optimum because it achieved comparable structural benefits while maintaining better concrete workability.

4.3.2 Joint Faulting Analysis

Joint faulting is one of the principal performance indicators used to evaluate the long-term serviceability of Jointed Plain Concrete Pavements (JPCP). It is defined as the difference in elevation between adjacent concrete slabs at a transverse

joint caused by repeated traffic loading, pumping of fine materials, erosion of supporting layers, and differential slab deflection. Excessive joint faulting reduces ride quality, increases vehicle dynamic loading, and accelerates pavement deterioration. Therefore, maintaining faulting within acceptable limits is essential for ensuring satisfactory pavement performance throughout the design life. In AASHTOWare Pavement ME Design (MEPD), joint faulting is predicted using empirical models that incorporate mechanistic pavement responses together with slab thickness, concrete stiffness, load transfer efficiency, traffic loading, climatic conditions, and foundation support. In this study, the allowable mean joint faulting was limited to 3 mm with a design reliability of 90%. The predicted joint faulting values for the four pavement sections are presented in Table 4.6. The simulation results show that all pavement sections satisfied the allowable joint faulting criterion throughout the 20-year design period. The predicted faulting values ranged from 1.14 mm to 1.67 mm, which are considerably lower than the allowable limit of 3 mm, indicating that all pavement structures provided adequate load transfer and structural support under the projected traffic and environmental conditions. The conventional PCC pavement exhibited the lowest predicted joint faulting (1.14 mm). However, this performance was achieved using a 380 mm slab, which provides greater flexural rigidity and reduces slab deflection under wheel loading. Since joint faulting is directly related to differential slab movement at transverse joints, the higher slab stiffness naturally limits vertical displacement and minimizes faulting.

TABLE 4.6: Predicted joint faulting for different pavement sections

Pavement Type	Slab Thickness (mm)	Distress @ Specified Reliability		Reliability (%)		Criterion Satisfied?
		Target	Predicted	Target	Achieved	
PCC	380	3	1.14	90	100	Pass
JFRC-1	360	3	1.67	90	99.91	Pass
JFRC-2	265	3	1.24	90	100	Pass
JFRC-3	265	3	1.23	90	100	Pass

The JFRC-1 pavement produced the highest predicted faulting (1.67 mm) despite

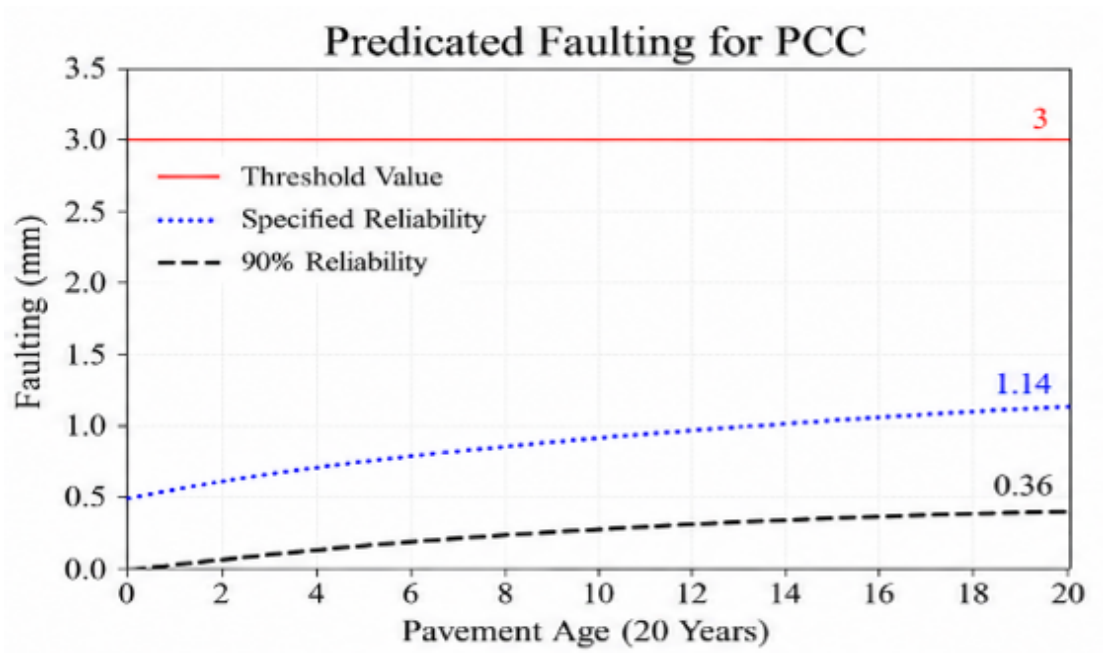
requiring a thinner 360 mm slab. This behavior is attributed to the combined effect of reduced slab thickness and lower slab stiffness. Although the addition of 1% jute fiber improved the flexural behavior of concrete, the improvement was not sufficient to completely offset the reduction in slab thickness, resulting in slightly higher joint deflections. In contrast, JFRC-2 and JFRC-3 demonstrated excellent structural performance. Both mixtures satisfied the joint faulting criterion with a slab thickness of only 265 mm, while the predicted faulting values (1.24 mm and 1.23 mm, respectively) remained close to that of the much thicker PCC pavement. This improvement can be attributed to the enhanced crack resistance and post-cracking behavior provided by jute fibers.

The predicted faulting values of JFRC-2 and JFRC-3 were close to that of PCC despite their substantially lower slab thicknesses. This performance reflects the combined influence of concrete material properties, slab thickness, traffic loading, foundation support, environmental conditions, and joint load-transfer characteristics included in the MEPD analysis. The predicted faulting values of JFRC-2 and JFRC-3 differed by only 0.01 mm, indicating that increasing the fiber content beyond 2% offers no meaningful improvement in joint faulting performance as shown in Figure 4.8. This finding agrees with the experimental results presented in Phase I, where the 3% fiber mixture exhibited lower workability with only marginal improvements in mechanical properties compared with the 2% mixture. Therefore, increasing the fiber content from 2% to 3% did not provide a meaningful additional pavement-performance benefit. From an engineering standpoint, these results demonstrate that slab thickness alone is not the primary indicator of pavement performance.

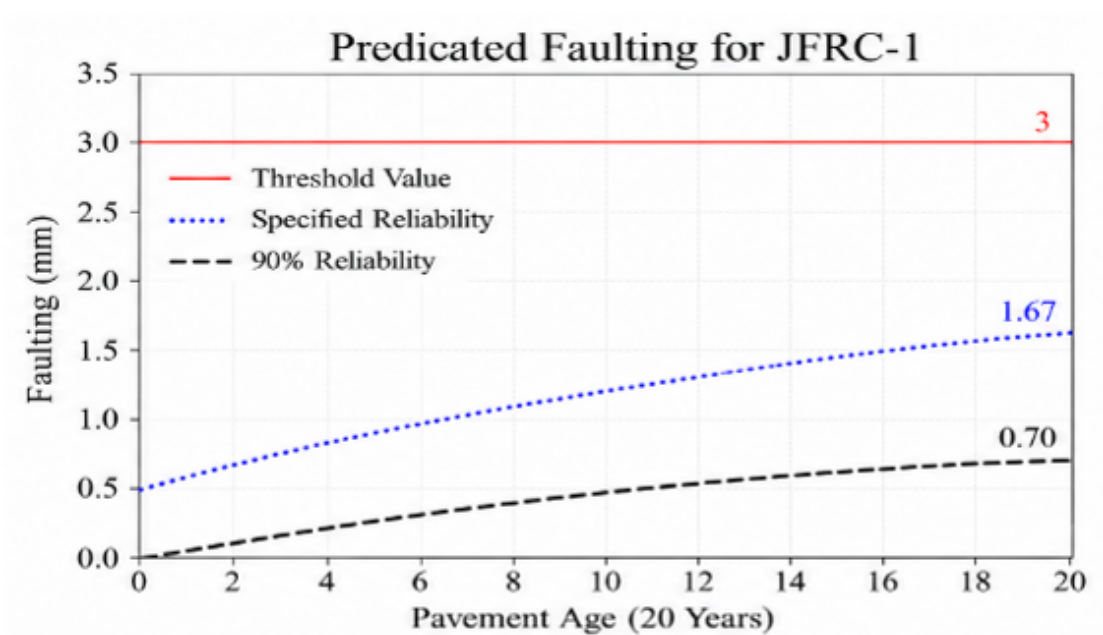
Although PCC produced the lowest absolute faulting value, it required a substantially thicker slab. Conversely, JFRC-2 achieved nearly the same level of performance with a 265 mm slab, representing a reduction of approximately 30% in slab thickness while maintaining satisfactory long-term serviceability. This reduction can significantly decrease concrete consumption, construction cost, and environmental impact without compromising pavement performance. Overall, the joint

faulting analysis confirms that jute fiber reinforcement improves the structural efficiency of rigid pavements.

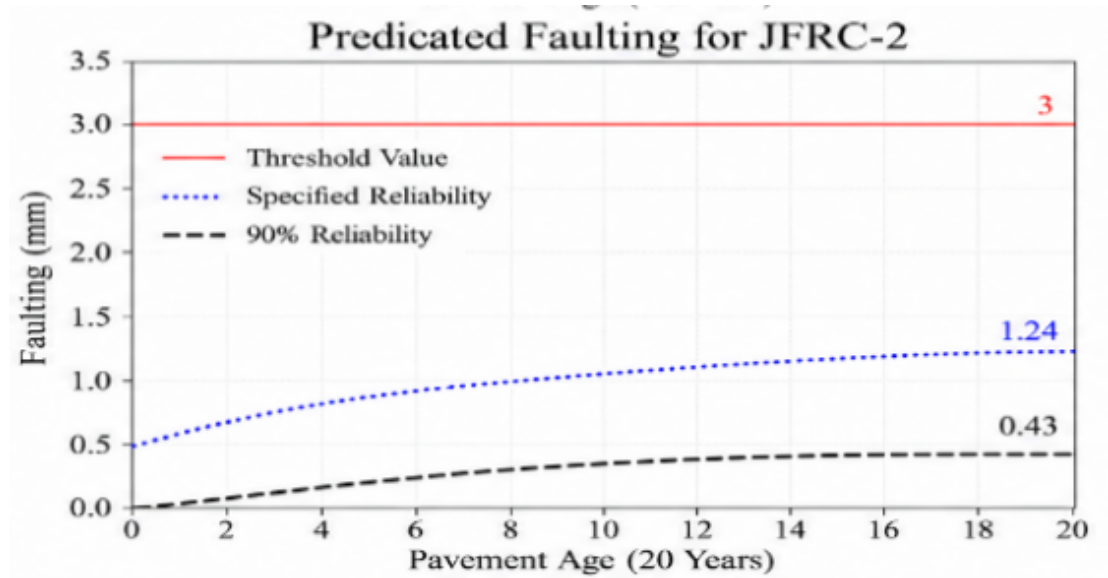
Among the mixtures investigated, JFRC containing 2% jute fiber provided the optimum balance between joint faulting resistance, slab thickness, material efficiency, and long-term performance, making it the most suitable pavement alternative under the traffic and climatic conditions considered in this study.



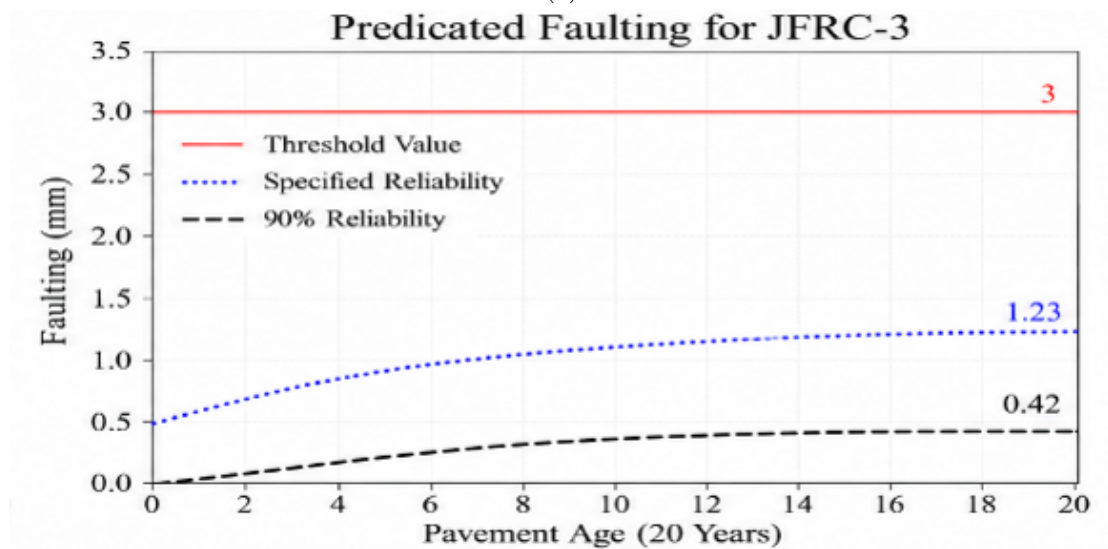
(a)



(b)



(c)



(d)

FIGURE 4.8: Predicted joint faulting for PCC and JFRC pavements over 20 years.

The predicted joint faulting values for all pavement sections remained well below the allowable design limit of 3 mm, with predicted values of 1.14 mm, 1.67 mm, 1.24 mm, and 1.23 mm for PCC, JFRC-1, JFRC-2, and JFRC-3, respectively. These results are consistent with previous mechanistic-empirical investigations [16–19][32, 62], which reported that improved slab performance and enhanced crack resistance contribute to lower joint faulting throughout the pavement service life. Accordingly, the findings of the present study agree with the existing

literature. The similar faulting values of JFRC-2 and JFRC-3, despite their substantially lower slab thickness, indicate satisfactory joint performance under the specified design conditions. Small differences among the pavement sections are expected because joint faulting is also affected by traffic loading, foundation support, environmental conditions, and joint load-transfer efficiency.

4.3.3 International Roughness Index Analysis

The International Roughness Index (IRI) is a key functional performance indicator used to assess pavement ride quality and overall serviceability throughout its design life. It reflects the cumulative effect of surface irregularities caused by traffic loading and the progression of structural distresses such as transverse cracking and joint faulting.

In AASHTOWare Pavement ME Design (MEPD), IRI is predicted using mechanistic - empirical models that account for pavement responses, traffic, and environmental conditions. In this study, the allowable IRI limit was 2.70 m/km at a 90% design reliability, and the predicted IRI values for all pavement sections are presented in Table 4.7.

The simulation results indicate that all pavement sections satisfied the acceptable ride quality criteria throughout the design period. The predicted IRI values remained within allowable limits for all cases, confirming that both conventional PCC and jute fiber reinforced concrete (JFRC) pavements provide adequate functional performance under the considered traffic and environmental conditions.

This behavior is primarily associated with its higher slab thickness requirement and reduced ability to control micro-crack development, which contributes to gradual surface roughness accumulation over time. This improvement is attributed to the presence of jute fibers, which enhance the tensile resistance of the concrete matrix and reduce the rate of crack propagation.

As a result, surface irregularities develop more slowly under repeated loading conditions. Despite having a significantly reduced slab thickness of 265 mm, both

mixtures maintained excellent ride quality over the design life as shown in Figure 4.9.

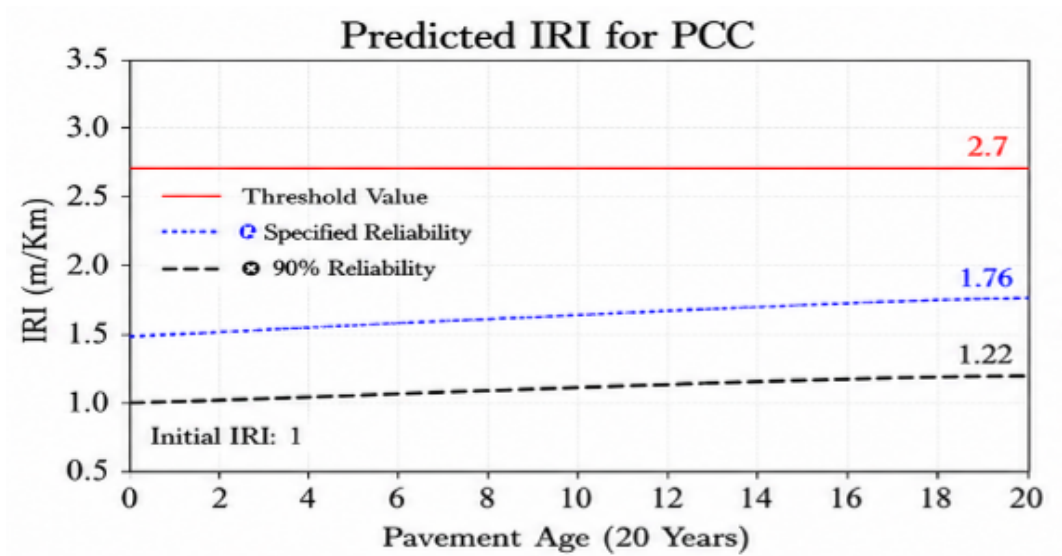
TABLE 4.7: Predicted International Roughness Index (IRI) for Different Pavement Sections

Pavement Type	Slab Thickness (mm)	Distress @ Specified Reliability		Reliability (%)		Criterion Satisfied?
		Target	Predicted	Target	Achieved	
PCC	380	2.7	1.76	90	99.97	Pass
JFRC-1	360	2.7	1.98	90	99.69	Pass
JFRC-2	265	2.7	1.79	90	99.96	Pass
JFRC-3	265	2.7	1.79	90	99.96	Pass

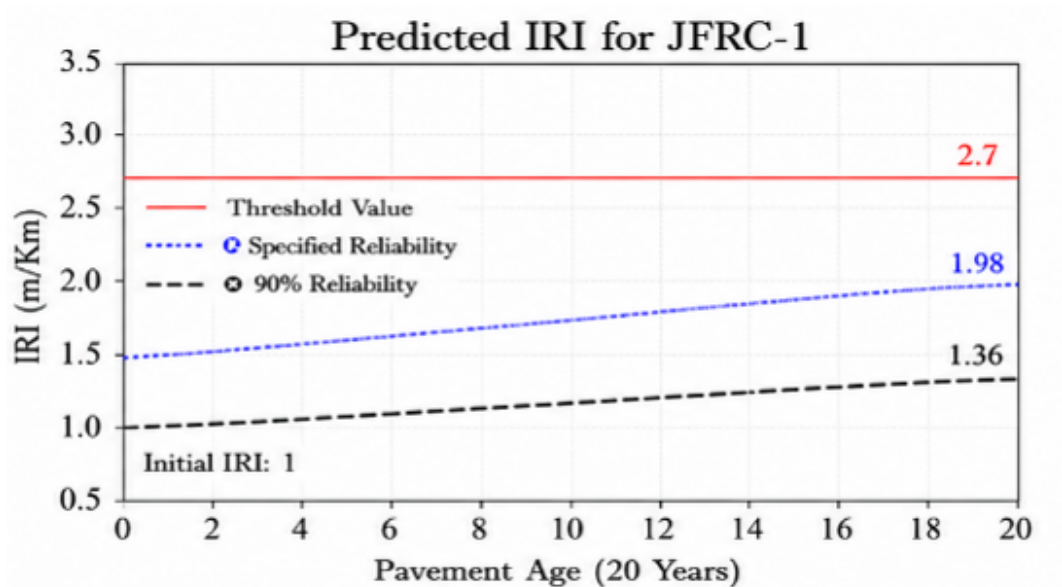
This indicates that fiber reinforcement effectively compensates for the reduction in structural thickness by improving post-cracking behavior and maintaining slab integrity under repeated traffic loading. The comparable performance of JFRC-2 and JFRC-3 further suggests that increasing jute fiber content beyond 2% does not result in any significant additional improvement in ride quality.

This observation is consistent with the mechanical behavior of fiber-reinforced concrete, where excessive fiber content may lead to reduced workability without proportionate gains in stiffness or crack control efficiency. From an engineering perspective, the results clearly demonstrate that IRI is not governed solely by slab thickness but is strongly influenced by the overall structural response and cracking behavior of the pavement system.

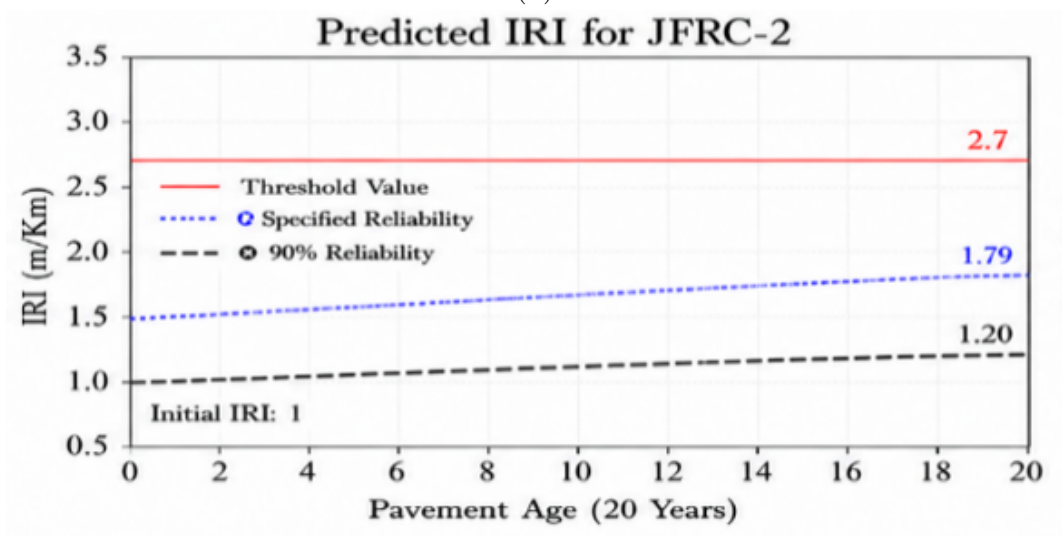
Although PCC provides adequate ride quality performance, it requires a substantially thicker slab compared to JFRC alternatives. In contrast, JFRC-2 achieves comparable or better ride quality performance with a significantly reduced slab thickness, indicating improved structural efficiency. The predicted International Roughness Index (IRI) values for all pavement sections remained below the terminal design criterion of 2.7 m/km, with values of 1.76 m/km, 1.98 m/km, 1.79 m/km, and 1.79 m/km for PCC, JFRC-1, JFRC-2, and JFRC-3, respectively.



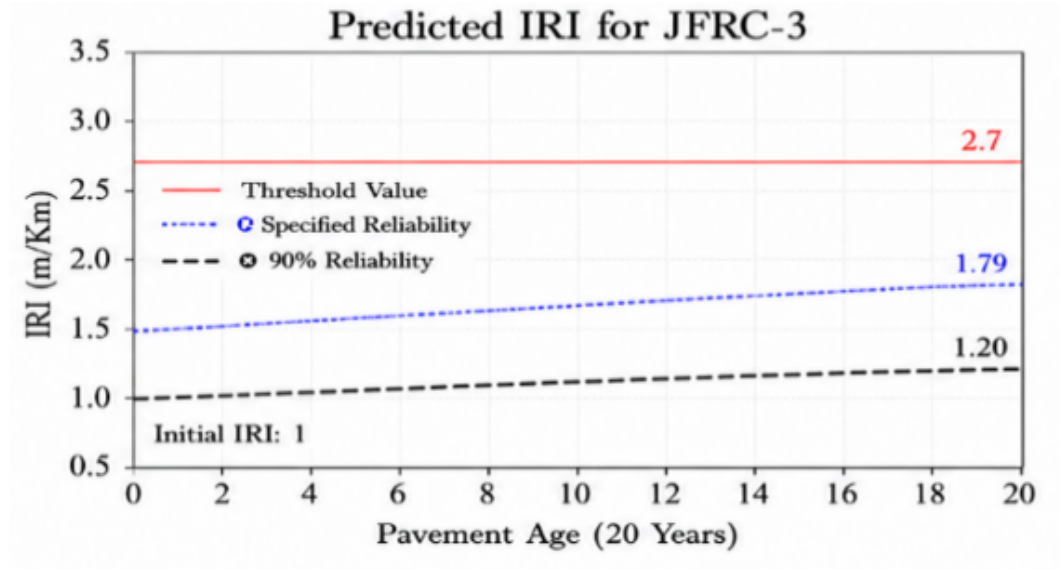
(a)



(b)



(c)



(d)

FIGURE 4.9: Predicted International Roughness Index (IRI) for PCC and JFRC pavements over 20 years.

These results are consistent with previous studies [16–19], which reported that pavements with lower cracking and joint faulting generally maintain better riding quality and surface smoothness throughout their design life. Therefore, the findings of this research are in agreement with the published literature. The satisfactory IRI values obtained for all JFRC mixtures indicate that the inclusion of jute fibers improved structural performance without compromising pavement serviceability.

The nearly identical IRI values for the 2% and 3% fiber mixtures further indicate that increasing the fiber dosage beyond the optimum level did not produce additional improvements in long-term pavement smoothness.

4.3.4 Comparison of Slab Thickness Using AASHTO and AASHTOWare Pavement ME Design

The design example reported by Khan and Ali [63], Wu et al. [64], and Huang [58] was used as a basis for independently checking the slab thickness obtained

for the present study using the AASHTO (1993) rigid pavement thickness design equation.

This approach provides an independent comparison of the thickness obtained from AASHTOWare Pavement ME Design with the conventional AASHTO (1993) design method. The modulus of rupture and modulus of elasticity are important concrete properties in rigid pavement thickness design because they influence the tensile stress capacity and structural response of the concrete slab.

In the present study, the experimentally determined modulus of rupture and elastic modulus of PCC, JFRC-1, JFRC-2, and JFRC-3 were used as the material properties for the thickness calculations. The calculated slab thicknesses were then compared with those obtained from AASHTOWare Pavement ME Design.

The calculated thickness for PCC was 325 mm, while JFRC-1, JFRC-2, and JFRC-3 required 313, 282, and 284 mm, respectively. Compared with PCC, this represents thickness reductions of 3.69%, 13.23%, and 12.62%, respectively. The maximum reduction was obtained with JFRC-2, which also recorded the highest modulus of rupture of 3.10 MPa as shown in table 4.8.

TABLE 4.8: Thickness design of concrete road for PCC and JFRC using AASHTO equation

Material	Modulus of Rupture ' S_c ' (MPa)	Compressive Strength ' f'_c ' (MPa)	Elastic modulus ' E_c ' (MPa)	Thickness 'D' (mm)
PCC	2.36	17.83	19840	325
JFRC-1	2.53	16.1	18850	313
JFRC-2	3.1	15.5	18490	282
JFRC-3	3.06	14.4	17820	284

Using $W18 = 5100,000$, $R = 90\%$, $Po = 4.2$, $Pt = 2.5$, $ZR = -1.28$, $So = 0.29$, $\Delta PSI = 1.7$, $J = 3.2$, $Cd = 1$, and $k = 72$ pci in above AASHTO equation.

$$\begin{aligned}
\log(W_{18}) = & Z_R \times S_0 + 7.35 \log(D + 1) \\
& - 0.06 \frac{\log\left(\frac{\Delta PSI}{4.2 - 1.5}\right)}{1 + \frac{624 \times 10}{(D + 1)^{8.46}}} \\
& + (4.22 - 0.32p_t) \log \left[\frac{S'_c \times C_d (D^{0.75} - 1.132)}{215.63 \times J \left[D^{0.75} - \frac{18.42}{\left(\frac{E_c}{k}\right)^{0.25}} \right]} \right] \quad (4.1)
\end{aligned}$$

The AASHTOWare MEPD analysis showed the same overall trend but a greater reduction in thickness. The required thickness decreased from 380 mm for PCC to 360 mm for JFRC-1 and 265 mm for both JFRC-2 and JFRC-3. These values represent reductions of 5.26% for JFRC-1 and 30.26% for JFRC-2 and JFRC-3 as shown in table 4.9.

The difference between the two methods is due to their design approaches. AASHTO (1993) uses an empirical thickness-design equation, whereas AASHTOWare MEPD evaluates pavement response and predicts transverse cracking, joint faulting, and IRI under traffic and climatic conditions. Both methods, however, confirmed the benefit of jute fiber reinforcement in reducing slab thickness.

TABLE 4.9: Thickness design of concrete road for PCC and JFRC using AASHTOWare Pavement ME Design Software

Material	Modulus of Rupture ' S_c ' (MPa)	Compressive Strength ' f'_c ' (MPa)	Elastic modulus ' E_c ' (MPa)	Thickness 'h' (mm)
PCC	2.36	17.83	19840	380
JFRC-1	2.53	16.1	18850	360
JFRC-2	3.1	15.5	18490	265
JFRC-3	3.06	14.4	17820	265

JPCP; 20-year design period; R=90%; Level-3 traffic inputs; Bahawalpur climate station; initial IRI = 1.0 m/km; terminal IRI = 2.70 m/km; allowable transverse cracking = 15%; allowable mean joint faulting = 3 mm; 150-mm non-stabilized crushed-stone base; base resilient modulus = 300 MPa; A-6 subgrade with resilient modulus = 100 MPa.

The results indicate that the higher flexural strength of the JFRC mixtures contributed to the reduction in required slab thickness.

Although compressive strength and elastic modulus decreased with fiber addition, the increase in modulus of rupture improved the flexural capacity of the pavement slab. JFRC-2 therefore provided the best overall result, reducing the MEPD slab thickness by 115 mm (30.26%) compared with PCC.

Increasing the fiber content from 2% to 3% produced no further reduction in MEPD thickness, confirming 2% jute fiber as the optimum content.

4.4 Parametric Analysis

4.4.1 Slab Thickness Reduction

The slab thickness obtained from the AASHTO (1993) equation and AASHTO-Ware MEPD analysis is compared in Table 4.10. The AASHTO (1993) equation resulted in required slab thicknesses of 325, 313, 282, and 284 mm for PCC, JFRC-1, JFRC-2, and JFRC-3, respectively.

Compared with PCC, the thickness reductions were 12 mm (3.7%) for JFRC-1, 43 mm (13.2%) for JFRC-2, and 41 mm (12.6%) for JFRC-3. The highest reduction using the AASHTO equation was therefore obtained with JFRC-2.

The AASHTOWare MEPD analysis showed a greater reduction in slab thickness. The required thickness decreased from 380 mm for PCC to 360 mm for JFRC-1, representing a 20 mm (5.3%) reduction, while both JFRC-2 and JFRC-3 required only 265 mm, representing a 115 mm (30.3%) reduction.

The larger reduction predicted by MEPD results from its mechanistic-empirical evaluation of pavement performance under the specified traffic, climate, material, and foundation conditions, rather than relying only on an empirical thickness relationship.

TABLE 4.10: Comparison of Slab Thickness Reduction Using AASHTO (1993) and AASHTOWare

Pavement Type	AASHTO Thick-ness (mm)	AASHTO Reduc-tion (mm)	AASHTO Reduc-tion (%)	MEPD Thick-ness (mm)	MEPD Reduc-tion (mm)	MEPD Reduc-tion (%)
PCC	325	0	0	380	0	0
JFRC-1 (1% JF)	313	12	3.7	360	20	5.3
JFRC-2 (2% JF)	282	43	13.2	265	115	30.3
JFRC-3 (3% JF)	284	41	12.6	265	115	30.3

Both design approaches showed the same overall trend: jute fiber reinforcement reduced the required slab thickness, with JFRC-2 providing the most favorable result. Although JFRC-3 also achieved a 30.3% reduction in MEPD, it provided no additional thickness benefit over JFRC-2. Therefore, considering the higher flexural strength of JFRC-2 (3.10 MPa) and its better workability compared with JFRC-3, 2% jute fiber was identified as the optimum reinforcement level.

4.4.2 Comparison with Previous Studies

The present results were also compared with the jute fiber-reinforced concrete study reported by Zia and Ali (2017) [65]. Their investigation used 50 mm jute fibers at 5% by mass of cement and evaluated the mechanical properties, water absorption, and linear shrinkage of jute fiber-reinforced concrete. Compared with plain concrete, their JFRC showed reductions of 36% in compressive strength and 19% in splitting-tensile strength, while the modulus of rupture increased by 8%. They also reported considerable improvements in compressive, splitting-tensile, and flexural energy absorption and toughness indices, indicating improved post-cracking and toughness characteristics. In comparison, the present study used a shorter fiber length of 25 mm and lower fiber contents of 1%, 2%, and 3% by mass

of wet concrete. The present results showed compressive-strength reductions of 9.7%, 13.1%, and 19.2%, while flexural strength increased by 7.2%, 31.4%, and 29.7% for JFRC-1, JFRC-2, and JFRC-3, respectively. The differences in the magnitude of strength changes may be attributed to the different fiber lengths, fiber contents, basis of fiber proportioning, mix proportions, and testing conditions used in the two studies. Overall, both studies indicate that the incorporation of jute fiber can improve the flexural performance of concrete, although increasing fiber content may reduce compressive strength. The present results further indicate that 2% jute fiber provided the most favorable balance between compressive and flexural performance for the pavement application considered in this study.

The pavement performance of the present JFRC was compared with the wheat straw reinforced concrete (WSRC) pavement investigated by Farooqi and Ali (2018) [66] as shown in table 4.11. Their study reported a 13.8% reduction in PCC slab thickness, from 290 mm to 250 mm, using 1% wheat straw fiber. In comparison, the present study achieved a substantially higher slab thickness reduction of 30.3%, from 380 mm to 265 mm, using 2% jute fiber.

TABLE 4.11: Comparison of Slab Thickness Reduction in Natural Fiber-Reinforced Concrete Pavements.

Study	Fiber	Optimum content	MOR (MPa)		Ec (MPa)		PCC thickness	Optimized thickness	Reduction
			PCC FRC		PCC FRC				
Farooqi & Ali (2018)	Wheat straw	1%	3.3	3.59	19445	18742	290 mm	250 mm	13.80%
Present study	Jute	2%	2.36	3.1	19840	18490	380 mm	265 mm	30.30%

Therefore, the JFRC pavement provided an additional 16.5 percentage-point reduction in slab thickness and approximately 2.2 times greater relative thickness reduction than the reported WSRC pavement. This indicates that jute fiber at the optimized 2% content has considerable potential for improving the structural efficiency of rigid pavement. However, the comparison should be interpreted with

caution because the two studies used different natural fibers, fiber contents, material properties, and pavement design inputs.

4.5 Pavement Service Life Analysis

Pavement service life represents the period during which a pavement satisfies the specified structural and functional performance criteria without requiring major rehabilitation. In AASHTOWare Pavement ME Design (MEPD), service life is evaluated based on the progression of key distress indicators, including International Roughness Index (IRI), joint faulting, and transverse cracking. In this study, the service life of PCC and JFRC pavements was evaluated over a 20-year design period to determine whether each pavement section satisfied the specified design criteria.

The simulation results show that all pavement sections successfully achieved the required 20-year design life, with predicted values of IRI, joint faulting, and transverse cracking remaining within the specified design limits. This confirms that all pavement alternatives can provide satisfactory long-term performance under the projected traffic and environmental conditions. The conventional PCC pavement achieved the required service life with a slab thickness of 380 mm, while JFRC-1 satisfied the same design requirements with a reduced thickness of 360 mm. The best performance was observed for JFRC-2 and JFRC-3, both of which maintained the required service life using a slab thickness of only 265 mm. This improvement is attributed to the enhanced flexural performance, crack resistance, and post-cracking behavior provided by jute fibers, which delayed fatigue damage and reduced the progression of pavement distresses as shown in Table 4.12. The similar performance of JFRC-2 and JFRC-3 indicates that increasing the fiber content beyond 2% offers little additional benefit in terms of pavement service life.

This finding agrees with the laboratory results presented in Phase I, where the 3% fiber mixture showed reduced workability with only marginal improvements

in mechanical properties compared with the 2% mixture. From an engineering perspective, the results demonstrate that jute fiber reinforcement significantly improves the structural efficiency of rigid pavements.

Although all pavement sections achieved the target service life, JFRC-2 provided the same 20-year performance with a 265 mm slab compared with 380 mm for conventional PCC, resulting in approximately 30% reduction in slab thickness. This reduction can lower concrete consumption, construction costs, and environmental impacts while maintaining satisfactory pavement performance.

TABLE 4.12: Pavement Service Life Performance of Different Pavement Sections

Pavement Type	Slab Thickness (mm)	Design Life (Years)	Performance Status	Service Life Requirement
PCC	380	20	Pass	Achieved
JFRC-1	360	20	Pass	Achieved
JFRC-2	265	20	Pass	Achieved
JFRC-3	265	20	Pass	Achieved

Overall, the pavement service life analysis confirms that JFRC containing 2% jute fiber provides the optimum balance between structural performance, service life, material efficiency, and constructability under the conditions considered in this study.

4.6 Comparative Analysis of PCC and JFRC Pavements

The comparison of PCC and JFRC pavements shows that all four alternatives satisfied the specified MEPD performance criteria over the 20-year design period. PCC required the greatest slab thickness of 380 mm, whereas JFRC-1, JFRC-2, and JFRC-3 required 360, 265, and 265 mm, respectively. JFRC-2 therefore

achieved a 115 mm (30.3%) reduction in slab thickness while maintaining acceptable transverse cracking, joint faulting, and IRI. Although JFRC-3 produced similar pavement-scale performance, its higher fiber content resulted in lower workability without providing an additional thickness reduction. Therefore, JFRC-2 was identified as the optimum mixture based on the combined experimental and MEPD results.

4.7 Summary

This chapter presented the results of the experimental investigation (Phase I) and the mechanistic-empirical pavement analysis (Phase II) to evaluate the suitability of jute fiber-reinforced concrete (JFRC) for rigid pavement applications.

In Phase I, the mechanical properties of PCC and JFRC mixtures containing 1%, 2%, and 3% jute fiber were evaluated. Increasing the fiber content reduced compressive strength and workability, while flexural strength increased. The highest modulus of rupture was obtained for JFRC-2 at 3.10 MPa, representing a 31.4% improvement over PCC. Although JFRC-3 also showed improved flexural strength, it provided no additional structural benefit compared with JFRC-2 and had considerably lower workability. Therefore, JFRC-2 provided the most suitable balance of mechanical performance and workability.

In Phase II, the pavement performance of PCC and JFRC sections was evaluated using AASHTOWare Pavement ME Design for a 20-year design period. All pavement alternatives satisfied the specified limits for transverse cracking, joint faulting, and IRI. The required MEPD slab thickness decreased from 380 mm for PCC to 360 mm for JFRC-1 and 265 mm for both JFRC-2 and JFRC-3.

Thus, JFRC-2 achieved a maximum thickness reduction of 115 mm (30.3%) compared with PCC. The independent AASHTO (1993) calculation showed the same trend, with JFRC-2 reducing the required thickness from 325 mm to 282 mm (13.2%). Overall, both design approaches showed a consistent reduction in the required slab thickness with jute fiber reinforcement. Among the investigated

mixtures, JFRC-2 was identified as the optimum mixture, providing the highest flexural strength and the greatest reduction in slab thickness while maintaining better workability than the 3% jute fiber mixture.

Chapter 5

Conclusion and Recommendations

5.1 Conclusion

This study evaluated the potential of jute fiber-reinforced concrete (JFRC) for rigid pavement applications through laboratory experimentation and mechanistic-empirical analysis using AASHTOWare Pavement ME Design. Laboratory tests were conducted to determine the engineering properties of conventional concrete and JFRC mixtures, while pavement simulations were performed to evaluate their long-term performance under traffic and environmental conditions. The combined findings demonstrated that incorporating jute fibers improves pavement performance and enables a reduction in slab thickness without compromising structural or functional performance.

- i. The incorporation of jute fiber improved the flexural performance of concrete but reduced compressive strength and elastic modulus. Compared with PCC, the modulus of rupture increased by 7.2%, 31.4%, and 29.7% for JFRC-1, JFRC-2, and JFRC-3, respectively, while compressive strength decreased by 9.7%, 13.1%, and 19.2%, and elastic modulus decreased by approximately 5.0%, 6.8%, and 10.2%, respectively. The highest modulus of

rupture was obtained with 2% jute fiber, reaching 3.10 MPa compared with 2.36 MPa for PCC.

- ii. Among the investigated mixtures, JFRC-2 (2% jute fiber) provided the most favorable overall balance of mechanical properties and workability. It achieved the highest modulus of rupture of 3.10 MPa, representing a 31.4% improvement over PCC, with a compressive strength of 15.50 MPa and elastic modulus of 18.49 GPa. Increasing the fiber content to 3% did not provide additional flexural improvement, as the modulus of rupture slightly decreased to 3.06 MPa, while the slump decreased substantially to 18.2 mm.
- iii. The AASHTOWare Pavement ME Design analysis demonstrated that jute fiber reinforcement reduced the required slab thickness while satisfying the specified pavement performance criteria. The required thickness decreased from 380 mm for PCC to 360 mm for JFRC-1 and 265 mm for both JFRC-2 and JFRC-3, corresponding to reductions of 5.3%, 30.3%, and 30.3%, respectively. The independent AASHTO (1993) thickness calculation showed the same overall trend, with thicknesses of 325, 313, 282, and 284 mm for PCC, JFRC-1, JFRC-2, and JFRC-3, respectively.
- iv. At the selected slab thicknesses, the predicted transverse cracking was 14.32%, 14.38%, 12.32%, and 12.21%; joint faulting was 1.14, 1.67, 1.24, and 1.23 mm; and IRI was 1.76, 1.98, 1.79, and 1.79 m/km for PCC, JFRC-1, JFRC-2, and JFRC-3, respectively. All alternatives remained within the adopted design limits of 15% transverse cracking, 3 mm joint faulting, and 2.7 m/km terminal IRI over the 20-year design period. JFRC-2 and JFRC-3 achieved comparable pavement performance despite requiring a substantially thinner slab.
- v. The combined experimental and mechanistic-empirical results identified JFRC - 2 as the optimum mixture. Compared with PCC, JFRC-2 increased the modulus of rupture by 31.4% and reduced the required MEPD slab thickness by 115 mm (30.3%), while maintaining acceptable transverse cracking, joint faulting, and IRI over the 20-year design period. For a 1 km $\times$ 3.65 m

pavement section, the reduced slab thickness decreased the concrete volume from 1,387 m³ to 967.25 m³, saving approximately 419.75 m³ of concrete and an estimated PKR 4.68 million/km in material cost.

Overall, the findings of this research demonstrate that the use of jute fiber can improve the flexural performance of rigid pavement concrete when incorporated at an appropriate content. The experimental and mechanistic-empirical analyses consistently identified 2% jute fiber as the optimum content, providing the highest modulus of rupture and the greatest reduction in required MEPD slab thickness while maintaining acceptable pavement performance over the 20-year design period. However, the practical implementation of JFRC in actual pavement construction requires further field-based validation under real traffic, environmental, and construction conditions. Therefore, the findings of this study provide a basis for future practical evaluation rather than direct field validation of JFRC pavement performance.

5.2 Future Work

Although the objectives of this study were achieved, further research is required to establish the practical implementation and long-term field performance of jute fiber reinforced concrete in rigid pavements. Future studies should focus on field validation, durability, construction practices, and optimization of material and pavement design parameters under different environmental and traffic conditions.

- i. Field trials should be conducted using the optimized 2% jute fiber content to evaluate its practical application in rigid pavement construction. The field performance should be monitored under actual traffic loading, climatic variations, construction conditions, and seasonal effects. This would help verify whether the pavement performance predicted by AASHTOWare Pavement ME Design can be achieved under real field conditions.

- ii. Future investigations should evaluate the long-term durability of JFRC under moisture, temperature variation, drying and wetting cycles, and other environmental conditions. Long-term monitoring of cracking, joint faulting, roughness, and structural performance should also be considered to establish the actual service performance of JFRC pavements.
- iii. Further research should investigate different jute fiber lengths, aspect ratios, surface treatments, orientations, and fiber contents to determine their effects on mechanical and pavement performance. The use of jute fiber in combination with supplementary cementitious materials such as fly ash, silica fume, or ground-granulated blast-furnace slag may also be investigated to improve durability and material efficiency.
- iv. The mechanistic-empirical pavement design analysis should be further evaluated using local pavement performance data and, where sufficient field data become available, calibrated for JFRC pavement applications. Future studies should also investigate different traffic levels, climatic conditions, foundation properties, and pavement configurations to determine the applicability of the proposed JFRC pavement design under a wider range of conditions.

The completion of these future research activities would provide the field evidence required to support the practical implementation of JFRC in rigid pavement construction. In particular, field trials and long-term monitoring would help establish whether the laboratory-measured material properties and MEPD-predicted pavement performance can be reproduced under actual construction and service conditions. This would provide a stronger basis for the future adoption of jute fiber reinforced concrete as a potentially sustainable and cost-effective pavement material.

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