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Surface Texture Performance Evaluation of Fiber Reinforced Ultra High-Performance Concrete Pavement Overlay

by

Saad Ahmed

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I want to dedicate this achievement my parents, teachers and friends who always encourage and support me in every crucial time

CERTIFICATE OF APPROVAL

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by
Saad Ahmed
Registration No: (MCE213028)

THESIS EXAMINING COMMITTEE

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

Dr. M. Usman Farooqi
Thesis Supervisor
May, 2025

Dr. Majid Ali
Head
Dept. of Civil Engineering
May, 2025

Dr. Imtiaz Ahmad Taj
Dean
Faculty of Engineering
May, 2025

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Abstract

The global transportation infrastructure heavily relies on concrete as its primary building material, particularly for rigid pavements designed to withstand substantial loads and ensure network stability. However, conventional concrete inherently possesses several limitations, including high brittleness, low tensile strength, inadequate crack resistance, and limited strain capacity, which collectively contribute to frequent maintenance demands. The concept of fiber reinforcement in concrete, systematically explored since the early 1960s with pioneers like Batson, has proven effective in mitigating these shortcomings by enhancing toughness. Concurrently, the mid-1990s saw the development of Ultra-High Performance Concrete (UHPC) in response to the escalating demand for materials with exceptional strength and durability, characterized by its very compact microstructure and superior mechanical properties. The strategic inclusion of polypropylene (PP) and polyethylene (PE) fibers in UHPC for rigid pavements directly aims to further address critical challenges such as crack formation and propagation, tensile strength deficiencies, and overall durability, leveraging the fibers' high tensile strength, impact resistance, and ability to distribute stresses within the concrete matrix.

This study addresses these specific challenges by thoroughly investigating the effects of PP and PE fibers on UHPC for rigid pavement applications. The central research problem revolves around enhancing the performance and extending the service life of concrete pavements through advanced material design. To this end, the specific objectives were to comprehensively evaluate the impact of varying PP and PE fiber dosages (1%, 2%, and 3% by volume) on the fresh properties (flowability) and hardened properties of UHPC. This included a detailed examination of mechanical properties such as compressive strength, flexural strength, and toughness, alongside serviceability checks focusing on skid resistance and shrinkage, all conducted in accordance with international ASTM standards.

The experimental program yielded significant and varied results regarding fiber inclusion. Notably, PP fibers at 1% by volume proved to be the most effective, producing the highest measured compressive strength of 376.8 kN (compared to 220.6 kN for plain UHPC) and the highest flexural strength of 4.2 kN (compared to

3.6 kN for plain UHPC). This specific mix also exhibited superior skid resistance with a value of 58 BPN (compared to 63 BPN in plain UHPC) and a significant reduction in shrinkage to 0.189% (from 0.208% in plain UHPC). In contrast, PE fibers generally resulted in lower compressive and flexural strengths compared to plain UHPC, with a 28% reduction in compressive strength and a 25% reduction in flexural strength at 2% PE fiber content, respectively. While both fiber types reduced workability and PE fibers showed varied or negative impacts on skid resistance, they did contribute to shrinkage reduction, albeit less consistently than PP fibers. Based on these comprehensive findings, UHPC with 1% PP fibers is highly recommended for rigid pavement applications, offering an optimal balance of enhanced mechanical properties, improved crack resistance, superior serviceability, and reduced shrinkage for creating high-performance, long-lasting, and sustainable infrastructure solutions.

Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1 Theoretical Background

Concrete, one of the most widely used building materials in the world today, is made by mixing the right amounts of cement, water, and stone (sand). The simplest and least expensive materials are used to create this composite material, and concrete's strength, flexibility, and durability have led to its widespread application [13]. One of the main disadvantages of concrete is its tensile performance; on the other hand, reinforcement rods should be used to increase tensile strength; however, with the advancement of technology, fibers are now used to increase the tensile performance of concrete. Concrete is a common building material that is naturally weak and has a limited tensile strength. With polyethylene and polypropylene fibers emerging as promising reinforcements, fiber integration has grown in popularity as a means of addressing these issues [4]. By utilizing its remarkable material qualities to improve performance and longevity, Ultrahigh Performance Concrete (UHPC) in rigid pavement provides a revolutionary solution for contemporary infrastructure. Because steel fiber reinforcing greatly lowers the chance of cracking and deformation, UHPC has excellent tensile strength, ductility, and compressive strengths surpassing 150 MPa. In comparison to conventional concrete, its tight microstructure and low permeability offer strong resistance against environmental deterioration, including chemical attacks, chloride penetration, and freeze-thaw cycles, guaranteeing a significantly longer service life [5]. Despite larger initial investments, this resilience results in longer maintenance intervals and cheaper lifecycle costs. Furthermore, UHPC's better load-bearing capability enables thinner pavement designs, which lower overall structural weight and material consumption. This can be especially advantageous in high-traffic areas, bridges, and airport runways where durability and weight reduction are crucial. Precasting UHPC panels also speeds up construction and repair projects while reducing interruptions and downtime [6]. The use of rigid pavement over flexible pavement, is primarily justified by the inherent structural advantages that promote superior load-bearing capacity and long-term durability compared to flexible alternatives. Rigid pavements, due to their high flexural stiffness, distribute concentrated traffic loads over a wider area, thereby reducing stress on the subgrade and minimizing fatigue damage. This characteristic, combined with their significant resistance to common distresses such as rutting and shoving, is crucial for maintaining consistent surface integrity and the designed surface texture performance over an extended service life, which is particularly vital for high-performance applications [7].

Although UHPC necessitates specific expertise, careful quality control, and accurate mix design, its advantages for the environment due to lower resource consumption and less frequent maintenance, along with its financial benefits over the pavement's lifespan, make it a more alluring choice for resilient and sustainable infrastructure development. Case Studies and Field Applications include the Case studies and real-world applications offer important insights into how well Polypropylene fibers [PP] and Polyethylene fiber [PE] reinforced UHPC performs in stiff pavements. Fiber reinforced UHPC has been successfully applied in bridge decks and highway pavements, as evidenced by field studies like those published by Nguyen et al. (2020), which highlight improvements in load bearing capacity and service life [7]. Additionally, it shows that the performance of UHPC on rigid pavements can be significantly enhanced by polypropylene and polyethylene fibers. Among the main advantages are improved mechanical properties, crack prevention, and overall structural performance. To maximize their utilization, however, issues with practicality and environmental effects need to be resolved. The basic properties of polypropylene and polyethylene fibers, such as their tensile strength, modulus of elasticity, aspect ratio, surface features, and chemical composition, are essentially included in the material of fibers. Comprehending these characteristics is crucial for assessing their suitability for UHPC and forecasting how they would affect the performance of concrete.

These fibers' characteristics include their length, diameter, tensile strength, mass density, and elasticity modulus. PE fibers range in diameter from 0.1 to 0.15 mm, which is less than that of PP fibers. The fiber length for both types falls between 30 and 50 mm [8]. Fibers made of PP and PE have a bulk density of 0.91 grams per cubic centimeter. The elastic modulus of polypropylene fibers is between 300 and 400 MPa, while that of polyethylene fibers is between 550 and 650 MPa. In contrast, the tensile strength of polypropylene fibers is between 300 and 400 MPa, whereas that of polyethylene fibers is between 500 and 600 MPa [9].

1.2 Research Motivation and Problem Statement

Rigid pavements are essential to modern transportation networks because they provide vital stability for heavy traffic loads. However, because concrete pavements are prone to cracking, cracking and other forms of deterioration over time, they need to be maintained and repaired on a regular basis. This study intends to offer important insights into improving pavement performance, reducing maintenance requirements, as well as extending the service life of infrastructure by examining the effects of PP and PE fibers on UHPC properties specifically for rigid pavement applications.

"The performance of rigid pavements is compromised by the brittle nature of UHPC and the corrosion susceptibility of steel fibers, which enhance toughness. Any nation's economy depends heavily on its road networks, which necessitate high-performance, low-maintenance paving systems. Pavement overlays are essential for improving surface quality and prolonging pavement life, but it can still be difficult to guarantee sufficient resistance to cracking and skids. The investigation of PP and PE fibers in UHPC is motivated by the demand for sustainable substitutes with improved qualities. These fibers present a viable option for UHPC pavement overlays by boosting mechanical qualities, enhancing surface texture, and removing cracking hazards. In order to create a pavement that is more dependable and resistant to skids, this study examines their effects"

1.2.1 Research Questions

The research questions examined in this study are as follows:

1. How does the incorporation of fibers address the brittleness of UHPC?
2. How do PP and PE fibers effect the mechanical properties of UHPC?
3. How do PP and PE fibers influence the surface texture characteristics of UHPC used in pavement overlays?
4. How do PP and PE fibers affect the skid resistance performance of UHPC pavement overlays, and how is this performance related to changes in surface texture?
5. What is the influence of polypropylene (PP) and polyethylene (PE) fibers on the shrinkage behavior of ultra-high-performance concrete (UHPC).

1.3 Overall Goal of the Research Program and Specific Aim of this MS Thesis

The overall goal of this research program is to contribute to the body of knowledge on sustainable and high-performing concrete materials by providing data-driven insights for the design of UHPC mixes incorporating PP and PE fibers for various infrastructure uses, including rigid pavement overlays. Following are the specific objectives:

- To evaluate the impact of varying PP and PE fiber dosages (1%, 2%, and 3% by volume each) on the mechanical properties (e.g., compressive strength, flexural strength, toughness etc.) of UHPC for rigid pavement overlay applications.

- To assess the influence of PP and PE fiber incorporation on the workability and fresh properties of UHPC mixes, specifically considering the selected fiber dosages, for rigid pavement overlay applications.
- To determine the optimal PP and PE fiber dosages (individual and/or combined) that enhance UHPC pavement overlay performance, particularly in terms of surface texture and skid resistance, while maintaining practical workability.

1.4 Scope of Work

This research thoroughly investigates the impact of PP and PE fibers on UHPC for rigid pavement applications. The experimental program focuses on evaluating fresh properties through flowability checks for each of the seven distinct UHPC mixes. For mechanical properties, the study determines compressive strength from 21 cube specimens and flexural strength from 21 prism specimens. Additionally, toughness is calculated from the stress-strain behavior observed during the compressive testing of the cubes. The research also assesses skid resistance as a critical serviceability indicator for pavement quality and measures shrinkage to understand the volumetric stability of the UHPC mixes.

1.4.1 Study Limitations

While this study provides valuable insights, it's important to note its limitations. The laboratory testing conditions may not fully replicate the complex, long-term conditions that pavements encounter in the field, such as continuous traffic loading, diverse environmental exposure, or extreme temperature variations. Specifically, detailed durability testing beyond shrinkage, including freeze-thaw resistance or sulfate attack evaluations, is not within the scope of this research. Furthermore, this study does not include a cost analysis comparing flexible and rigid pavement options, nor does it evaluate the long-term performance through extensive field testing.

1.5 Rationale behind Variable Selection

The selection of UHPC is grounded in its compressive strength exceeding 150 MPa, providing a durable and thinner pavement overlay with superior resistance to traffic and environmental stressors [11]. PP and PE fibers are chosen to enhance UHPC's performance by bridging micro-cracks and preventing their propagation, thereby significantly improving the material's flexural strength, tensile ductility, and toughness [12-13]. These fibers transform UHPC's brittle nature into a more ductile behavior, crucial for pavement longevity. The chosen fiber dosages of 1%, 2%, and 3% allow for a systematic evaluation of their impact. This range is common in research and enables the investigation of how increasing fiber content incrementally influences both the fresh properties (like workability) and the hardened properties (such as crack control and strength), aiming to identify an optimal balance between performance enhancement and practical considerations like potential fiber balling at higher volumes [11]. Finally, skid resistance was selected as the pavement performance indicator because it directly reflects the friction between tires and the pavement surface, offering vital insights into safety and the presence of distresses on rigid pavements [14].

1.6 Novelty of Work, Research Significance and Practical Implementation

The innovative aspect of the experiment is the use of varying dosages of polyethylene (PE) and polypropylene (PP) fibers (1%, 2% and 3%) to UHPC for rigid pavement application prospective, in order to examine the impact of the fibers on UHPC. The specimens had been subsequently underwent mechanical testing, which includes tests for compressive strength, flexural strength, and surface texture performance evaluation testing such as shrinkage and skid resistance.

1.7 Brief Methodology

In an effort to assess the long-term performance of UHPC, a rigid pavement, different dosages of polyethylene and polypropylene fibers will be systematically added to the concrete. The specimens cubes (50x50x50mm) and prisms (40x40x160mm) will then undergo extensive mechanical testing in terms of compression and flexure tests, some tests for serviceability check is included in this research, like Skid resistance & Shrinkage. Material is mixed in small automatic mixer with specified dosages 1%, 2% and 3% of each PP & PE fibers by volume of concrete and then shaped in required standard sizes for testing. In mechanical testing, compression test on cubes are performed. Skid resistance and shrinkage is performed on the paste of 4 in x 6in pasted on 1ft x2ft slab of concrete. All the tests are performed on American standards of testing materials (ASTM) standards. UHPC with 1% polypropylene (PP) fibers is shows highest compression and flexural strength with more skid resistance and less shrinkage as compared to plain UHPC.

1.8 Thesis Outline

Chapter 1: The introduction is in Chapter 1. The backdrop of the thesis research, the purpose for the research, the problem statement, the general goal of the research program, the particular goal of the MS thesis, the scope of work, study limitations, the research technique, and the thesis outline are all explained in this chapter.

Chapter 2: The literature on the issues with rigid pavements, the manner in which to address these defects and how they affect pavement performance, the characteristics of fiber-containing sustainable concrete, and the characteristics of ultra-high performance concrete are reviewed in Chapter 2.

Chapter 3: The testing methodology for the samples is covered in Chapter 3. It discusses the history and the raw resources. The method for evaluating UHPC and polyethylene and polypropylene fibers, the specimen details, and the mixing and casting process. The chapter's conclusion includes a synopsis of chapter 3.

Chapter 4: The findings of the tests are presented in Chapter 4. Additionally, this chapter has discussed the analysis of the test results. It includes background information on the tests, the parameters of the various mixes, including reference concrete, concrete with polypropylene and polyethylene fibers, and the mechanical qualities of the fibers, including shrinkage and skid resistance. A succinct synopsis has been supplied at the end of the chapter.

Chapter 5: Discussions of pavement performance are covered in Chapter 5. Also mentioned is the connection between polypropylene and polyethylene fibers and the functionality of pavements covered with UHPC. A summary of the entire conversation of this research is provided at the end of this chapter.

Chapter 2

Literature Review

2.1 Background

Rigid pavement made of Ultra-High Performance Concrete (UHPC) uses its remarkable material qualities to improve performance and endurance, providing a revolutionary solution for modern infrastructure. Because steel fiber reinforcing greatly lowers the chance of cracking and deformation, UHPC has excellent tensile strength, ductility, and compressive strengths surpassing 150 MPa [1-6]. In comparison to conventional concrete, its tight microstructure and low permeability offer strong resistance against environmental deterioration, including chemical attacks, chloride penetration, and freeze-thaw cycles, guaranteeing a significantly longer service life [8, 11]. Despite larger initial investments, this resilience results in longer maintenance intervals and cheaper lifecycle costs. Furthermore, UHPC's better load-bearing capability enables thinner pavement designs, which lower overall structural weight and material consumption. This can be especially advantageous in high-traffic areas, bridges, and airport runways where durability and weight reduction are crucial. Precasting UHPC panels also speeds up construction and repair projects while reducing interruptions and downtime. Although UHPC necessitates specific expertise, careful quality control, and accurate mix design, its advantages for the environment due to lower resource consumption and less frequent maintenance, along with its financial advantages over the pavement's lifespan, make it a more alluring choice for resilient and sustainable infrastructure development [9].

The cementitious composite material known as ultra-high performance concrete (UHPC) is made up of a high percentage of discontinuous internal fiber reinforcement, an optimum gradation of granular elements, and a water-to-cementitious materials ratio of less than 0.25. Conventional concrete lacks discontinuous internal fiber reinforcement and typically has a water-to-cementitious materials ratio of 0.4 to 0.6. Compressive strength exceeding 150 mega Pascals (MPa) and sustained post-cracking tensile strength exceeding 0.72 ksi or 5 MPa are among UHPC's mechanical characteristics. The compressive strength of conventional concrete is often less than 8 ksi [10]. Compared to ordinary and high performance concrete, UHPC's interrupted pore structure greatly improves durability by lowering the quantity of liquid that enters the concrete. Research on UHPC for se has been done for a number of purposes. Precast concrete piles, thin-bonded overlays on degraded bridge decks, seismic rehabilitation of subpar bridge substructures, and security and blast mitigation applications are some examples of these uses. When traditional concrete is insufficient, UHPC has generally shown itself to be a workable solution [10].

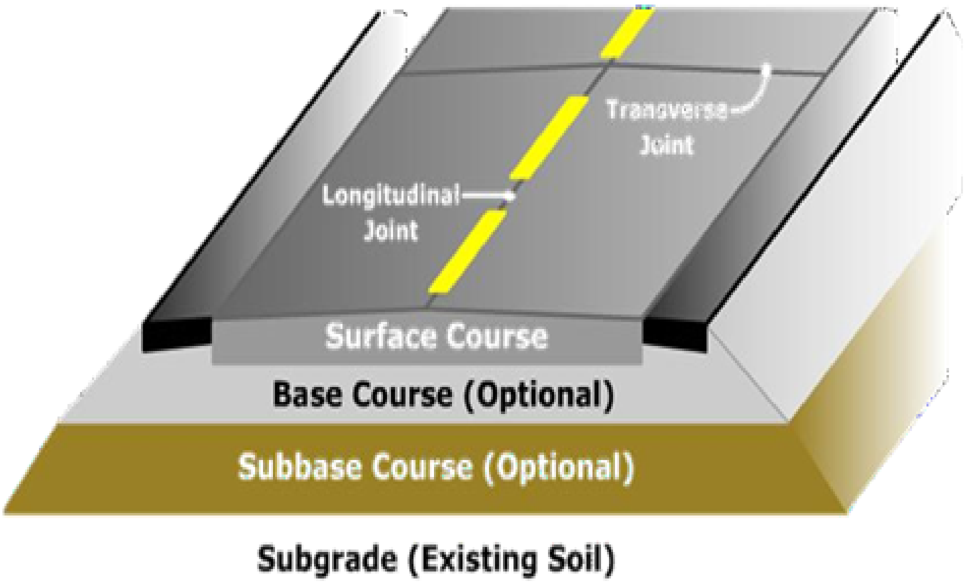


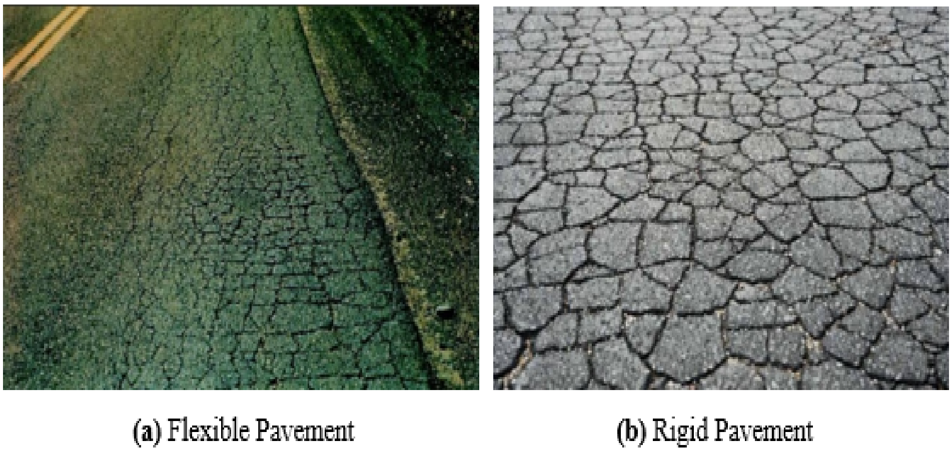
Figure 2.1: Cross-Sectional View of Typical Rigid Pavements [11].

For instance, the usage of prefabricated elements has been hampered by connections with traditional concrete; however, field-cast UHPC enables the redesign and simplification of prefabricated element connections while also enhancing durability and construction speeds. Compared to producing the same volume of ordinary concrete, the cost of producing UHPC is significantly higher. Applications have therefore concentrated on lowering the thickness of concrete members, altering the forms of concrete structures, or creating methods to solve issues with current non-concrete structural materials. Compared to structures constructed with traditional concrete, UHPC constructions are anticipated to last longer and require less maintenance [10].

2.2 Repeated Distress in Rigid Pavements

2.2.1 Fatigue Cracking

The main structural distress that happens on asphalt pavements with granular and weakly stabilized bases is fatigue cracking, also known as alligator cracking, which is brought on by fatigue damage. Initially manifesting as parallel longitudinal fractures in the wheel tracks, alligator cracking develops into a network of interconnected cracks that resemble chicken wire or an alligator's skin [11]. As seen in figure 2.2, alligator cracking may spread to localized failures and potholes, especially where the support is the weakest. Alligator cracking is influenced by a number of factors, including the quantity and size of applied loads, the pavement's structural design (layer materials and thicknesses), the quality and consistency of foundation support, the asphalt cement's consistency, the asphalt content, the aggregate characteristics and air voids of the asphalt concrete mix, and the site's climate (i.e., the seasonal range and distribution of temperatures). It is generally advised that low-stiffness (low viscosity) asphalt cements be used for thin asphalt concrete layers (less than 125 mm), and that constant-strain testing be used to assess the fatigue life of such mixes. On the other hand, high-stiffness (high viscosity) asphalt cements should be used for asphalt concrete layers that are 125 mm or thicker, and that constant-stress testing be used to assess the fatigue life of such mixes [11]. Modifying the mixture's stiffness for varying asphalt concrete layer thicknesses is uncommon in reality, though.



(a) Flexible Pavement (b) Rigid Pavement

FIGURE 2.2: Fatigue Cracking in Pavements [11].

2.2.2 Corner Breakage

One of the main structural distresses in jointed concrete pavements is corner breaking. A corner break occurs when a diagonal crack crosses a longitudinal joint or transverse joint less than six feet from the slab's corner. In contrast to a corner spall, which runs diagonally downward through only a portion of the slab thickness, a corner break is a vertical crack that penetrates the entire thickness of the slab corner breaks [12]. Fatigue damage is what causes corner breaks: repetitive strong wheel loads at slab corners lead to corner deflections and stresses in the slab's top surface, which eventually produce fatigue damage and cracking. Corner breaks are caused by a variety of factors, such as the frequency and magnitude of applied loads, the concrete slab's thickness and stiffness, the base's uniformity and stiffness, the degree of load transfer at longitudinal and transverse joints and cracks, the drainage system's quality, and climatic factors (daily and seasonal temperature and moisture cycles that affect slab curling, joint and crack opening, and foundation support). The application of significant wheel loads to unsupported corners causes high slab stresses and fatigue damage, which ultimately leads to corner breakdowns, as illustrated in figure 2.3. Either the approach side or the left side of the transverse joint may experience corner breaks in this scenario [13]. Curling-related corner breaks in jointed concrete pavements with perpendicular joints are more likely to occur along the slab's outer edge; however, in pavements with skewed joints, as illustrated in figure 2.3, corner breaks may occur at the acute-angled corners along the slab's inner and outer edges [13].

Figure 2.3: Corner Break on a Residential Street [13].

2.2.3 Spalling and Scaling

Concrete slab edges that crack, chip, or tear within roughly two feet of transverse joints are referred to as joint spalling or joint deterioration, as illustrated in figure 2.4. Depending on the climatic conditions at the time of construction, joint spalling may occur mostly in the top few centimeters of the slab or deeper below the surface [11].

Figure 2.4: Spalling from a Bad Construction Joint [11].

Extremely early wet sawing of transverse joints, infiltration of incompressible (particularly where delamination has occurred due to inadequate curing), high reinforcing steel, alkali-aggregate reaction, "D" cracking, misaligned or corroded load transfer devices, weak concrete near the joint (e.g., honeycombing caused by poor consolidation), or damage from cold milling, grinding, or joint cleaning are some of the potential causes of joint spalling. Scaling can degrade the pavement's life span and riding quality by causing loose bits of the concrete surface. Additionally, scaling might happen if the reinforcing steel is too near the surface. This kind of scaling, which doesn't include crazing, is typically identified by reddish brown discoloration or exposed reinforcing steel [16].

2.2.4 Blow-Ups

A blowup, which frequently happens in both traffic lanes at once, is the fracturing or upward buckling of concrete pavement slabs at a joint or working fracture. Blowups happen when the slab's horizontal compressive forces increase significantly as a result of the slabs' expansion, and the joints either entirely close or the infiltration of incompressible material hinders the closure of the joints and fractures, as seen in figure 2.5. between mid-morning and mid-day (when the warmth of the pavement rises). For a few feet on each side of the joint or crack, the concrete will crumble due to a shattering blowup. The pavement on one or both sides of the joint or fracture will rise by several centimeters as a result of a buckling blowup. Both types of explosions are dangerous and need to be fixed right away. One of the main factors influencing blowup potential is joint and fracture spacing [11].

Since the joints and cracks in JRCP and CRCP are spaced widely enough apart to allow for significant incompressible infiltration during cool times, they are vulnerable to blow-ups. In JPCP, blowups are uncommon. When full-depth repairs are being made in a nearby lane during hot weather and the repair area is left open during the day or is filled with asphalt concrete instead of Portland cement concrete, blowups may also happen in one lane of a concrete pavement [12]. Therefore, even if only one lane actually needs repair, full-depth repairs are frequently built across all lanes in such circumstances. When necessary, pressure relief joints should always be positioned across all traffic lanes rather than just one for the same reason. Concrete pavements that expand as a result of reactive aggregates are also particularly vulnerable to explosions. It is also thought that

Figure 2.5: Severe Blowup [12].

erodible foundation materials and poor joint sealant conditions increase the risk of blowup.

2.2.5 Joint Deterioration

There have been reports of early concrete corrosion at the joints in parking lots and concrete pavements throughout the northern states. When water is trapped by microcracks close to the joints, the distress initially manifests as shadowing. Later, it manifests as a substantial loss of material. Although not all roads are in difficulty, the issue is widespread enough to make some local governments reevaluate using concrete for their pavements, as figure 2.6 illustrates. Many possible reasons have been proposed, and it is probable that variations in construction techniques and design elements are causing the reported suffering to vary. The information presented in this article details investigations into some of the most plausible mechanisms. Other projects being carried out at the same institutions under different funding sources overlap with this work [11]. Traffic can cause degradation to rigid pavement construction in a number of ways, including increasing load (vehicle axis) that surpasses the design load and load repetitions (vehicle volumes) that surpass the plan volume, preventing the road plan from reaching its age [15]. Additionally, it is anticipated that a poor road drainage system will allow water to enter the pavement structure through joints, cracks, and the sides of the road, dampening the soil foundation and weakening the pavement, which will cause the pavement to deteriorate quickly [14]. This deterioration may also be brought on by the type of materials used to construct the pavement or

Figure 2.6: Joints Deterioration [14].

by an inadequate material processing system. High temperatures and precipitation, unstable subgrade conditions, poor soil properties, rod straightness bending or improper dowel use, stressing from expansion and shrinkage, slab corner rupture, connection deterioration, and other conditions resulting in decreased quality because of the concrete pavement's strength [14].

2.3 Remedial Measures for Rigid Pavements

2.3.1 Conventional Techniques

Rigid pavements, primarily composed of Portland Cement Concrete (PCC), are crucial for modern infrastructure due to their high strength and durability. For rigid pavements, traditional corrective actions include joint repair, dowel bar retrofitting, diamond grinding, crack filling, crack sealing, partial-depth, full-depth, and hard concrete surface texturing [17]. By addressing typical problems including cracking, faulting, spalling, and rutting, these methods prolong the pavement's service life and guarantee its structural integrity [18]. Conventional repair methods, such as overlays and joint sealing, provide temporary solutions but fail to address the inherent material weaknesses that lead to recurring failures.

2.3.2 Fiber Reinforcement as a Solution

In recent years, fiber reinforcement has emerged as a promising technique to enhance the mechanical properties of rigid pavements and mitigate distress mechanisms effectively [10]. Fiber-reinforced concrete (FRC) consists of discrete fibers uniformly dispersed within the concrete matrix, improving its toughness, ductility, and crack resistance. Research has demonstrated that fiber reinforcement significantly enhances the tensile and flexural strength of concrete, thereby reducing its susceptibility to cracking and structural failure [10]. The incorporation of fibers in concrete helps to bridge micro-cracks and distribute stresses more efficiently, thereby delaying the onset and propagation of cracks. This property improves the long-term performance of rigid pavements, reducing maintenance costs and extending service life [11]. Steel fibers, glass fibers, polypropylene fibers, and synthetic macro fibers are among the several fiber types utilized in pavement repair. Steel fibers are appropriate for high-traffic locations because of their well-known capacity to enhance load transfer, flexural strength, and impact resistance [12]. Synthetic macro fibers, such as nylon and polyethylene, provide excellent crack control, corrosion resistance, and durability, which makes them a viable alternative to steel reinforcement in certain applications [13]. Polypropylene fibers are commonly used to reduce plastic shrinkage cracking in early-age concrete, improving its overall durability [14]. Glass fibers, although less frequently used, contribute to enhanced tensile strength and resistance to environmental degradation [15]. In some cases, hybrid fiber systems are utilized, combining multiple fiber types to optimize performance and achieve synergistic benefits [16].

The implementation of fiber reinforcement in rigid pavements can be achieved through various methods, including fiber-reinforced overlays, full-depth slab replacements, and crack repairs. Fiber-reinforced overlays provide an additional protective layer that enhances the structural performance and service life of existing pavements. Studies have shown that these overlays significantly improve fatigue resistance and reduce the occurrence of reflective cracking, thereby extending pavement service life [17]. Similarly, full-depth slab replacements incorporating fiber reinforcement ensure long-term stability by enhancing load distribution and mitigating crack development. Additionally, fiber-reinforced materials used in joint and crack repairs contribute to the reduction of further deterioration and improve pavement durability [18].

The effectiveness of fiber reinforcement is influenced by several factors, including fiber type, dosage, aspect ratio, and dispersion within the concrete mix. Proper mixing techniques are essential to achieving uniform fiber distribution, as inadequate dispersion can result in clumping and reduce the material's effectiveness. Advanced mixing technologies, such as high-energy mixers and automated fiber dispensers, have been developed to enhance fiber integration in concrete pavements [19]. Furthermore, selecting the appropriate fiber dosage is critical for optimizing performance. Excessive fiber content can lead to workability issues, whereas insufficient fiber dosage may not provide adequate reinforcement benefits. Research suggests that an optimal fiber dosage range of 0.5% to 2% by volume is suitable for most pavement applications [20].

Field studies have demonstrated that fiber-reinforced pavements offer significant advantages in terms of reduced maintenance costs, improved load-bearing capacity, and enhanced durability. Highways and airport runways incorporating fiber-reinforced overlays have exhibited superior resistance to fatigue cracking and surface wear, highlighting the long-term benefits of fiber reinforcement in pavement infrastructure [21]. Additionally, fiber-reinforced concrete slabs have shown resilience in extreme weather conditions, making them an ideal choice for regions exposed to harsh environmental factors [22].

FIGURE 2.7: Fiber Reinforced Concrete for rigid pavement [11].

Beyond structural improvements, fiber reinforcement also contributes to sustainability and economic efficiency. By minimizing crack formation and improving pavement life, fiber-reinforced concrete reduces the need for frequent repairs, lowering overall maintenance costs and material consumption. Furthermore, the use of recycled fibers, such as those derived from waste plastics or industrial by-products, enhances the environmental benefits of fiber-reinforced pavements, aligning with global sustainability goals [23]. Cost-benefit analyses indicate that although fiber-reinforced concrete has a higher initial cost compared to conventional PCC, the extended service life and reduced maintenance expenses make it a cost-effective solution over the long term.

Fiber reinforcement has proven to be an effective and sustainable solution for enhancing the performance and durability of rigid pavements. By improving crack resistance, tensile strength, and load distribution, fiber-reinforced concrete addresses many of the challenges associated with traditional pavement repair methods. The selection of suitable fiber types, optimal dosage, and proper implementation techniques are crucial for maximizing its benefits. As research and field applications continue to expand, fiber reinforcement is expected to play a vital role in the future of pavement engineering, offering both structural and economic advantages.

2.4 Fiber Reinforced Ultra-High-Performance Concrete (FR-UHPC)

2.4.1 Properties of UHPC

Fiber-reinforced ultra-high-performance concrete (FR-UHPC) is an advanced construction material that combines ultra-high-performance concrete (UHPC) with various types of fibers to enhance its mechanical and durability properties. UHPC itself is characterized by its exceptionally high compressive strength (typically exceeding 150 MPa), low porosity, and superior durability due to its dense microstructure achieved through optimized particle packing and the use of fine materials like silica fume [3]. The addition of fibers, such as steel, synthetic, or natural fibers, further improves the tensile strength, toughness, and crack resistance of UHPC, making it highly suitable for demanding structural applications like bridges, high-rise buildings, and protective structures. Fibers in FR-UHPC act as a reinforcement mechanism, bridging micro cracks and preventing their propagation, which significantly enhances the material's post-cracking behavior and energy absorption capacity as illustrated by literature. Steel fibers are the most commonly used due to their high strength and stiffness, while synthetic fibers like polypropylene and polyvinyl alcohol (PVA) offer corrosion resistance and improved ductility [27]. Natural fibers, such as cellulose or sisal, are emerging as sustainable alternatives but face challenges related to durability in alkaline environments. Hybrid fiber systems, combining different fiber types, are also employed to optimize performance by leveraging the unique benefits of each fiber.

2.4.2 Types of Fibers in FR-UHPC

Fiber-reinforced ultra-high-performance concrete (UHPC) is a cutting-edge material that combines high-strength concrete with various types of fibers to enhance its mechanical properties, durability, and toughness. The incorporation of fibers into UHPC significantly improves its tensile strength, crack resistance, and energy absorption capacity, making it suitable for demanding applications such as bridges, high-rise buildings, and protective structures [40, 41]. The types of fibers used in UHPC can be broadly categorized into metallic, synthetic, and natural fibers, each contributing unique properties to the composite material.

2.4.2.1 Metallic Fibers

Metallic fibers, particularly steel fibers, are the most commonly used fibers in UHPC due to their high tensile strength, stiffness, and ability to bridge cracks effectively. Steel fibers enhance the post-cracking behavior of UHPC by providing ductility and preventing sudden failure. They are typically classified into straight, hooked, or deformed fibers, with hooked and deformed fibers offering better bonding with the concrete matrix [24]. The addition of steel fibers can increase the flexural strength, impact resistance, and fatigue performance of UHPC [25]. However, steel fibers are susceptible to corrosion in aggressive environments, which can limit their long-term durability.

2.4.2.2 Synthetic Fibers

Synthetic fibers, such as polypropylene, polyethylene and polyvinyl alcohol (PVA) are widely used in UHPC due to their lightweight, corrosion resistance, and versatility. Polypropylene fibers are particularly effective in controlling plastic shrinkage cracking during the early stages of concrete curing [26]. PVA fibers, on the other hand, are known for their high tensile strength and excellent bonding with the cementitious matrix, making them suitable for enhancing the toughness and strain-hardening behavior of UHPC [27]. Carbon fibers, although expensive, offer exceptional strength-to-weight ratios and electrical conductivity, making them ideal for specialized applications such as smart structures and electromagnetic shielding [28].

2.4.2.3 Natural Fibers

Natural fibers, such as cellulose, sisal, and bamboo, are emerging as sustainable alternatives to synthetic and metallic fibers in UHPC. These fibers are biodegradable, renewable, and have a lower environmental impact compared to their synthetic counterparts. Cellulose fibers, derived from plants, can improve the toughness and crack resistance of UHPC while reducing its density [29]. Sisal and bamboo fibers, although less common, have shown potential in enhancing the mechanical properties of UHPC, particularly in regions where these materials are locally available [30]. However, natural fibers are prone to degradation in alkaline environments, which can limit their long-term performance in UHPC.

2.4.2.4 Hybrid Fiber Systems

To optimize the performance of UHPC, hybrid fiber systems combining two or more types of fibers are often employed. For example, a combination of steel and polypropylene fibers can provide both high strength and crack control, while a blend of carbon and PVA fibers can enhance both mechanical and functional properties [31]. Hybrid fiber systems leverage the complementary characteristics of different fibers to achieve a balance between strength, ductility, and durability.

2.4.2.5 Carbon Fibers

In Ultra-High Performance Concrete (UHPC), carbon fibers are frequently utilized to improve mechanical qualities, which makes them perfect for rigid pavements. They offer exceptional crack resistance against environmental deterioration, and high tensile strength (3,0007,000 MPa). With compressive strength reaching 150 MPa and post-cracking tensile strength surpassing 5 MPa, carbon fiber-reinforced UHPC guarantees long-term performance under demanding loads. Because they are lightweight, pavement sections can be thinner, using less material without sacrificing structural integrity [68]. They are more expensive, but they outperform steel and synthetic fibers in terms of fatigue performance and corrosion resistance [69].

2.4.2.6 Basal Fibers

Ultra-High Performance Concrete (UHPC) for rigid pavements is increasingly using basalt fibers, which are generated from volcanic rock, because of their high tensile strength (3,0004,840 MPa), durability, and affordability. They are appropriate for industrial floors, bridge decks, and highway pavements because they increase load-bearing capacity, improve fracture resistance, and resist environmental deterioration. With compressive strength reaching 150 MPa and post-cracking tensile strength above 5 MPa, basalt fiber-reinforced UHPC provides a sustainable and environmentally beneficial substitute for carbon fibers [70, 71].

2.4.3 Mechanisms of Fiber Action in UHPC

In UHPC, fibers enhance performance through crack bridging, stress redistribution, and energy absorption. Fibers inhibit crack propagation by transferring stresses across microcracks, improve tensile strength by reinforcing the cementitious matrix, and increase toughness by absorbing energy during deformation. Advanced fibers like ultra-high-molecular-weight polyethylene (UHMWPE) and hybrid systems further optimize these mechanisms, enhancing ductility and durability [32-36]. Fiber reinforcement in Ultra-High Performance Concrete (UHPC) is defined by material type (steel, mineral, or synthetic), geometry, aspect ratio, and mechanical properties. Fibers vary in shape (straight, hooked-end, corrugated, twisted) and size, with longer fibers controlling macro-crack propagation and smaller fibers mitigating micro-cracks. UHPC typically contains 26 vol-% fibers, compared to 0.252 vol-% in conventional Fiber-Reinforced Concrete (FRC), significantly enhancing ductility, toughness, and post-cracking behavior. The fiber-matrix interface, optimized through low water-to-cement ratios and fine aggregates (¡1 mm), plays a critical role in UHPC's strength and durability. Supplementary cementitious materials like silica fume further improve density and strength, while high-strength fibers enhance crack resistance and structural performance [36].

The aspect ratio of fibers (length/diameter) impacts workability, with higher ratios reducing it. To achieve optimal UHPC performance, four key factors are essential: (1) fine sand (150600 μm) for homogeneity, (2) cement and silica fume for increased density, (3) steel fibers for enhanced ductility, and (4) thermal curing (90°C) to improve mechanical properties. Fibers prevent explosive failure by increasing stiffness and compressive strength, though their effect on compressive strength is often minimal (<10%). Instead, fibers primarily improve tensile strength, toughness, and crack control, ensuring long-term durability [33].

2.5 Performance of Fiber Reinforced Concrete and UHPC in Pavements

2.5.1 Mechanical Properties

A significant recent advancement in building materials, Ultra High Performance Concrete (UHPC) has excellent compressive strength and other desirable qualities [3739]. Fibers should be added to the cement matrix to improve the cracking deformation characteristics of the resulting composite and to increase the toughness and tensile strength of this type of concrete, which exhibits very brittle failure behavior and limited post-crack behavior, causing the elements to fail explosively without any warning. Ultra High Performance Fiber Reinforced Concrete is the name given to this kind of concrete (UHPFRC). The type of fiber-reinforced concrete (FRC) that exhibits strain hardening under uniaxial tension force is known as High Performance Fiber Reinforced Cement Composites (HPFRCC), and UHPFRC is a member of this group [41]. Furthermore, in contrast to HPFRCC and regular strength concretes, UHPFRC has a dense matrix and, as a result, very low permeability. Precast elements like bridge components, arch structural features, durable components exposed to harsh environments like the sea, blast or impact protection structures, and strengthening materials for repairs and rehabilitation of deteriorated reinforced concrete structures can all be made with UHPFRC. The removal of coarse aggregate to improve concrete homogeneity is one of the unique methods and raw materials required to prepare UHPC in order to achieve outstanding mechanical behavior [40].

Compared to traditional concrete, UHPFRC has numerous advantages for constructions. These include: improved absorption resistance extends the life of bridge decks and industrial floors; superior corrosion resistance protects against deicing, chemicals, and constant exposure to humid environments; superior strength results in significant weight reduction, which creates more slender transportation structures; elimination of supplemental reinforcing steel allows nearly limitless shape and form freedom for structural members and also lowers the high labor costs associated with it; and superior ductility and energy absorption provide greater structural reliability even under overload conditions or seismic events [41].

Numerous studies have been conducted to examine the UHPFRC's mechanical characteristics. Nevertheless, there is an absence of published research on the structural behavior of UHPFRC [40, 41]. The effects of using fly ash and rice husk ash as mineral admixtures (10% and 20% as replacement by weight of cement) on the properties of UHSFRC with 2.5% steel fibers by volume of concrete and 25% silica fume as addition by weight of cement were experimentally investigated. According to test results, the mechanical performance of UHSFRC with mineral admixtures is satisfactory [40]. Greater compressive and split tensile strengths were obtained when 20% rice husk ash was substituted for cement. Cornelia and Victor demonstrate how UHPFRC beams bend. Eight beams (I-shaped cross section) were created and tested for the experiment, two simultaneously for each percentage of reinforcement (1.5% and 2.55%) and for each type of fiber employed (long and hybrid fibers). In order to lower the cost of UHPC, our investigation produced UHPC with acceptable workability and a compressive strength of roughly 149 MPa without removing the coarse aggregate. It involves researching how the flexural behavior of UHPC beams with conventional steel reinforcement is affected by the steel fibers' content, shape, and dispersion depth [41].

The behavior of the reinforced concrete sections under tension is the fundamental characteristic of tension stiffening. Think about a reinforced concrete member that is encircled by a concrete cylinder and composed of reinforcing rebar. The two ends of the rebar are subject to the tension force. The concrete cylinder's stresses and strains rise with increasing force because of the link between the concrete and rebar at their interface, and breaking happens at a specific force level where the strains satisfy the cracking criterion. As seen in graph figure 2.5, the formation of a fracture in the member causes internal strains and stresses to be redistributed inside the member, altering the stiffness of the reinforced concrete member. In some locations, increased loading may result in more cracks. The process of increasing loading on a reinforced concrete part continues until the rebar yields at either one of the two ends or the cracking cross section. The stiffness and behavior of the reinforced concrete member are affected when cracks appear in the concrete cylinder around the reinforcement rebar. We refer to this phenomenon as "tension stiffening" [42].

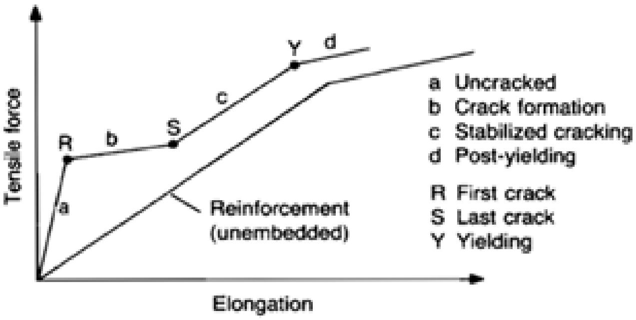


FIGURE 2.8: Force-strain relation of a reinforced concrete member under tension [42].

The suggested approach enables the precise computation of reinforcement stresses at fracture locations and, consequently, the average strain conditions that lead to reinforcement rupture. As a result, the uniaxial, flexural, and shear ductility of reinforced concrete members can be predicted with greater accuracy. Experimental research was conducted to examine and evaluate the tension stiffening impact of chemically pre-stressed concrete (CPC) and reinforced concrete (RC) under uniaxial tension [42]. Their study's findings demonstrate that CPC has better tension stiffening than RC and that the traditional model for RC significantly understates CPC's tension stiffening. Furthermore, even if the average bond is about the same, the number of cracks in CPC is lower than in RC at the same load, and the bond of CPC is higher than that of RC close to loading.

Because they allow for a better distribution of load over the subgrade and require a smaller total structural depth than flexible asphalt pavements, rigid concrete pavements are frequently employed in the construction of long-lasting highways. Road pavement slabs, however, are exposed to constant thermal loads and cyclic traffic, which can weaken the material's mechanical qualities, cause fractures to spread, and ultimately result in fatigue fracture, which can cause premature pavement failure. Using waste tire rubber (WTR) particles in place of some of the natural aggregates in concrete pavements could improve their flexibility, toughness, and fatigue resistance. Rubber aggregates can significantly impair mechanical qualities, particularly at high rubber contents (up to 90% reduction in compressive strength for 100% natural aggregates replacement), although they are also known to improve impact and skid resistance and reduce stiffness in concrete [4344]. Because of this, rubberized concrete (RuC) is still mostly used in non-structural, low-strength applications, such as concrete pedestrian blocks. There are currently few studies on RuC's fatigue performance, and even fewer on its performance in structural applications. Researchers investigated the impact of substituting tiny amounts of crumb rubber particles (015% by volume) for fine natural aggregates and discovered that the RuC mixes outperformed regular concrete in terms of fatigue performance. The improvement was explained by rubber's capacity to stop cracks from spreading by occupying internal gaps and absorbing energy through deformation [45]. Steel fibers can be utilized to create steel fiber reinforced rubberized concrete (SFRRuC), which helps increase the strength of RuC for structural purposes, particularly flexural strength. While these studies looked at the fatigue of mixes with small amounts of rubber (less than 20% by total aggregate volume), more recent research by Gupta et al. found that adding rubber ash and rubber fibers to concrete as a replacement for fine natural aggregates (up to 35% by volume) improved the flexural impact and fatigue resistance by up to 217% and 52%, respectively [46].

2.5.2 Serviceability

2.5.2.1 Ride Quality and Surface Smoothness

Ride quality and surface smoothness are critical factors in pavement performance, influencing both safety and user comfort. While road realignment or reconstruction offers the most comprehensive solution to address accident-prone areas, these methods are often cost-prohibitive and impractical. As an alternative, surface treatments provide a viable, cost-effective solution to restore pavement conditions and enhance safety. High Friction Surface Treatments (HFST), for instance, improve texture and friction, significantly reducing crashes and enhancing ride quality [47]. Ultra-High Performance Concrete (UHPC) further elevates pavement performance, offering exceptional compressive strength, durability, and abrasion resistance due to its advanced formulation, which includes supplementary cementitious materials (SCMs), superplasticizers, and fiber reinforcement [48]. UHPC's low water-to-cement ratio and optimized particle packing result in a dense, impermeable surface, contributing to superior ride smoothness and long-term performance. Fibers in UHPC enhance toughness and strain capacity, reducing cracking and maintaining surface integrity over time [48]. These innovations collectively improve ride quality and surface smoothness, offering safer, more durable pavements without the need for extensive reconstruction.

2.5.2.2 Skid Resistance and Surface Texture

Skid resistance and surface texture are critical for rigid pavement safety. Fiber-inclusive concrete enhances these properties by improving surface roughness and durability. Fibers, such as steel or synthetic types, reduce cracking and maintain surface integrity, ensuring consistent friction over time. The textured surface of fiber-reinforced concrete provides better tire-pavement interaction, increasing skid resistance, especially in wet conditions [59]. This makes fiber-inclusive concrete an effective solution for improving pavement safety and service life while maintaining cost efficiency compared to traditional methods.

2.6 Pavement Overlays: Concepts and Applications

2.6.1 Importance and Applications of Pavement Overlays

Pavement overlays are a cost-effective and efficient solution for restoring and enhancing the performance of existing pavements. They involve applying a new layer of material over the existing surface to address issues such as cracking, rutting, surface deterioration, and reduced skid resistance. Overlays improve ride quality, extend pavement life, and enhance safety by restoring surface texture and friction. They are widely used in both flexible (asphalt) and rigid (concrete) pavements, offering a quicker and less disruptive alternative to full reconstruction [47].

Overlays can be single-layered or multi-layered, with materials ranging from conventional asphalt and concrete to advanced options like latex-modified concrete, silica fume concrete, and Ultra-High Performance Concrete (UHPC). UHPC overlays, in particular, provide exceptional durability, waterproofing, and resistance to chemical penetration, making them ideal for bridge decks and high-traffic areas. Proper surface preparation, including cleaning and roughening, ensures strong bonding between the overlay and the existing pavement [48].

Applications of overlays include highway resurfacing, airport runways, and urban roads, where they improve skid resistance, reduce maintenance costs, and enhance structural capacity. By addressing surface defects and extending service life, pavement overlays play a vital role in sustainable infrastructure management [59].

2.6.2 UHPC as a Pavement Overlay Material

Ultra-High Performance Concrete (UHPC) is an advanced overlay material known for its exceptional strength, durability, and resistance to environmental degradation. With compressive strengths exceeding 120MPa, UHPC provides superior waterproofing, abrasion resistance, and chemical penetration protection, making it ideal for bridge decks and high-traffic pavements [49]. Its dense microstructure, achieved through low water-to-cement ratios and optimized particle packing, ensures overall performance and reduced maintenance. Typical HUPC overlay is shown in figure 2.9. UHPC overlays also enhance skid resistance and surface texture, improving safety and extending pavement service life [50].

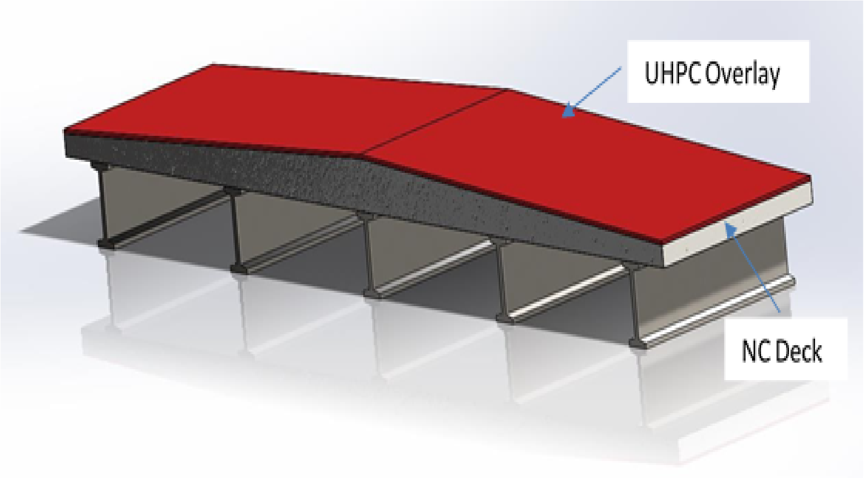


FIGURE 2.9: UHPC overlay [50].

2.6.3 Fiber Reinforced UHPC Overlays for Surface Renewal

Fiber-reinforced Ultra-High Performance Concrete (UHPC) overlays offer exceptional surface renewal for pavements, combining high strength, durability, and crack resistance. The addition of macrofibers to UHPC enhances post-cracking toughness and flexural fatigue performance, ensuring long-term durability under heavy traffic loads [51]. While fibers may reduce workability, adjustments such as water-reducing admixtures or increased cementitious content can maintain adequate slump and finishability. UHPC's dense microstructure, achieved through low water-to-cement ratios, ensures superior waterproofing and resistance to chemical penetration, making it ideal for overlays [50].

Fibers in UHPC overlays maintain tight crack widths (¡0.5 to 1.0 mm), reducing the need for joint sealing and minimizing water infiltration. This improves the overlay's service life and reduces maintenance costs. Diamond grinding can address surface roughness or faulting, though the increased toughness of fiber-reinforced UHPC may require additional energy for grinding or slab removal. Replacement panels without fibers may need increased thickness to compensate for reduced crack resistance [59].

Overall, fiber-reinforced UHPC overlays provide a robust solution for surface renewal, enhancing skid resistance, durability, and structural performance while minimizing long-term maintenance.

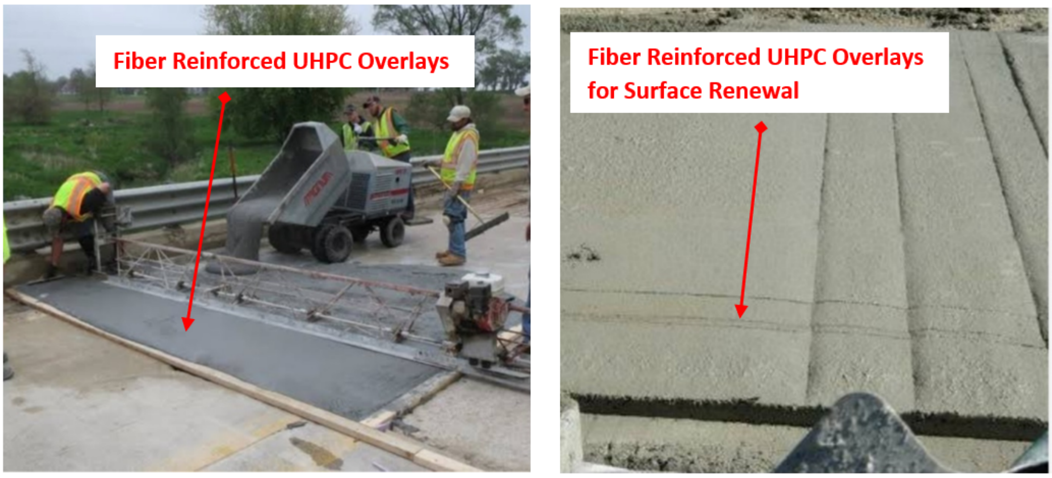


FIGURE 2.10: Fiber Reinforced UHPC overlay [50].

2.7 Evaluation of Surface Texture and Shrinkage in Pavement Overlays

2.7.1 Shrinkage Behavior in Fiber Reinforced UHPC Overlays

Ultra-high performance concrete (UHPC) possesses remarkable durability and mechanical qualities that could significantly extend the service lives of current bridge decks and superstructure. In comparison to proprietary UHPC products, non-proprietary UHPC can be more cost-effective and environmentally friendly by utilizing locally accessible materials. The qualities of UHPC are attained by meticulously choosing the materials that make up the material to guarantee optimal gradation and packing density, as well as by using precise preparation techniques to combine and cure UHPC components. Existing constructions' service lives and durability could be greatly increased because to UHPC's special qualities. Shear and tensile pressures at the bond interface brought on by UHPC shrinkage may result in bond cracks and delamination. ACI 546 [52] advises choosing an overlay material that may shrink without losing bond, hence measuring UHPC's shrinkage effects on NSC substrates is crucial. Figure 2.11 shows the steps to measure shrinkage.

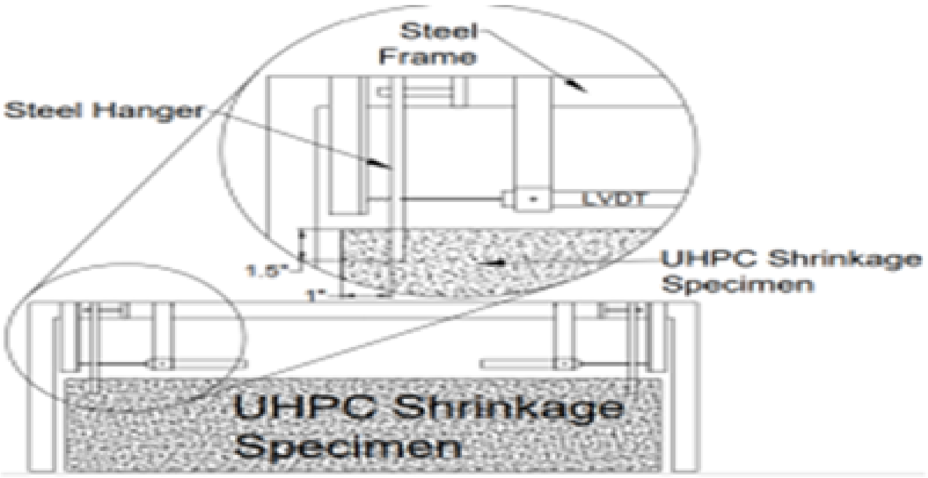


Figure 2.11: Early-age shrinkage setup (top), illustration of setup (bottom) [60].

2.7.2 Surface Texture and Skid Resistance Assessment

The study of pavement texture has a very recent history. The Oregon State Highway Department was among the first to report on the role of texture in relation to skid resistance. It was discovered during a two-year testing period in 1938 and 1939 that open-textured pavements outperformed closed-textured surfaces in terms of skid resistance. It was thought that the open texture allowed for the quick and efficient evacuation of three surface water and gave the impression of a closer tire-to-pavement contact than that found on pavements with dense textures. Interestingly, according to Moyer's findings, tire manufacturers were creating "tire tread designs that provided good drainage for the rapid removal of water" in 1938. When it was discovered that a car's tires can genuinely hydroplane in specific rainy situations, texture was indirectly highlighted once more [53]. As early as 1959, it was discovered that when specific water film depths, tire pressures, and vehicle speeds are formed, a moving vehicle's tire might actually stop rotating and lose all touch with the road. Nonetheless, the idea proposed by the Oregon Highway Department still offers context for understanding how roughness affects hydroplaning. A British researcher examined the pressure distributions of conical and spherical shapes that were pressed into a rubber block or sheet's flat surface [54]. These two geometric forms represent the pressure and penetration depths. Around the world, roads are essential to the commercial and transportation networks. Roads can be divided into flexible and stiff pavements based on their surface and structural characteristics. 95% of the highways on the planet are made of flexible pavement. The common layers of flexible pavement are sub-grade, sub-base, road base, and surface, which includes wearing course and binder course. The exposed uppermost layer, known as the wearing course, gives the road user comfort, safety, skid resistance, and a travel path. To guarantee road users' safety and comfort, regular and series maintenance must be performed throughout the lifespan. Road maintenance is typically the duty of the local government or organizations that respond to structural or functional issues. severe environmental and load demands on the road system, necessitating an improvement in the current road's performance. One of the crucial parameters used to assess a road's functional failure is friction, often known as skid resistance. Road agencies employ a variety of instruments to detect skid resistance or friction. The frictional resistance of rubber (car tires) across the road surface is measured by all of the equipment. Since every piece of equipment measures according to a separate set of physical principles, measurements cannot be directly compared.One of the older, manually operated instruments is the British Pendulum. It features a pendulum that sweeps over the road surface with a tiny rubber foot (75 x 25 mm) attached. A scale that is fixed to the apparatus is used to measure the frictional resistance. It has gained acceptance all over the world and is incredibly adaptable in its applications to a wide range of test scenarios. The instrument is frequently used to evaluate the micro-texture of pavement surfaces and measures low speed friction (about 10 km/h). A rubber slider is fastened to the end of the pendulum; when the slider travels across the pavement, frictional force lowers the pendulum's kinetic energy. The difference in the pendulum's height before and after the slider traverses the pavement can be used to calculate the amount of kinetic energy lost and, consequently, the strength of the frictional force in the pavement. British Pendulum Number (BPN) is the name given to the data or value generated by this gadget. Another element that contributes to the likelihood of accidents is skidding or friction, particularly on wet roads. because different instruments are typically used by road organizations to compare friction measurements. Using different measurement instruments may yield different results. However, it lacked information about the test temperature and the type of pavement surface. The roughness index of the Surface Dressing (SD), Stone Mastic Asphalt (SMA), and Asphaltic Concrete Wearing (ACW) road surfaces, on the other hand, has a poor link with texture depth, according to a study. However, the overall pattern indicates that the roughness index (IRI) and BPN increase with texture depth (TD) [54].

2.8 Summary

This work specifically demonstrate the impact of various fibers specially polypropylene (PP) and polyethylene (PE) fibers on UHPC for road construction and again significant changes in various characteristics like overlay, shrinkage, faults in pavement types of distress occurs in pavement with time were observed and discussed in detail . These different fibers boosted the mechanical, thermal and durability properties of UHPC which would make it a very useful material in road construction where durability is of immense importance. They prevent different distress which occurs with time in pavements. The studies showed that the incorporation of PP and PE fibers improves the compressive, flexural and tensile strengths of UHPC mainly by crack healing and improving toughness of concrete matrix.

These fibers are important in diminishing micro-cracking, hence creating improved roads which can withstand regular traffic and have a longer life cycle.

Chapter 3

Experimental Program

3.1 Background

In recent years, the use of fiber reinforced ultra-high performance concrete has granted significant attention due to its excellent mechanical properties and durability. Polypropylene PP and polyethylene PE fibers are among the most studied synthetic fibers. This study explore the impact of these fibers on the performance of ultra-high performance concrete in rigid pavement applications. This experimental study involves systematically incorporating varying dosages of polyethylene and polypropylene fibers into Ultra-High Performance Concrete (UHPC) of rigid pavement and subjecting the specimens to mechanical testing, including compressive strength, flexural strength. Durability tests such as shrinkage and skid resistance will also be conducted to evaluate the long-term performance of UHPC in term of rigid pavement.

The consistency of the fresh mix properties is checked after preparation of each mix proportion. Delve into the specifics of the polypropylene and polyethylene fibers used, the UHPC mix design, and the properties of each material. Explore the meticulous process of designing the UHPC mix and how the fibers are strategically incorporated. Detail the dosages of fibers, percentage by volume, mixing techniques, and consistency of the mix. Outline the precise methodologies involved in preparing UHPC specimens for mechanical tests. Elaborate on the rigorous long-term performance tests devised to evaluate the durability of the UHPC, such as shrinkage. Discuss testing methodologies, measurement techniques, and the anticipated impact of fiber inclusion on concrete properties. Provide an in-depth discussion on the methodologies and standards adhered to for testing the mechanical properties of UHPC. Breakdown the testing for compressive strength, flexural strength, flow ability, skid resistance, and shrinkage.

3.2 Raw Materials

In addition to sand, fly ash, silica fume, super plasticizer, and the fibers polypropylene and polyethylene, the materials utilized to prepare the reference concrete, or cement, were routine Portland cement purchased from a nearby factory. Details and pictorial presentation of each material used in this research is described in detail.

3.2.1 Cement

Cement is purchased in Rawalpindi, Pakistan, from the local market. Alumina (argillaceous), silica (siliceous), iron (ferriferous), and lime (calcareous) are the four main raw materials used to produce cement. For testing, about 150 kilograms (kg) of cement are purchased. The hard porous solid is created when cement is hydrated. The cement used is Lafarge Stallion, Ordinary Portland Cement, EN 197-1 (42.5 grade), which has clinker with a low C3A concentration and is ground with less gypsum than other cements on the market. It has a fineness of 200-400 m2/kg and a sieve residue greater than 45m of 9-11% by mass. Expansion is less than 4mm. These properties along with table no 3.1 are provided by the cement supplier. Presentation of cement used in this research is shown in figure 3.1.

3.2.2 Sand

The locally available fine sand is used in this research. The type of sand used has a big impact on the quality, durability, strength and stability of building or road

Figure 3.1: Ordinary Portland Cement (EN 197-1, 42.5 grade)

Table 3.1: Ordinary Portland Cement (EN 197-1, 42.5 grade)

Physical & Chemical Properties [OPC EN-197-1, 42.5 Grade]	
Property	**Value**
Fineness	200-400 m^2/kg
Soundness	$\leq$ 10 mm (Le Chatelier Test)
Consistency	10±1 mm (Vicat Penetration)
Strength	42.5 MPa (28-day compressive strength)
Setting Time	Initial: 30-45 minutes, Final: 6-10 hours
Heat of Hydration	500-800 J/g
Loss of Ignition	$\leq$ 5%
Bulk Density	1.4-1.6 g/cm
Specific Gravity	3.15-3.20
Chemical Composition	CaO: 60-67%, SiO2: 17-25%, Al2O3: 3-8%, Fe2O3: 0.5-6%

components. The density of dry sand is 1602 kg/m3. It is in its natural state, and having size of 0.0075-0.425mm where it has dried out and been compacted over time by gravity and rain. Sand is sieved from sieve no 4 (ASTM E-11) before used as shown in figure 3.2. The density of packed sand is 1682 kg/m^3.

3.2.3 Fly Ash

Fine-grained pozzolanic binder, classified as class F fly ash because silica, alumina and ferric oxides exceed 70% of the total composition. The fly ash offers cement replacement, with reduction of systems water demand, improved workability, higher compact ability and resistance to chemical attacks. As moisture

Figure 3.2: Fine Sand (Sieve No. 4 passing)

affects the pozzolanic natured powder, so fly ash was also stored in air-tight buckets. Fly ash, a locally accessible class F, can replace up to 30% of the mass of Portland cement in the cement paste mix depicted in figure 3.3, while it may be utilized at a larger proportion in specific applications. The Fly Ash vendor provides the fly ash attributes listed in table no. 3.2. Fly ash can sometimes improve the ultimate strength, durability, and chemical resistance of concrete. To improve the workability of fresh concrete, lower the heat of hydration, increase concrete impermeability, and strengthen resistance to sulfate attack, fly ash can be used in place of some of the cement and sand in concrete.

Table 3.2: Properties of Fly Ash

Physical Shape	**Fine Powder**
Color	Dark grey
Loss on Ignition	5.00%
Bulk Density	1200 kg/m^3
Particle Density	2300 kg/m^3
Sieve Residue > 45 μm	(20 ± 10) % by mass

3.2.4 Silica Fume

Silica is a highly reactive pozzolanic material due to its chemical makeup and extremely tiny particles. It can have cementitious and pozzolanic qualities. The silica fume utilized in this study is a gray, glassy powder. The vendor claims that the particles of silica fume are about 100 times smaller than those of ordinary Portland cement. The characteristics of silica fume according to the supplier's datasheet are displayed in Table 3.3.

TABLE 3.3: Properties of Silica fume

Physical Shape	**Fine Glassy Powder**
Color	Dark grey
Loss on Ignition	>6.0%
Bulk Density	421 kg/m^3
Particle Density	1400 kg/m^3
Sieve Residue > 45 μm	(30 ± 10) % by mass

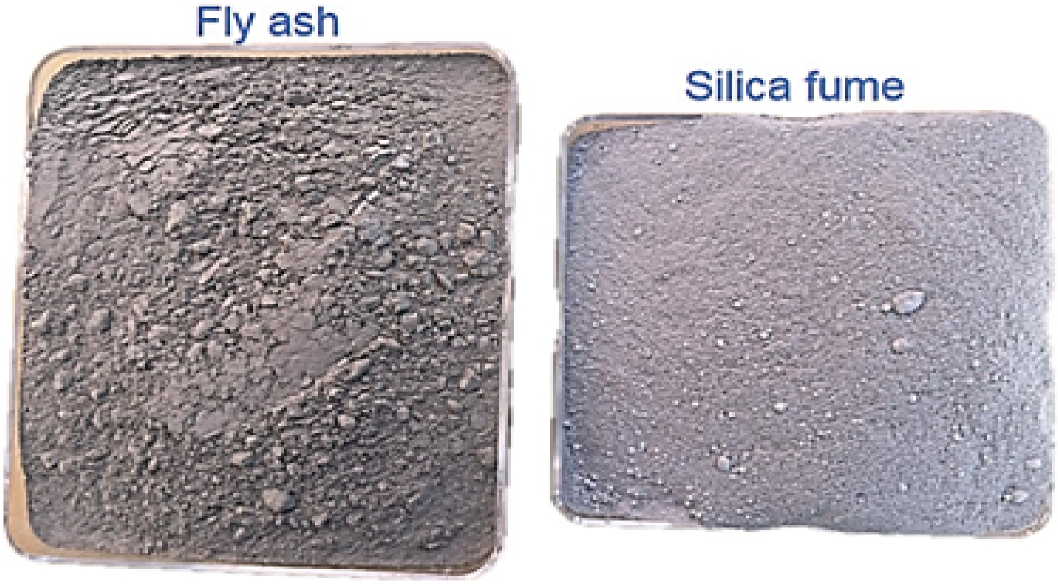


FIGURE 3.3: Fly Ash & Silica fume

3.2.5 Super Plasticizer

A specialised chemical solution called Fast Chem 950 is intended to operate as an accelerator in the field of activating cementitious mix. Dosage of Fast Chem 950 is fixed at 3% in all mix. Super plasticizer HRWR used in this study is one of the most important constituents of cement cementitious mixes. It makes cementitious mix flow able at a low water-cement ratio without segregation and bleeding as required for high-performance concrete Specific gravity of HRWR admixture is given by supplier which is in the range of 1.15 to 1.17. These properties, chemical code (Fast Chem 950) and properties mentioned in table no 3.4 are as per datasheet of material. Fast Chem SP-950 is shown in figure 3.4.

TABLE 3.4: Properties of SP-950

Property	**Value**	**Unit**	**Notes**
Appearance	Clear liquid	-	Dark brown Liquid.
Density	1.05 - 1.20	g/cm^3	Depends on formulation.
pH	2.0 - 12.0	-	Could be highly acidic or alkaline depending on use.
Boiling Point	100 - 150	°C	Varies based on solvent or active ingredients.
Flash Point	30 - 80	°C	Indicates flammability risk.
Reaction Time	< 5	minutes	Fast-acting, but exact time depends on application.
Storage Temperature	May-40	°C	Store in a cool, dry place.
Environmental Impact	Requires proper disposal	-	May contain hazardous components.

FIGURE 3.4: Fast Chemical SP-950

3.2.6 Polypropylene Fibers

The polypropylene fiber used in this study in range from 0% to 3% by weight of cement. Varying properties are exhibited by different types of polypropylene, which is usually dependent on the crystallinity, molecular weight distribution, and length of the chain. Polypropylene fibers are shown in figure 3.5 along with its properties in table 3.5 which is given by the vendor. These polypropylene fibers are purchased from local market (Fast Chemical Pvt Ltd) renowned vendor in Islamabad Pakistan.

Literature explore the benefits of enhancing pavement performance with polypropylene fiber reinforcement. Their results demonstrates the positive impact on both tensile strength and fatigue resistance, making polypropylene fibers and effective solution for modern pavement engineering [56]. Recent research focused on the effect of polypropylene fiber reinforcement on the durability of concrete payment. Their study highlighted the role of polypropylene fibers in mitigating cracks formation and enhancing service life [57]. Scientists also explored the benefits of polypropylene fibers integration in concrete pavement performance under various stress scenarios [58]. The key characteristics exhibited by almost all types of polypropylene are: Toughness and flexibility (exhibited to a large extent especially when the polymerization process involves copolymerization with ethylene).

- Large thermal expansion.
- Resistant to organic solvents.
- Resistant to weak oxidizing agents.

FIGURE 3.5: Polypropylene Fibers

TABLE 3.5: Physical and chemical properties of polypropylene fibers

Properties	**Value**
Length (millimeter)	12
Diameter (millimeter)	0.6
Density (grams/centimeter cube)	0.91
Elastic Modulus (Gpa)	3.5
Alkali Resistance	High
Melting Point (Degree)	160-165
Water Absorption	0

3.2.7 Polyethylene Fibers

The polyethylene fiber used in this study are purchased from sadder bazar, Rawalpindi and has nearly similar length and flexible molecules and only by physical treatments can the molecules be forced to assume the straight (extended) conformation and orientation in the direction of the fiber. Researchers explored the engineering performance of concrete incorporating recycled high-density polyethylene (HDPE) fibers [59]. The review highlighted the mechanical and surface texture performance evaluation benefits of using recycled plastic waste in concrete, demonstrating its potential for sustainable pavement materials. All the physical and chemical properties of polyethylene used in this research are given in table 3.6 which is given by the vendor and presentation is shown in figure 3.6. These polyethylene fibers are also purchased from local market (Fast Chemical Pvt Ltd) renowned vendor in Islamabad Pakistan.

3.3 Mix Design and Casting Procedure

The selection of these specific mix designs is driven by the aim to produce UHPC with a high compressive strength usually required for high-performance pavement

Table 3.6: Physical and Chemical properties of Polyethylene Fiber

Properties	**Value**
Length (millimeter)	14
Diameter (millimeter)	0.6
Crystallinity	Low Linear
Density (grams/centimeter cube)	0.91
Breaking Tensile Strength (Mpa)	3500
Alkali Resistance	Very Good
Melting Point (Degree)	160-165
Water Absorption	<0.1%
Refractive index	1.51 to 1.52

Figure 3.6: Polyethylene Fiber

overlay applications. The base mix, incorporating C, S, FA, and SF, along with a low water-to-cement ratio, is a well-established formulation for achieving the dense microstructure and high strength characteristic of UHPC. The proportions of FA and SF (450g each, relative to 3kg of C) are consistent with common practices in UHPC development, where these supplementary cementitious materials are used to enhance particle packing, improve pozzolanic reactions, and refine the pore structure, contributing significantly to strength and durability [11]. HRWR is crucial for maintaining workability despite the low water content, ensuring proper mixing and compaction. This allows for the investigation of PP and PE fiber effects within a true UHPC matrix, rather than a more conventional concrete, specifically for overlay applications.

The incremental addition of PP and PE fibers (30g, 60g, and 90g) is a methodical approach to evaluate their individual impact across a practical range of dosages for UHPC overlay applications. This systematic variation allows for the observation of how increasing fiber content influences fresh properties (like flowability), mechanical properties (such as crack resistance and toughness), and ultimately, surface texture performance including skid resistance. By comparing these fiber-reinforced mixes to a plain UHPC reference, the study aims to quantify the specific benefits and potential trade-offs associated with each fiber type and dosage, informing optimal mix designs for rigid pavement overlays.

During the concrete mixing process, we conducted experiments to ensure the mixture would achieve a compressive strength of 150 MPa. We used a specific water-to-cement ratio and allowed the concrete to cure for 28 days before testing its water absorption capacity. Subsequently, we evaluated its performance under various stress conditions. The mechanical tests were conducted after a 28-day curing period. The experimental program included reference specimens of plain concrete tested under identical conditions. We then prepared and tested concrete with PE and PP fibers, comparing the results to the plain concrete. Additionally, we assessed the strengthening properties at 60 and 90 days, as outlined in the scope of work. The same mix design and water-to-cement ratio were used for both the reference concrete and the concrete containing PE and PP fibers, designed for overlay use.

Furthermore, a superplasticizer HRWR (Fast Chem SP-950) has been used to increase the workability of the concrete, as the water-cement ratio is kept very low. To prepare the UHPC, water and raw materials, including cement, fly ash, and silica fume, are mixed in a concrete mixer for three minutes. Once the concrete is prepared, fibers are added, and the mixture is poured into an open tray for flowability tests. Samples are then placed in a curing tank for 28 days to achieve maximum strength, all intended for evaluation in UHPC pavement overlay applications.

For research purposes, 21 samples were cast. Each batch consists of 3 cubes, and 3 prisms for compression and flexure tests. Each specimen is marked for identification. The current experimental program employs a relative approach to evaluate the effectiveness of PP and PE fibers in concrete for rigid pavement overlay applications. The reference specimens of plain concrete are tested under the same conditions as the concrete containing PE and PP fibers.

TABLE 3.7: Casting Details & Mix proportion Quantities

C = Cement, S = Sand, FA = Fly Ash, SF = Silica Fume, HRWR= High Range water Reducer Chemical, PP fiber, PE fiber	**Casting of specimens**
3kg C + 3.6kg S + 450grams FA + 450 grams SF + 90grams HRWR	Cube = 3, Prisms = 3, Slab = 1
3kg C + 3.6kg S + 450grams FA + 450 grams SF + 90grams HRWR + 30grams PP Fiber	Cube = 3, Prisms = 3
3kg C + 3.6kg S + 450grams FA + 450 grams SF + 90grams HRWR + 60grams PP Fiber	Cube = 3, Prisms = 3
3kg C + 3.6kg S + 450grams FA + 450 grams SF + 90grams HRWR + 90grams PP Fiber	Cube = 3, Prisms = 3, Slab = 2
3kg C + 3.6kg S + 450grams FA + 450 grams SF + 90grams HRWR + 30grams PE Fiber	Cube = 3, Prisms = 3
3kg C + 3.6kg S + 450grams FA + 450 grams SF + 90grams HRWR + 60grams PE Fiber	Cube = 3, Prisms = 3,
3kg C + 3.6kg S + 450grams FA + 450 grams SF + 90grams HRWR + 90grams PE Fiber	Cube = 3, Prisms = 3
Total Casting = Cube 21, Prism 21 Slabs 3	

3.4 Testing Plan

In the testing plan for this research thesis, compressive strength, flexural strength, and flow ability of materials are tested using ASTM standards. Shrinkage is measured to evaluate dimensional changes, while skid resistance tests to ensure surface safety. Detail testing plan is shown on table no 3.8. Each experiment flows rigorous procedure to gather accurate data analyze material behavior, and validate hypotheses. Combining these tests provide a comprehensive understanding of material properties for sustainable and smart material for industrial use.

Table 3.8: Testing Plan

Sr. No	Test	ASTM Code	Dimensions
1	Compression Test	ASTM C109/C109-20	Cube (100mmx200mm)
2	Flexural Test	ASTM C348-14	Prism (40mmx40mmx160mm)
3	Flow ability Test	ASTM C1437	-
4	Skid Resistance	ASTM E303	Slab (1ft x 2ft)
5	Shrinkage	ASTM C157	Slab (1ft x 2ft)

3.5 Fresh Properties of Specimens

After blending the essential components cement, sand, fly ash, silica fume, and respective fibersthe flow ability of the mix is rigorously tested to ensure it meets the necessary standards for effective application. This process is conducted using a flow ability apparatus, which is specifically designed to measure the mixs workability and consistency. Adhering to ASTM C1437 standards, the apparatus evaluates the ability of the mix to flow, which is a crucial factor in ensuring that the final concrete product will have uniform density and strength throughout. During each trial, the mix's flow ability is assessed to ensure it achieves the required specifications as shown in figure 3.7. This thorough evaluation process helps in identifying any necessary adjustments in the mix composition, ensuring optimal performance and durability in the final application. The consistent testing and adherence to standards guarantee that the concrete will perform well under various conditions, providing long-lasting and reliable pavement.

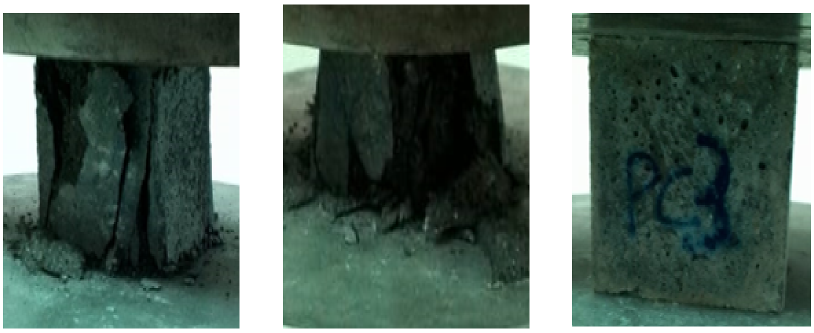
a) *Mix 1: 0% PP + 0% PE* ***b)*** *Mix 4: 3% PP + 0% PE* ***c)*** *Mix 5: 3% PP + 3% PE*

FIGURE 3.7: Flow ability of Mixes

3.6 Mechanical Properties

3.6.1 Compressive Strength

Compressive testing has been conducted on cubes using ASTM C109/C109-20 standards. This testing method is used to determine the strength and behavior of the mix under compressive loading, ensuring it meets the required performance criteria. By evaluating the compressive strength, we can assess the material's ability to withstand loads and ensure its suitability for rigid pavement applications. In process of testing, sample testing can be seen in figure 3.8.

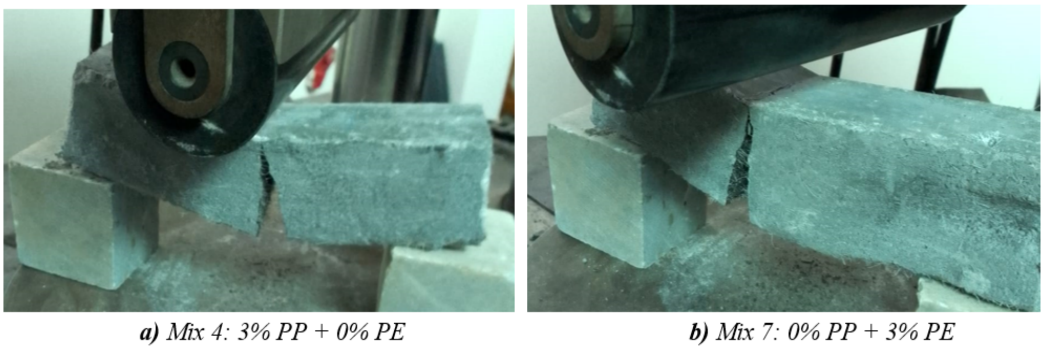


a) *Mix 2: 1% PP + 0% PE* ***b)*** *Mix 3: 2% PP + 0% PE* ***c)*** *Mix 4: 3% PP + 0% PE*

FIGURE 3.8: Compressing Testing of Specimens

3.6.2 Flexural Strength

Flexural testing has been conducted on beams following the ASTM C348-14 standard, using prisms with dimensions of 40mm x 40mm x 160mm shown in figure 3.9. This method evaluates the flexural strength and behavior under bending loads, which helps to estimate the tensile strength of pavement for future applications. By understanding the material's performance in bending, we can ensure its suitability and durability for use in rigid pavements.



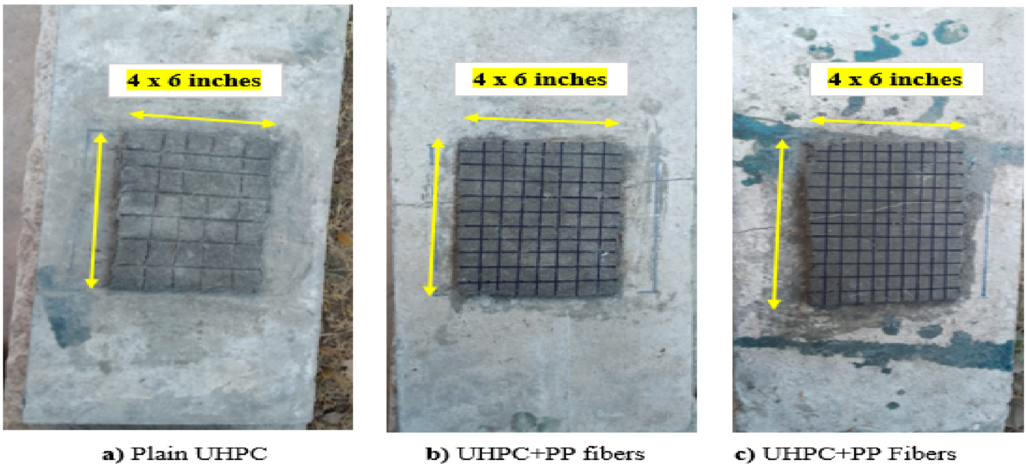
a) *Mix 4: 3% PP + 0% PE* ***b)*** *Mix 7: 0% PP + 3% PE*

Figure 3.9: Flexural Testing of Specimens

3.7 Surface Performance Testing

3.7.1 Shrinkage

The shrinkage of PP and PE paste slabs is determined using ASTM C157, which measures the length change of hardened hydraulic-cement mortar and concrete. 1ft x 2ft slabs are casted, moist-cured for 28 days, and then placed in a controlled environment. The change in length is measured over time, providing data on volumetric contraction due to moisture loss as shown in figure 3.10. Researchers in 2024 explored the impact of polypropylene fibers on drying shrinkage cracking in concrete pavements using response surface methodology. The study highlighted that the inclusion of polypropylene fibers reduced drying shrinkage and improved the overall performance of the concrete [60]. Research study in 2023 investigated the effects of polypropylene fibers on the drying shrinkage and cracking of concrete. The research found that concrete mixtures containing PP fibers exhibited higher drying shrinkage compared to those without fibers, especially in slag concretes and concretes cured for only one day 1. For this, idea to find out effect of PP and PE fibers shrinkage when it used in case of rigid concrete pavements [61].



a) Plain UHPC b) UHPC+PP fibers c) UHPC+PP Fibers

Figure 3.10: Slabs (1ftx2ft) having UHPC and fibers paste for Shrinkage Testing

3.7.2 Skid Resistance

Using ASTM E303, skid resistance was evaluated for three UHPC overlay slabs to assess rigid pavement performance. The test surface was cleaned and wetted before testing. One slab was simple UHPC without fibers, while the second and third slabs contained polypropylene fibers with and without texture, respectively. The pendulum slider was carefully positioned to barely touch the test surface as shown in figure 3.11. This method measures the frictional property and micro texture of surfaces, providing critical data on the safety and performance of rigid pavements. It ensures that the pavement surface offers adequate skid resistance, enhancing road safety in both field and laboratory settings. Researchers evaluated the skid resistance characteristics of pavement surfaces. The study emphasized the importance of skid resistance in ensuring road safety and explored various methods to enhance this property. The findings highlighted that the incorporation of PP and PE fibers contributed to improved skid resistance, thereby enhancing the performance of rigid pavements [62].

3.8 Summary

In this research study, the performance of Ultrahigh Performance Concrete (UHPC) relative to its potential use in rigid pavements is examined with particular regard

***a)** Plain UHPC* ***b)** UHPC+PP fibers* ***c)** UHPC+PP Fibers*

FIGURE 3.11: UHPC Slabs and fibers paste for Shrinkage Testing

to the addition of polyethylene (PE) and polypropylene (PP) fibers. This study researches how such fibers influence the strength and the durability of the concrete. Various experiments such as compression test, flexural test, skid resistance and shrinkage were conducted to evaluate strength, durability, anti-cracking and anti-wear properties of the concrete. As one of the most important experimental tests, flow ability test investigated the workability of fresh concrete or the ability of the concrete to spread in the forms combining this with a mixing of the fibers within the concrete. The design of the UHPC mix included various quantities of the fibers and use of water and certain chemicals to improve the flow of the mix while maintaining the desired properties. They were then compared with one another and single fiber reinforced UHPC was developed with the objective of improving the strength of the concrete target and long-term durability and serviceability of the pavements.

Chapter 4

Results and Discussion

4.1 Background

Polypropylene (PP) and polyethylene (PE) fiber-reinforced Ultra-High-Performance Concrete (UHPC) exhibits exceptional promise for pavement applications. In order to address the inherent brittleness of traditional concrete and achieve exceptional outcomes for ultra-high performance concrete (UHPC), these fibers dramatically increase tensile strength, ductility, and crack resistance [70]. While PE fibers offer better mechanical qualities, endurance, and resistance to environmental deterioration, PP fibers help to improve fire resistance. Because of their improved load-bearing capability, longer service life, and lower maintenance needs, UHPC pavements with these fibers are ideal for heavy-duty infrastructure and high-traffic locations [71, 72].

However, issues including uniform fiber dispersion, increased material cost, and processing complexity must be resolved. To guarantee the cost-effectiveness and broad use of UHPC with PP and PE fibers in pavement construction, more investigation and optimization are necessary. The American Society of Testing Materials (ASTM) guidelines are followed in all mechanical and durability testing conducted for this study.

4.2 Fresh State Properties

According to ASTM C1437 guidelines, the flow ability test yielded remarkably favorable results. The outcomes demonstrate the outstanding flow properties of the material under test and show a high degree of performance and applicability. Following ASTM guidelines guarantees a consistent and trustworthy evaluation of flow ability, providing important information about how the material will behave in particular scenarios. The outstanding outcomes highlight the material's positive qualities and confirm that it can flow easily and consistently in accordance with industry requirements, improving its performance and application in a variety of settings.

Table 4.1: Flow ability Results

Flow Test for UHPC mortar (ASTM C1437)

ID	**Material / Mix**	**Dia of flow mold (mm) Do**	**Diameter D1 (mm)**	**Diameter D2 (mm)**	**Average dia of Flow (mm) Davg**	**Flow (%)**
Mix 1	UHPC	100	329	319	324	224
Mix 2	1% PP + UHPC	100	317	299	308	208
Mix 3	2% PP + UHPC	100	286	301	293.5	193.5
Mix 4	3% PP + UHPC	100	292	291	291.5	191.5
Mix 5	1% PE + UHPC	100	309	311	310	210
Mix 6	2% PE + UHPC	100	278	299	288.5	188.5
Mix 7	3% PE + UHPC	100	273	270	271.5	171.5

The effects of adding polypropylene (PP) and polyethylene (PE) fibers to Ultra-High Performance Concrete (UHPC) are demonstrated by the flow ability test results. A measure of workability called flow ability falls as the fiber content rises from 1% to 3%. From 224% (plain UHPC) to 208% (1% PP), 193.5% (2% PP), and 191.5% (3% PP), the flow ability of PP fibers progressively decreases. Conversely, flow ability is significantly reduced by PE fibers, falling to 120% (1% PE), 188.5% (2% PE), and 171.5% (3% PE).

This disparity demonstrates that PE fibers substantially impair flow ability more than PP fibers, most likely as a result of differences in fiber geometry, surface roughness, or contact with the UHPC matrix. PE fibers' greater stiffness or surface area may more successfully impede the flow of the concrete. In order to balance fiber reinforcement for improved mechanical properties with sufficient workability for real-world applications, these findings are essential for optimizing UHPC mixes. Another noteworthy fact is that the percentage difference between PP and PE fibers is relatively small.

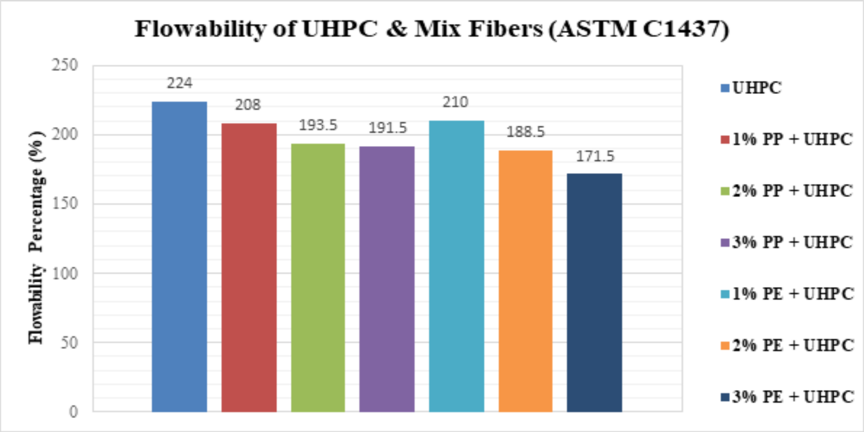
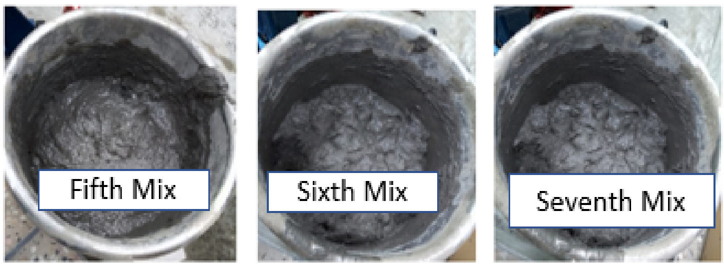


Figure 4.1: Flow ability of UHPC with PP and PE fiber percentages.

4.3 Mechanical Properties

In compression and flexural tests, Ultra-High-Performance Concrete (UHPC) reinforced with polypropylene (PP) and polyethylene (PE) fibers has remarkable mechanical qualities. Because of its dense microstructure and fiber reinforcement, UHPC with these fibers exhibits ultra-high compressive strength in compression testing. Additionally, the fibers improve post-cracking behavior, avoiding abrupt failure. With PE fibers offering more stiffness and load-bearing capability than PP fibers, UHPC exhibits noticeably better flexural strength in flexural testing. As previously mentioned in the literature, both fiber kinds help the material to withstand greater stresses and deformations without failing by increasing its ductility and resistance to cracking. UHPC with PP and PE fibers is perfect for demanding pavement applications because of these qualities. Figure 4.2 illustrates the mixing of materials with fibers. This mixture is then layered three times in molds.

a)Mix 1: 0% PP + 0% PE *b)Mix 2: 1% PP + 0% PE* *c)Mix 3: 2% PP + 0% PE* *d)Mix 4: 3% PP + 0% PE*



e)Mix 5: 0% PP + 1% PE *f)Mix 6: 0% PP + 1% PE* *g)Mix 7: 0% PP + 3% PE*

FIGURE 4.2: Mixes of UHPC.

4.3.1 Properties under Compression Loading

Ultra-high compressive strength is attained by UHPC with PP and PE fibers during compression loading because of its dense matrix and fiber reinforcement. By regulating microcrack propagation, the fibers improve energy absorption, avoid brittle failure, and increase post-cracking ductility. This makes it perfect for challenging pavement applications needing long-term performance and load-bearing capacity since it produces higher resilience and durability under severe stress. The numerical data and graphical representation of the test findings for this mix proportion with UHPC are displayed in figure No. 3, table No. 2 and table No. 2 (a). The findings show the compressive strength (Pmax in kN) of fiber-reinforced UHPC (FR-UHPC) and Ultra-High Performance Concrete (UHPC) cubes with 1%, 2%, and 3% concentrations of polyethylene (PE) and polypropylene (PP) fibers. The maximum strength (376.8 kN) is attained by PP 1%, demonstrating remarkable reinforcing efficiency. Strong baseline performance is shown by UHPC without fibers (220.6 kN). PE 2% (208.3 kN) is the ideal fiber percentage for PE, as it performs better than PE 1% (181 kN) and PE 3% (178.8 kN). Even at larger percentages, PP fibers continuously increase strength, but performance somewhat declines as fiber content rises. These results demonstrate the significance of fiber concentration and type in maximizing compressive strength in FR-UHPC.

Table 4.2: Compression Properties of UHPC and FR-UHPC Cubes under Compression Loadings

Sample (Compression)	σ	**CE**α	**CE**β	**CE**	**CTI**
	MPa	**MJ/m**^{3}	**MJ/m**^{3}	**MJ/m**^{3}	**-**
UHPC	66.6±2.97	0.485±0.02	0.053±0.01	0.538±0.03	1.10±0.01
PE 1%	27.7±2.14	0.364±0.1	2.549±0.52	2.913±0.62	8.06±0.53
PE 2%	48.0±3.14	0.988±0.02	3.375±0.37	4.364±0.39	4.41±0.31
PE 3%	34.9±1.19	0.433±0.17	2.541±0.67	2.973±0.5	8.19±0.96
PP 1%	75.8±2.78	0.548±0.01	2.190±0.43	2.738±0.45	4.98±0.71
PP 2%	42.3±2.88	1.130±0.10	2.990±1.31	4.021±1.21	4.05±1.56
PP 3%	28.1±4.2	1.03±0.132	1.21±0.401	2.25±0.268	2.24±0.54

According to the cube testing findings from figure 4.3, Ultra-High Performance Concrete (UHPC) and fiber-reinforced UHPC (FR-UHPC) with polyethylene (PE) and polypropylene (PP) fibers at 1%, 2%, and 3% concentrations have compressive strengths. High strength (66.6 MPa) is demonstrated by UHPC without fibers. The maximum strength (75.8 MPa) is attained by PP 1%, demonstrating efficient fiber reinforcing. At larger fiber percentages, however, PP performs worse. PE 2% exhibits a notable increase (48 MPa), but decreases at 3% (34.9 MPa), indicating that the ideal fiber content is essential. Although adding fiber generally increases compressive strength, too much fiber can degrade the matrix, underscoring the significance of balanced fiber-polymer interactions for the best mechanical performance. The efficiency of 1% polypropylene fibers in reinforcing UHPC is demonstrated by the maximum compressive strength of 75.8 MPa attained by PP 1%. The lowest strength, 28.1 MPs, is found in PP 3%, suggesting that too much fiber might weaken the matrix. By preventing micro cracks, PP fibers frequently increase strength at low dosages ($\leq$1%) [74], but at higher dosages ($\geq$2%), they create voids, which weakens the fiber [75].

4.3.2 Properties under Flexural Loading

UHPC with PP and PE fibers exhibits enhanced toughness and high flexural strength under flexural loading. By bridging microcracks, the fibers improve crack resistance and slow down their spread. While PP fibers aid in ductility, PE fibers

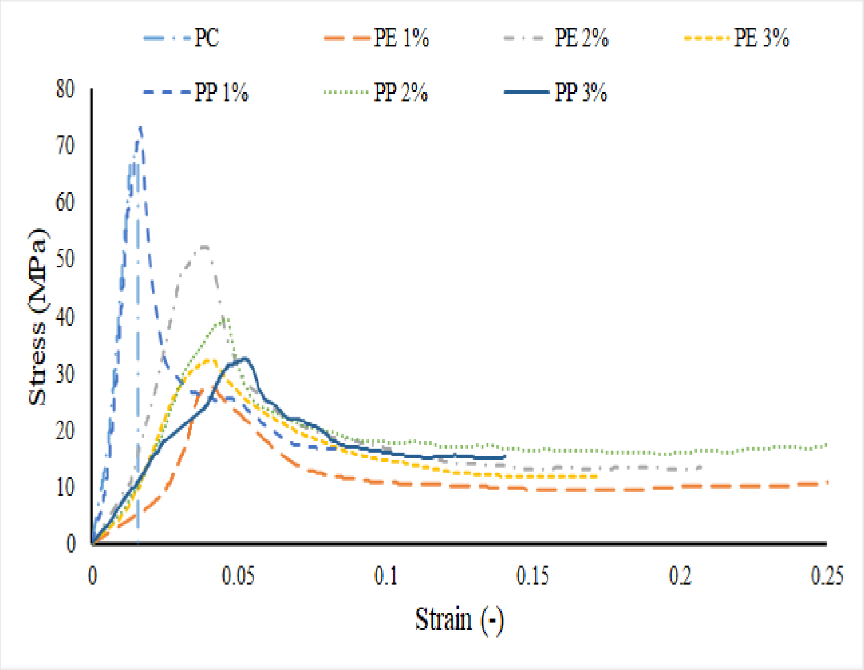


Figure 4.3: Stress-Strain Graphs of UHPC and FR-UHPC Cubes under Compression Loadings

in particular offer greater stiffness and load-bearing capacity. This prevents abrupt failure by increasing energy absorption, decreasing deflection, and increasing post-cracking ductility. Because of these characteristics, UHPC with PP and PE fibers is very useful for pavement applications, guaranteeing performance and durability under flexural forces.

The findings show the flexural strength (MPa) of fiber-reinforced composites with different fiber percentages (1%, 2%, and 3%), such as UHPC, PE, and PP. At 1.6 MPa, UHPC has the highest baseline strength when fiber reinforcing is absent. Although it gradually declines at higher fiber concentrations, PP exhibits the greatest improvement with fiber addition, peaking at 1.91 MPa at 1% fiber. With strength rising to 1.5 MPa at 2% fiber and falling to 1.3 MPa at 3% fiber, PE exhibits a non-linear pattern that may indicate poor dispersion or fiber-matrix incompatibility at higher percentages 1% gives 1MPa, 2% gives 1.2 MPa & 3% gives lowest 0.85 MPa. Although fiber reinforcement generally increases flexural strength, the type, concentration, and interaction of the fiber with the polymer matrix determine the best results. In order to achieve the appropriate mechanical qualities, our results emphasize the need of customized fiber-polymer combinations. Effective fiber reinforcement is demonstrated by the greatest flexural strength of 1.91 MPa is illustrated in figure 4.4, which is attained by PP with 1% fiber, which shows the best results. Without fibers, UHPC retains a good baseline performance. PE decreases at 3% fiber but peaks at 2% fiber (0.85 MPa), indicating that the ideal fiber concentration is essential for optimizing mechanical characteristics. The post-crack ductility of UHPC with PE and PP fibers is assessed using the Flexural Toughness Index (FTI). Toughness is increased by adding fibers; PE 3% performed best but had the largest variability, with the highest FTI (1.280.12). Toughness is substantially increased by PP fibers; PP 2% (1.10±0.05) outperforms PP 1% and 3%. More consistent results are indicated by lower PE 1-2% and PP 1% standard deviations.

TABLE 4.3: Flexural Properties of UHPC and FR-UHPC Beams under Flexural Loadings

Sample (Flexural)	**MOR (MPa)**	**FEα (MJ/m^3)**	**FEβ (MJ/m^3)**	**FE (MJ/m^3)**	**FTI (-)**
UHPC	1.6±0.3	1.466±0.05	0.044±0.01	1.510±0.05	1.03±0.01
PE 1%	1.0±0.04	0.656±0.27	0.036	0.692±0.29	1.05±0.01
PE 2%	1.2±0.04	1.154±0.25	0.097±0.01	1.251±0.26	1.08±0.01
PE 3%	0.85±0.07	0.256±0.08	0.067±0.04	0.332±0.04	1.28±0.12
PP 1%	1.91±0.07	2.561±0.25	0.066±0.01	2.720±0.15	1.02±0.01
PP 2%	1.5±0.08	1.446±0.02	0.152±0.09	1.598±0.31	1.10±0.05
PP 3%	1.3±0.21	1.497±0.5	0.116±0.04	1.613±0.6	1.08±0.03

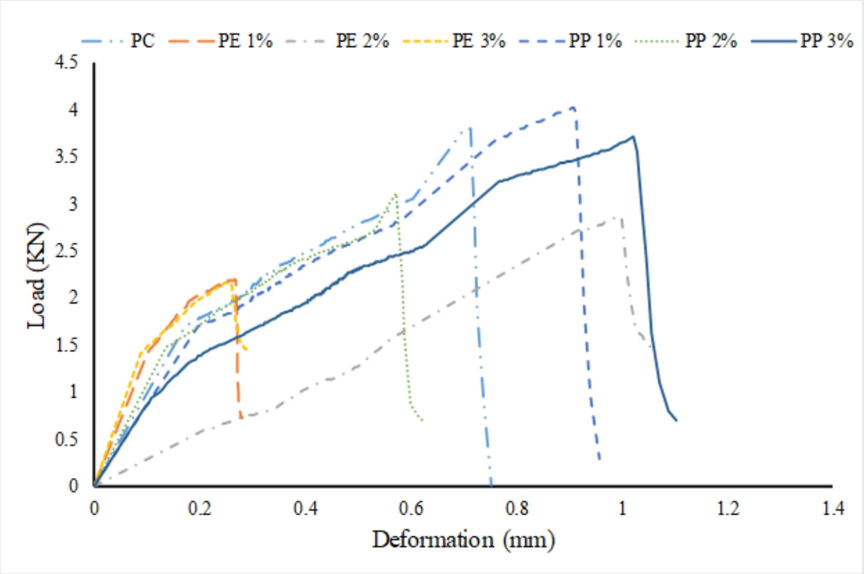


FIGURE 4.4: Stress-Strain Graphs of UHPC and FR-UHPC Beams under Flexural Loadings

4.4 Surface Texture Performance Evaluation Testing

Surface texture performance testing includes shrinkage and skid resistance to evaluate riding quality and performance of texture in rigid pavement performance when traffic pass through it.

4.4.1 Shrinkage

When polypropylene (PP) and polyethylene (PE) fibers are added to Ultra-High-Performance Concrete (UHPC), shrinkage is significantly reduced compared to conventional concrete. The dense, low-porosity matrix of UHPC prevents moisture loss, and the fibers serve as internal reinforcements, effectively restraining stresses caused by shrinkage. PP fibers are especially good at controlling early-stage plastic shrinkage, which prevents surface cracking during the initial curing phase. PE fibers, on the other hand, help reduce long-term drying shrinkage by increasing the material's tensile capacity and crack resistance. According to the results of the shrinkage test, adding 1% polypropylene (PP) fibers to UHPC lowers shrinkage from 0.208% (plain UHPC) to 0.189%. Shrinkage increases marginally to 0.192% when textured PP fibers are used, indicating that fiber texture has a negligible impact on shrinkage behavior is shown in figure 4.5 results. Overall, by preventing cracks from forming and strengthening internal bonding, PP fibers successfully reduce shrinking. This indicates their potential to enhance the dimensional stability and endurance of UHPC in real-world applications.

TABLE 4.4: Shrinkage results

Shrinkage Measurement ASTM C157 (Oven Dry)							
Type of Fiber/-paste	**Fiber Content**	**Time (Days)**	**Temperature (Degree Centigrade)**	**Shape & Size (mm)**	**Length Change (mm)**	**Total Shrinkage at 28 days (mm)**	**Shrinkage Reduction (%)**
UHPC (Plain)	0%	0	0	100x150	0	0.316	0.208
		7	110 ± 5 C		0.155		
		28	110 ± 5 C		0.316		
UHPC + 1% PP	1%	0	0	100x150	0	0.287	0.189
		7	110 ± 5 C		0.181		
		28	110 ± 5 C		0.287		
UHPC + 1% PP (With Texture)	1%	0	0	100x150	0	0.292	0.192
		7	110 ± 5 C		0.178		
		28	110 ± 5 C		0.292		

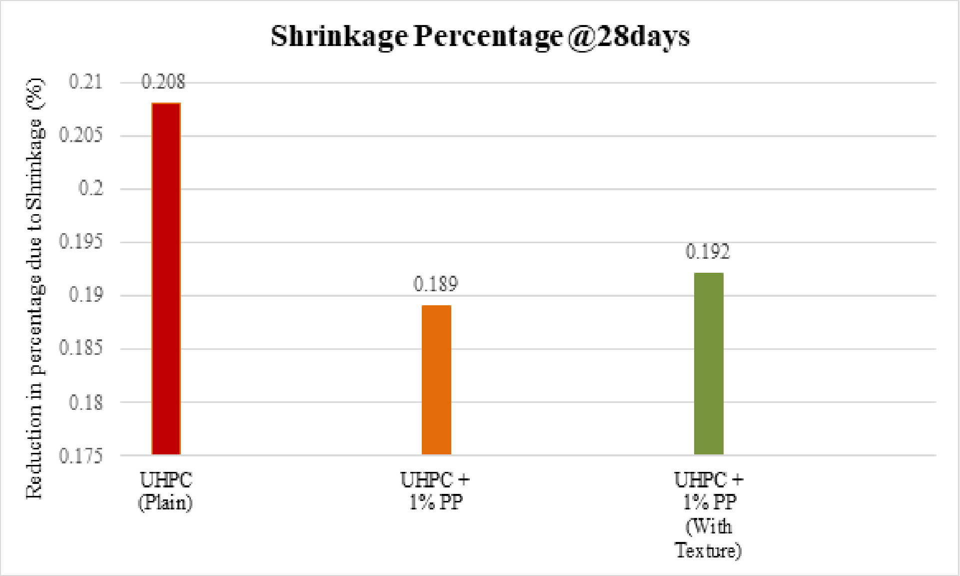


FIGURE 4.5: Shrinkage Results

4.4.2 Skid Resistance (British Pendulum Number)

The British Pendulum Number (BPN), which measures skid resistance, is an essential part of pavement safety. Because of its consistent and thick surface texturewhich can be further enhanced by finishing techniquesUHPC with PP and PE fibers usually shows favorable BPN values. According to studies, UHPC pavements provide sufficient friction for car tires by achieving BPN values well above the minimal safety requirements. As extensively covered in the literature, the use of fibers improves surface durability and maintains skid resistance over time by lowering surface wear and traffic-induced polishing effects and must lies within the Transportation Road Research Laboratory (TRRL) BPT range. Figure 4.6 shows the findings of skid resistance. For high-traffic regions, where consistent skid resistance is crucial for averting accidents and guaranteeing driver safety, UHPC with PP and PE fibers is a dependable option.

Reduced skid resistance is implied by lower BPN values, which could have an impact on applications where safety and surface texture are essential. According to the findings, the BPN drops from 63 (plain UHPC paste) to 58 when 1% polypropylene (PP) fibers are added to UHPC paste. The BPN further decreases to 57 when textured PP fibers are utilized. It implies that PP fibers, particularly textured ones, create a smoother surface, perhaps as a result of different fiber distribution or paste texture. Although safety will be somewhat jeopardized as BPN falls from 63 to 57, it is still within acceptable bounds. Resistance and grip would increase with a higher BPN, and vice versa. Therefore, it is advised to use paste PP with UHPC (without texture) while monitoring all outcomes.

TABLE 4.5: Skid Resistance results

Results of Skid Resistance (ASTM E303)							
Number	**Material**	**Distance from sides (in)**	**Surface Texture**	**Surface Temperature**	**Avg. BPN**	**Correction**	**BPN**
1	UHPC (Paste)	4"	Paste Top	27 5	60	(+) 1	61
2		4"	Paste Middle	27 5	61	(+) 1	62
3		4"	Paste End	27 5	65	(+) 1	66
							63
1	1% PP + UHPC (Paste)	4"	Paste Top	27 5	59	(+) 1	59
2		4"	Paste Middle	27 5	56	(+) 1	56
3		4"	Paste End	27 5	58	(+) 1	58
							58
1	1% PP + UHPC (Texture Paste)	4"	Paste Top	27 5	56	(+) 1	57
2		4"	Paste Middle	27 5	58	(+) 1	59
3		4"	Paste End	27 5	54	(+) 1	55
							57

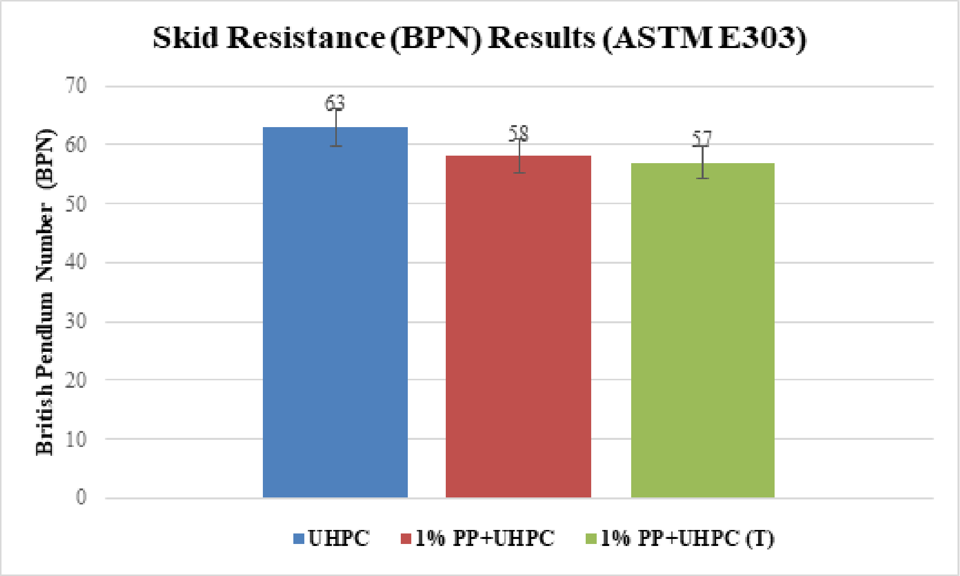


FIGURE 4.6: Skid Resistance Results

The Transportation Road Research Laboratory (TRRL) offers BPT results with minimum requirements illustrated in figure 4.7. Tools on motorway freight exceed

Table 4.6: Minimum number of skid resistance using BPT [76].

Category	**Location Type**	**Minimum Skid Resistance**
A	Tough locations such as: Roundabout; radius of bend ¡ 150m on the highway; slope of 1:20 or steeper, with length ¿100m; designated intersection arm on the highway.	65
B	Main/fast roads, continuous roads and first class roads and heavy urban roads (¿2000 vehicles per day)	55
C	Other locations	45

Note: For Category A and B locations where vehicle speeds exceed 95 km/h, a minimum texture depth of 0.65 mm is also required.

or equal 55 BPN for more than 2,000 vehicles per day [73]. Additionally, this complies with the TRRL (1989) standards, as seen in figure 4.7. The test's surface temperature is 27C. The concrete mix with all of the fiber mix and texture variations has met the requirements, according to the results of the skid resistance test. Increases in BPN values of 63%, 58%, and 57% of fiber-reinforced UHPC suggest that this material contributes favorably to increased skid resistance as the rigid pavement's surface layer.

4.5 Recommendations based on results

The presented table critically evaluates the performance of various UHPC mixes for rigid pavement overlay applications. While fiber incorporation generally reduces flowability, UHPC with 1% PP fibers demonstrates superior compressive (75.8 MPa) and flexural (1.91 MPa) strengths, making it ideal for high-strength requirements. Conversely, PE fibers, particularly 1% PE and 3% PE, excel in enhancing toughness (CTI and FTI), indicating improved energy absorption and crack resistance. Although comprehensive data for skid resistance and shrinkage is limited for all mixes, PE 1% shows promising results in these serviceability aspects. This comparative analysis underscores that optimal mix selection depends on balancing these diverse performance criteria, as different fiber types contribute distinct benefits to UHPC in pavement overlays.

Table 4.7: Summary of Key Performance Indicators for Various UHPC Mixes

Mix Type	**Flowability (%)**	**Compressive Strength (MPa)**	**MOR**	**CTI**	**FTI**	**Skid Resistance (BPN)**	**Shrinkage (%)**
UHPC	224	66.6 ± 2.97	1.6 ± 0.3	1.10 ± 0.01	1.03 ± 0.01	63	0.208
PE 1%	210	27.7 ± 2.14	1.0 ± 0.04	8.06 ± 0.53	1.05 ± 0.01	58	0.189
PE 2%	188.5	48.0 ± 3.14	1.2 ± 0.04	4.41 ± 0.31	1.08 ± 0.01	–	–
PE 3%	171.5	34.9 ± 1.19	0.85 ± 0.07	8.19 ± 0.96	1.28 ± 0.12	–	–
PP 1%	**208**	**75.8 ± 2.78**	**1.91 ± 0.07**	**4.98 ± 0.71**	**1.02 ± 0.01**	**–**	**–**
PP 2%	193.5	42.3 ± 2.88	1.5 ± 0.08	4.05 ± 1.56	1.10 ± 0.05	–	–
PP 3%	191.5	28.1 ± 4.2	1.3 ± 0.21	2.24 ± 0.54	1.08 ± 0.03	–	–

4.6 Summary

This study examines the mechanical, durability, and surface characteristics of Ultra-High-Performance Concrete (UHPC) reinforced with polypropylene (PP) and polyethylene (PE) fibers for pavement applications. Under compression loading, UHPC exhibits high ultra-high compressive strength, which is attributed to its dense microstructure and fiber reinforcement, which also enhances post-cracking ductility and energy absorption. Flexural testing reveals superior flexural strength and toughness, with PE fibers contributing to ductility and PP fibers providing higher stiffness, ensuring resistance to cracking and deformation. Shrinkage is significantly reduced, as PP fibers regulate plastic shrinkage and PE fibers mitigate long-term drying shrinkage, improving dimensional stability and minimizing crack formation.

These results collectively show that UHPC with PP and PE fibers is a highly recommendable, safe, and mechanically robust material for pavement applications, though cost and fiber dispersion challenges require further research for widespread adoption. Surface performance evaluations, including skid resistance measured by the British Pendulum Number (BPN), confirm that UHPC pavements meet safety standards, maintaining high friction levels under traffic as per TRRL standards.

Chapter 5

Conclusions and Recommendations

Polypropylene (PP) and polyethylene (PE) fibers are used in Ultra-High Performance Concrete (UHPC), which has been shown to have great promise for use in pavement applications. According to previous studies and this research, these fibers improve load distribution and reduce crack propagation, which improves mechanical qualities including tensile strength and durability. While PE fibers add to tensile strain capacity and ductility, PP fibers are especially good at minimizing shrinking. Better resistance to deformation and cracking under high traffic loads is ensured by this combination. Additionally, UHPC is appropriate for high-performance pavements due to its enhanced skid resistance with these fibers. In order to balance workability and mechanical performance and guarantee the material's efficacy in rigid pavement applications, researchers have also investigated the ideal fiber content and mix design. When combined, these characteristics make UHPC with PP and PE fibers an excellent option for building rigid pavements. This fiber-reinforced UHPC mix proves to be an excellent high-performing material for contemporary infrastructure requirements, especially in the field of pavement engineering, by guaranteeing structural integrity, long-term durability, and less maintenance.

5.1 Conclusions

According to the results, UHPC with 1% PP fibers is the best option for rigid pavements since it meets Transportation Road Research Laboratory (TRRL) requirements for excellent compressive and flexural strength, minimal shrinkage, and acceptable skid resistance. Performance and durability are guaranteed by the way its qualities are balanced. The specific results of this study include:

1. When fibers are added, UHPC's flowability declines, as shown by the lower values when compared to plain UHPC (224% flow). The flowability of polypropylene (PP) fibers is less affected; at 1% PP, the flow is comparatively higher (208%), but it decreases at increasing concentrations (191.5% at 3%). The effects of polyethylene (PE) fibers are more noticeable; 2% PE reduces flowability to 188.5%, while 3% PE further reduces it to 171.5%. Typically, the strength of the binding mix increases as flowability diminishes. In order to balance flowability and mechanical performance, the ideal fiber concentration is essential.

2. The results of Cubes Compression tests show that polypropylene (PP) fibers at 1% had the maximum compressive strength (75.8 MPa), indicating its effectiveness as reinforcing material. Baseline performance for UHPC without fibers is strong (66.6 MPa). Strength decreases at 3% (34.9 MPa), despite the fact that polyethylene (PE) fibers work best at 2% (48 MPa). The matrix is weakened by excessive fiber content, such as PP 3% (28.1 MPa), underscoring the importance of optimal fiber concentrations in improving the mechanical performance of fiber-reinforced UHPC in pavement applications.

3. The results demonstrate appropriate reinforcing, with polypropylene (PP) fibers at 1% achieving the maximum flexural strength (1.91 MPa). Without fibers, UHPC exhibits a strong baseline of 1.6 MPa. The strength of polyethylene (PE) fibers decreases at 3% (0.85 MPa), showing poor fiber-matrix compatibility at higher percentages. PE fibers perform best at 2%

(1.2 MPa). Efficiency is decreased by excessive fiber concentrations, highlighting the necessity of specialized fiber-polymer combinations. These findings highlight how crucial it is to choose the right fiber kinds and concentrations in order to maximize mechanical performance.

4. According to the shrinkage results, the most significant shrinkage decrease (0.208%) is attained by Ultra-High Performance Concrete (UHPC). The shrinkage reduction drops to 0.189% when 1% polypropylene (PP) fibers are added, suggesting that fiber inclusion influences shrinkage performance. Textured PP fibers reduce shrinkage by 0.192%, indicating that improved fiber-matrix bonding lessens the adverse effects of fiber addition. These results show that although fibers can affect shrinkage, the key to attaining the appropriate balance of shrinkage reduction in UHPC blends is to optimize fiber surface textures and interactions.

5. According to the results, all of the tested materialsUHPC (63 BPN), UHPC + 1% PP fibers without texture (58 BPN), and UHPC + 1% PP fibers with texture (57 BPN)fall well within the Transportation Road Research Laboratory's (TRRL) minimum skid resistance standards for road pavements, indicating their suitability for pavement applications and guaranteeing safety and durability under traffic loads. While plain UHPC offers the highest skid resistance, the addition of fibers slightly lowers it but still manageable, confirming its usefulness for use.

The extensive testing suggests that UHPC containing 1% polypropylene (PP) fibers is ideal for applications involving rigid pavement. It performs exceptionally well in all important areas, meeting or above required standards in compressive and flexural strength, shrinkage reduction, and skid resistance. Even though fiber inclusion somewhat lessens skid resistance, it nevertheless complies with Transportation Road Research Laboratory (TRRL) requirements, guaranteeing both functioning and safety. For long-lasting, high-performance rigid pavements, the optimal 1% PP fiber concentration improves mechanical qualities without sacrificing flowability or durability.

5.2 Recommendations

For rigid pavement applications, UHPC with 1% polypropylene (PP) fibers is highly recommended based on the results of the testing. This material has exceptional flexural and compressive strength, which reduces cracking and ensures resistance to large loads. Using textured PP fibers can enhance bonding and reduce shrinking. When long-term durability and low maintenance are needed, this material is perfect for industrial pavements, bridges, and busy highways. Overall, UHPC with 1% PP fibers provides an affordable and environmentally friendly answer to the demands faced by modern infrastructure.

5.3 Future Work

Future research on UHPC with 1% polypropylene (PP) fibers for rigid pavements could concentrate on the following areas:

1. Assess long-term performance under harsh environmental conditions, such as high temperatures, salt exposure, and freeze-thaw cycles;
2. Examine various fiber lengths, surface treatments, and combinations of PP with other fibers to further improve performance;
3. Investigate advanced surface treatments to improve skid resistance without compromising other mechanical properties;
4. Evaluate the environmental impact and optimize mix designs to reduce carbon footprint and promote recyclability;
5. Carry out extensive field testing to validate lab results and investigate real-world challenges.

These suggestions can help improve the material's practical utility and refine its application.

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