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Article

Mechanical Performance of Asphalt Mixtures Reinforced with Polypropylene Fibers

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Abstract

Plastic waste is a new environmental threat and potential resource at the same time. The use of plastic waste polymer polypropylene fibers in asphalt mixtures is a good eco-solution that increases the pavement's lifetime. With traffic rising, forcing the needs in classic asphalt for improved durability. The study aimed to investigate the reinforcement characteristics of plastic fibers of four different lengths in cm (FL1, FL2, FL3, and FL4), represented by 1 cm, 2 cm, 3 cm, and 4 cm, added to virgin asphalt mixtures (0.3% by total mix). Results by Marshall stability, Marshall stiffness, indirect tensile strength (ITS), moisture susceptibility (TSR), and deformation strength testing were quantified. The results showed that the stability of Marshall increased until the FL3 length, with FL1 and FL2 showing 23% and 10% enhancement, respectively, followed by a marginal decrease to FL4 as plastic fiber was introduced. Additionally, the moisture resistance improved with the fiber length, and the TSR values were significantly higher than that of the virgin mix. Regarding rutting resistance, fiber reinforcements greatly lowered deformation, most especially when fiber lengths were shorter. Generally, durability, moisture damage resistance, and rutting resistance are enhanced on a scale of 1–2 cm fiber length, hence being the most convenient quality for asphalt mixtures. In this research, the optimum length of PP fiber was specified to improve mechanical properties, and plastic waste was reused as a resource for sustainable road construction, both in accordance with SDG 9 and SDG 12 of the Sustainable Development Goals.

Keywords: Plastic fiber; Reinforcement asphalt mixtures; Fiber length; Performance tests; Marshall Stability.

1. Introduction

As the demand for eco-friendly and long-lasting pavement materials rises, the interest in fiber-reinforced asphalt pavement mixtures has increased. Plastic fiber, especially fibers made from recycled materials, is one of the promising additives among different fiber types used to promote the structural and ecological improvement of asphalt mixes [1], [2], [3]. Plastic fiber reinforcement enhances tensile strength, resists deformation, and enhances resistance to cracking and moisture damage [4]. These improvements are attributable to fibers bridging microcracks and distributing stresses more uniformly during traffic loading [5]. Moreover, the plastic waste in asphalt blends contributes to circular economy

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practices by diverting non-biodegradable materials from landfills [6]. Natural, synthetic, and recycled fibers are being increasingly used in asphalt blends, as these fibers improve the mechanical characteristics of the mixes [7].

Recent technological progress in pavement engineering has accentuated interest in incorporating recycled polymer materials in asphalt blends, aimed at achieving enhanced performance and sustainability. For example, the Performance Evaluation of Post-Consumer and Post-Industrial Recycled Plastics as Binder Modifier in Asphalt Mixes found that adding low-melting-point recycled plastics—including polyolefins such as polyethylene and polypropylene—into bitumen using the wet method can greatly improve asphalt concretes' cracking and rutting resistance [8]. Meanwhile, performance enhancement of the asphalt mixture through the addition of recycled polymer materials (2024) proved polymer waste (e.g., PVC, polystyrene) integrated into hot-mix asphalt resulted in increased softening point of the binder and lower penetration, suggesting increased resistance to temperature fluctuation and deformation [9]. Nowadays, in the thermochemical and microstructural assessment of polypropylene-modified asphalt concrete for sustainable pavement applications (2025), the thermal, rheological, and microstructural performances of bitumen modified with polypropylene in a wet process were analyzed, showing that the addition of PP increases the thermal and mechanical stability of asphalt mixtures, further supporting the applicability of PP as a modifier [10].

Current investigations also have identified modern techniques for assessing the fracture behavior of asphalt mixtures, especially under intermediate-temperature conditions. Hesham Akram et al. (2024) compared the semicircular bending (SCB) and Indirect Tensile Asphalt Cracking Test (IDEAL-CT) for asphalt mixtures reinforced with polypropylene fibers. The work established easier specimen preparation and lower variation than SCB using IDEAL-CT, and also the two tests showed a significant relationship between flexibility and cracking resistance indices ($R^2 = 0.86$ and 0.84). Polypropylene fibers were particularly suitable, contributing to improved fracture parameters in the asphalt mixing process, supporting the assertion that fiber reinforcement will yield better crack resistance properties and increased stiffness. This provides methodological directions for laboratories to use polymer fibers for the reinforcement of asphalt [11].

Recent research has demonstrated the importance of polypropylene fibers (PPF) to improve pavement properties. Another study researched the PPF (0%–2% PPF) in concrete mixes with FRAP (Fine Reclaimed Asphalt Pavement) partially replacing the fine aggregate. The addition of 2% PPF provided a 30–40% increase in tensile and flexural properties; improved ductility and post-cracking activity facilitated by the fiber bridging; and suppressed the water absorption and abrasion. Microstructure studies revealed denser interfacial zones with better C–S–H gel creation that support polypropylene fibers, providing concrete reinforcement with durable, sustainable, and economical pavement solutions [12].

The research investigates the influence of polypropylene (PP) fibers on the fracture stiffness and pre-cracking behavior of asphalt mixtures. Three PP fiber content levels (0.5%, 1%, and 1.5%) of each composite material type have been studied under short beam bending (SBB) geometry at lower (-18°C) and intermediate (+25°C) temperatures. The results indicated high improvement of elastic deformation resistance, fracture stiffness, and tensile strength with the incorporation of PP fibers and that 1% fiber content exhibited the highest performance. A comparison of two mixing techniques—Sequential Mixing Process (SMP) and Traditional Dry Mixing Process (TDMP)—revealed the SMP using 1% PP had the best deformation resistance pre- and post-cracking. Statistical analyses confirmed a strong relationship between tensile strength indexes and fracture stiffness indexes, indicating that PP fibers improve the pre-cracking strength, stiffness, and durability of asphalt mixtures [13].

While sustainable asphalt technologies have increased, a trial on waste LDPE as a binder modifier and crushed glass as an aggregate replacement in hot mix asphalt (HMA) was conducted. The addition of 4% LDPE and 10% glass increased the resilient modulus by 78% and the moisture resistance by 17%, indicating enhanced stiffness and durability. Examination of a highway section on the ground reported decreases in bitumen consumption, natural aggregate demand, construction costs, and CO_2 emissions and a significant diversion of waste from landfills. It has emerged that the resulting polymer-modified asphalt mixes (PP/other plastic) may at once have a possible mechanical performance enhancement and contribute towards the green initiatives and environmental sustainability along with reaching SDGs 9, 11, and 12 of sustainable infrastructure [14].

A technique was established, and the adhesion in terms of direct tensile strength of plastic fiber-reinforced hot-mix asphalt combinations indicated that plastic fibers contributed around 25.5% to the mixture's resistance against tensile failure [15], [16]. Recycled polyethylene terephthalate (PET) fibers, used in proportions of 0.3%, 0.5%, 0.7%, and 1.0% of the total asphalt weight in the concrete mixture, provide a sustainable reinforcement strategy. The use of these recycled fibers markedly enhanced the robust modulus of the mixes. The maximum improvement in mechanical strength was seen at a fiber level of 0.7%, demonstrating its efficacy in augmenting the structural performance of asphalt concrete [17]. Recycled PET fiber enhances the performance of asphalt concrete mixtures by increasing fatigue resistance, resilience modulus, and rutting resistance [16]. The characteristics of asphalt pavement were enhanced with the use of high-density polyethylene (HDPE) plastic waste [18]. Integrating fibers into asphalt mixes promotes environmental sustainability and provides economic benefits [6], [7]. ITS testing was used to investigate the effects of both short- and long-term aging on glass fiber (GF)-reinforced asphalt mixtures. Two lengths of glass fibers (6 and 12 mm) were added to the mixture at mass fractions of 0.3% and 0.6%. While GF reinforcing improves strength, rutting resistance, and moisture endurance [19], it also results in greater initial construction costs than unreinforced mixes [4].

In order to assess the effects of adding two types of fibers steel and polypropylene fibers on the performance of asphalt mixture grade (40–50), stability and indirect tensile strength tests were performed on four different percentages of each type of fiber. According to the findings, mixing 0.1% polypropylene fiber with 0.3% steel fiber improves flow and stability by 34.9% and 67.7%, respectively, while significantly lowering temperature susceptibility [20]. Because of their high flexibility, low density, and low absorption rate, synthetic fibers like polypropylene are ideal for use in dense asphalt mixes [7]. The behavior of fiber-reinforced asphalt mixtures is largely dependent on the kind, quantity, and length of the fibers [21]. By adding two waste percentages of plastic fiber (0.5% and 1% by total weight of mix) to hot mix asphalt, the optimum was found to be 0.5%; this percentage improved the cracking resistances, and rutting had a positive influence on the environment by the recycling of discarded waste plastic [22]. Testing at 20°C reveals that fibers play an important role in enhancing the stiffness modulus and fracture toughness of asphalt mixtures. They offer a modest improvement in the fatigue life of fiber-reinforced asphalt combinations, particularly at low strain levels. Among the fibers tested, steel fibers demonstrated the greatest enhancement in indirect tensile strength [23]. Bamboo fiber, an eco-friendly, affordable, and renewable material, enhances asphalt mixtures by increasing molecular crosslinking, slightly improving high-temperature stability, reducing temperature sensitivity, and forming a three-dimensional network that delays major crack formation [24].

A mix of aramid fibers and synthetic polyolefin for HMA applications was found to improve resistance to rutting and fatigue cracking. As fiber-reinforced asphalt concrete pavement (FR-AC) performed similarly in both laboratory and plant mixes, lab mix design results can reliably predict field performance [25]; using a fiber-reinforced mixture was found to be the most economical [25], [26]. Recommended incorporation of basalt fiber (BF) 0.2–0.4% into asphalt mixtures, with a focus on fiber properties, dosage levels, blending methods, mixture characteristics, and surface modification techniques, reveals that adding basalt fibers to asphalt mixes using the dry method enhances cracking, rutting, and fatigue resistance while also reducing costs and extending pavement service life. [26]. Cracking is a common issue in asphalt pavement due to its low tensile strength. Synthetic fibers enhance tensile strength and reduce cracking risk, with longer fibers improving crack-bridging potential. Aramid fibers of about 20 mm provide good bonding and dispersion in fiber-reinforced asphalt concrete, though care is needed to prevent uneven distribution [27]. Research of several aramid fiber kinds, lengths, and doses in dense-graded asphalt mixes discovered that performance varied with fiber attributes. When compared to unreinforced mixes, fiber-reinforced ones demonstrated better resilience to rutting and dampness. Using aramid fibers decreased building costs by 27–37%, according to a cost study [28].

While there has been a proliferation of studies on plastic-modified binders and recycled polymer-asphalt blends, there are few articles that have systematically investigated the impact of fiber geometry, in particular fiber length, on asphalt mixture performance. However, most of the studies to date have varied the quantity or type of plastic content, and we are unable to isolate fiber length as a distinct parameter in our work study area.

The test matrix included in the present study was developed to ensure that the conclusions made will be derived from an evaluation of the mechanical response to be obtained from a polypropylene–fiber-reinforced asphalt mixture, which includes a cross-section of the available literature. Four lengths of fiber (1, 2, 3, and 4 cm) were selected at a constant dose of 0.3% by total weight of the mixture to allow isolation of the effect of length as the independent variable, while avoiding the potential impact of fiber content. The controlled method guarantees that trends in performance can be solely traced toward fiber geometry. The matrix contained several complementary performance tests: Marshall stability and flow, Marshall stiffness, indirect tensile strength (ITS), tensile strength ratio (TSR), and deformation strength (rutting resistance), allowing strength, stiffness, moisture susceptibility, and permanent deformation to be encapsulated. These tests were selected because they are well-known standards for assessing hot-mix asphalt performance and together offer a solid insight into how fiber reinforcement affects the behavior of a mixture. By confirming all properties through more than one performance indicator, the addition of both strength tests and durability tests has led to the credibility of the reported findings. Hence, the test matrix that was implemented is sufficiently exhaustive to support the validity and generalization of our conclusion.

The most typical fiber dose in asphalt mixtures is 0.3% by aggregate weight. Performance at high and low temperatures is greatly improved by fiber integration [7], [29], [30]. The benefits of adding 0.3% Polypropylene (PP) as Plastic Fiber Reinforcement (PFR) by total aggregate weight to asphalt mixes at four various lengths (1, 2, 3, and 4 cm) are examined in this study with an emphasis on strength, durability, deformation resistance, and enhanced functionality.

It should be noted that this study considered a single fiber content (0.3%) in order to isolate the effect of fiber length. While this approach allows clear interpretation of fiber geometry influence, it may limit the generalizability of the findings. Although from previous research of literature review and practical applications: typical fiber content range is 0.1% – 0.5% by total mix weight, and most commonly reported "optimum" values: ≈0.2% – 0.3%.

2. Contribution and Novelty

This investigation adds to the body of knowledge by methodically determining the ideal polypropylene fiber length for maximum Marshall stability, tensile strength, rutting resistance, and moisture damage resistance. Unlike previous research, this study evaluates fiber length effects using a comprehensive performance matrix, including Marshall properties, ITS, TSR, and deformation strength tests. Additionally, the research demonstrates the effective reuse of waste PP fibers, contributing directly to the Sustainable Development Goals (SDG 9: Industry, Innovation, and Infrastructure; SDG 12: Responsible Consumption and Production).

3. Methodology and research objectives

Figure 1 illustrates the techniques used to accomplish the research goals. Different lengths of waste PP were incorporated, and its effects on the mechanical and durability characteristics of asphalt mixtures were assessed using various tests, such as the Marshall test, indirect tensile strength at 25°C and 60°C, moisture sensitivity (durability), and deformation strength in the Kim test at 60°C. The findings were subsequently compared to those of the reference mixtures. The total number of samples used in this research was 115 samples, as this number represents 15 samples to find the optimum asphalt content and 5 samples for each of the performance tests.

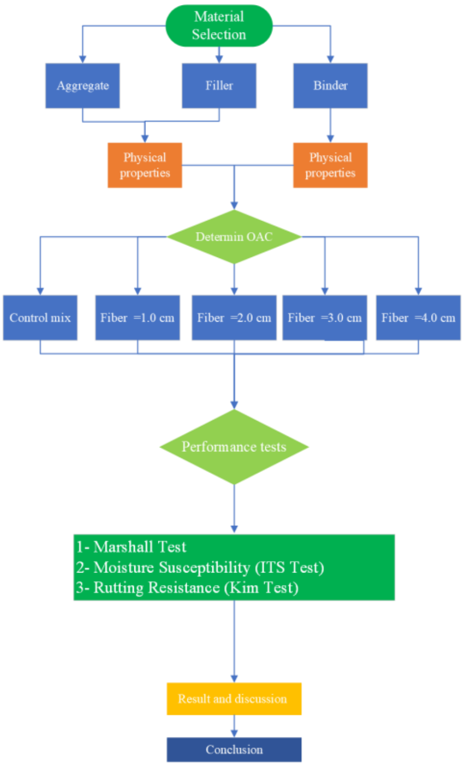

Figure 1. Flow chart for current study

The test matrix used in this study is adequate for evaluating fiber effects, as it incorporates all major pavement performance parameters. The number of samples, exceeding ASTM minimum requirements and ensuring statistical confidence. The variables were controlled such that fiber length was the only changing parameter, allowing direct assessment of its influence on mixture behavior.

The chosen fiber lengths (1–4 cm) surpass typical research standards to specifically evaluate how extended geometries affect crack-bridging and load transfer. While shorter fibers favor ease of dispersion, longer fibers can enhance mechanical interlocking. Thus, this study seeks to optimize the trade-off between fiber length and uniform distribution within the practical constraints of field application and mixing.

4. Materials and Procedures

4.1. Materials

The main materials employed in this research were locally accessible aggregates, filler, asphalt, and plastic fiber reinforcement. The use of virgin bitumen with a penetration grade between 40 and 50, which is often used in road building projects within the Duhok Governorate and the Kurdistan area, was the exploratory framework of this study. The physical characteristics of binder, including penetration, ductility, and softening point, were evaluated and compared against SCRB and ASTM standards, with detailed results summarized in Table 1.

A single source of binder, Al-Daurah asphalt cement from Baghdad (50/60 penetration grade) with a specific gravity of 1.03 g/cm³, was utilized for all asphalt mixtures in this research. To characterize the binder, a series of standardized tests were performed, including penetration (ASTM D-5) [25], softening point (ASTM D-36) [26], flash point (ASTM D-92) [27], rotational viscosity (ASTM D-4402) [28], and ductility (ASTM D-113) [29]. The comprehensive physical properties of the asphalt are summarized in Table 1.

Table 1. Physical properties of Virgin Bitumen

Characteristics	Result	Unit	SCRB	ASTM
Penetration	**45.2**	**1/10mm**	**40-50**	**D-5-13**
Ductility	**157**	**Cm**	**>100cm**	**D-113-17**
Softening point	**51.5**	**°C**		**D-36-14**

The aggregate was obtained from an asphalt plant, Kavin Company, near Grzhen, Zakho, Duhok. A nominal maximum particle size of 12.5 mm was adopted; the aggregate gradation follows the limits specified in ASTM D3515, as displayed in Figure 2 [31].

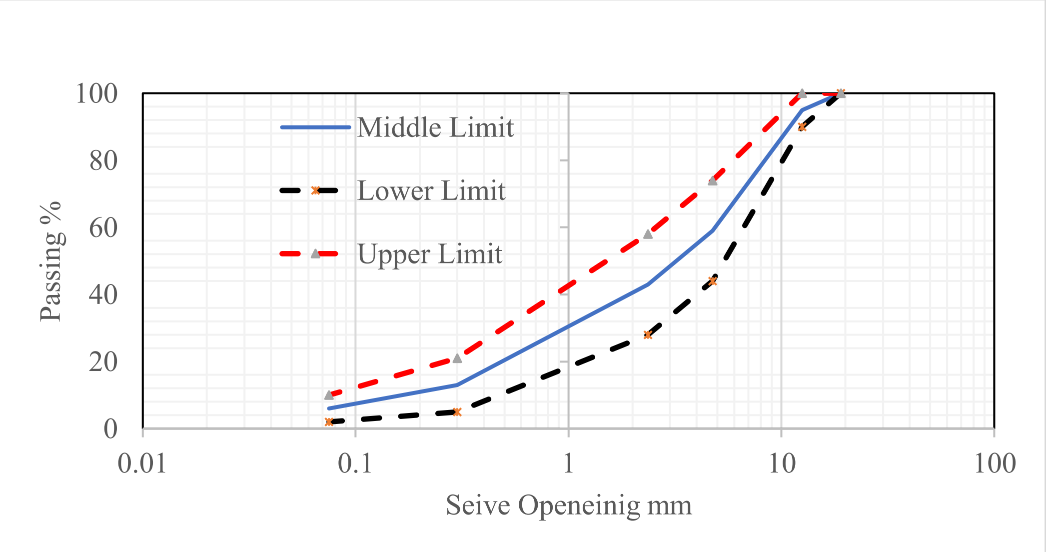

Figure 2. Dense Gradation Limits

The aggregate properties, including toughness, water absorption, and specific gravity, were evaluated at Duhok Construction Laboratories. The test results are obtainable in Table 2.

Table 2. Physical Characteristics of used Aggregate

Characteristics	Normal aggregate	
	Coarse aggregate	**Fine aggregate**
Bulk specific gravity	**2.662**	**2.650**
Apparent specific gravity	**2.719**	**2.713**
water absorption	**0.75%**	**1.11%**
Toughness	**23%**	**-----**
Los Angeles	**30.4%**	**----**

The 0.3% of the waste polypropylene (PP) by the total mix weight is used in this study that is made of bristles, a lightweight, chemical-resistant plastic that offers excellent flexibility and softness. The key physical characteristics of PP are displayed in Table 3. Figure 3 shows the shape of plastic fiber used in this research.

Table 3. Plastic Fiber Physical characteristics

Property*	Value	Description
Density	**0.90–0.91 g/cm³**	**Lightweight, floats on water**
Tensile Strength	**30–40 MPa**	**Moderate strength, flexible under load**
Elongation at Break	**Around 200–700%**	**High flexibility and stretchability**
Melting Point	**160–170°C**	**Good thermal resistance for normal use conditions**
Water Absorption	**Very low (<0.01%)**	**Making it resistant to moisture**
Hardness	**Shore D hardness around 55–65**	**Meaning it is relatively soft but tough**
Abrasion Resistance	**High**	**Allowing the fibers to endure frequent friction and sweeping action without wearing down quickly**
Chemical Resistance	**Excellent resistance to most acids, bases, and oils**	**---**

Figure 3. Shape of PP as Plastic Fiber Reinforcement.

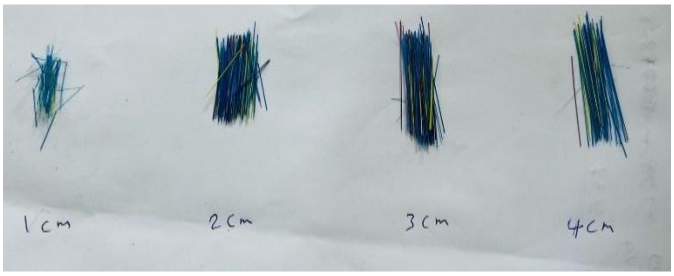

Figure 4. Lengths of plastic fibers used in this study

4.2. Preparation of Modified Asphalt Mixture

In this study, a dry process is used to prepare Fiber Reinforcement Asphalt Mixture (FR-AM) by incorporating 0.3% of PP by weight of the total mix into the HMA. At the same percentage, four lengths of plastic fibers (namely, 1, 2, 3, and 4 cm) were added to the mix as seen in Figure 4. PP added to the aggregate and mixed well before adding bitumen. The Plastic Fiber length in cm is abbreviated as (FL1, FL2, FL3, and FL4).

4.3 Performance Properties Tests

Marshall samples were prepared using a dense-graded asphalt mixture with a well-distributed gradation of aggregate, the most commonly specified mix type for pavement structures. Each sample measured 101.6 mm in diameter and 63.5 mm in height, consisting of coarse and fine aggregates along with filler, comprising 94–96% of the total mix, and using different percentages of asphalt binder (4–6%). method according to ASTM D6927 [32]. Samples were compacted with 75 blows per each side, simulating heavy-traffic conditions, to establish the optimum asphalt content (OAC) following the Asphalt Institute method [33]. The asphalt mixture was prepared at a mixing temperature of 160–170 °C using a mechanical mixer for 2 minutes, then compacted at a temperature approximately 10 °C lower. Following compaction, molds were tested for flow and stability in agreement with ASTM D6927-15. The specimens were then sited in a water bath at 60 ± 1°C for 30–40 minutes.

Following the above procedures, moisture sensitivity was evaluated by measuring the TSR. Indirect tensile strength specimens were organized according to ASTM D4867-14, targeting 7 ± 1% air voids at optimum asphalt content (OAC). Two groups of samples were prepared: the unconditioned (dry) group, placed in a water bath at 25 °C for 2 hours, and the moisture-conditioned (wet) group, kept in a water bath at 60 °C for 24 hours, then at 25 °C for 2 hours before testing [34], [35], [36], [37].

The ITS test was conducted to determine the tensile strength of the asphalt combination and assess its crack behavior under various loading conditions. An axial load was applied at a rate of 2 in/min using the Marshall testing device on specimens at 25 °C and 60 °C for both virgin and fiber-reinforced asphalt mixtures (FR-AM). The load was applied diametrically until failure, and the maximum load sustained at failure was recorded. Tensile strength was then calculated using Equation 1:

$$S_t=2000P/\pi tD \text{ (kPa)} \qquad (1)$$

Where:

St is Indirect tensile strength, (kPa); P is Ultimate load, (N); t is specimen thickness, (mm), and D is specimen dimeter, (mm).

Moisture damage resistance was assessed by calculating the (TSR), defined as the ratio of the wet group's tensile strength to that of the dry group, using Equation 2. A higher TSR value indicates greater effects to moisture resistance.

$$TSR=(S_{tm}/S_{td})100 \qquad (2)$$

Where:

TSR is tensile strength ratio, (%); Stm is average tensile strength of the conditioned group, (kPa), and Std is average tensile strength of the unconditioned group, (kPa)

The Deformation Strength (SD) Test, also known as the Kim test, was employed in this paper to assess the rutting resistance of asphalt mixes at high temperatures. This test creates a load-induced surface deformation similar to that caused by a static wheel, allowing the establishment of the material's resistance to high-temperature deformation. To better simulate field conditions, the load was applied in both the compaction direction and the wheel load direction. Figure 5 shows tire loading and the conceptual static load producing concave deformation on the asphalt concrete surface at elevated temperatures.

The asphalt mixture property most closely associated with rutting parameters is the deformation strength (SD), making it a consistent indicator of high-temperature performance and rutting resistance. In this test, Marshall samples are conditioned in a water bath at 60°C for 30 minutes, then dried and placed in the loading mold. A constant perpendicular load is then applied to the top of the specimen—aligned with the compaction direction—at a rate of 50.8 mm/min using a loading head. Figure 6 presents a side view of the test setup. The loading head features a 30 mm radius, a 7.5 mm curvature radius, and a flat bottom with a rounded edge. This method provides both force and displacement data, from which the deformation strength (SD) is calculated using Equation 3 [38].

$$SD=\frac{4P}{\pi\left[D-2\left(r-\sqrt{2ry-y^2}\right)\right]^2} \qquad (3)$$

Where;
SD – Deformation resistance (MPa)
y – Vertical deformation of specimen (mm)
D – Loading head diameter (30 mm)
P – Maximum load the specimen at failure (N)
r = radius of curvature at the bottom edge of loading head (cm)

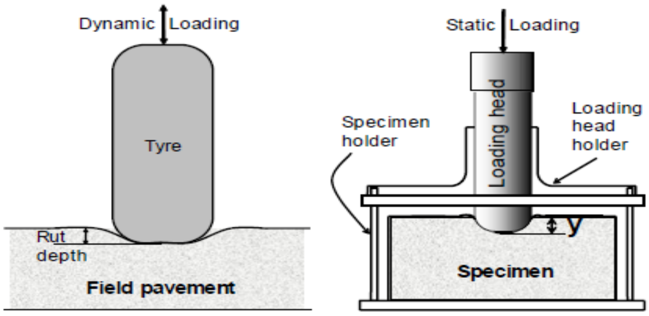

Figure 5. A Schematic Illustration of Load Application via Tire and Loading Head

Figure 6. Kim Test (A- Mold, B- Kim Test)

5. Results and Discussion

Statistical Considerations

In this study, the Virgin and PP mixtures were statistically evaluated using a null hypothesis ($H_0 = 0$) at a significance level of 0.05 through one-way ANOVA. Following this, the Least Significant Difference (LSD) post-hoc test was employed to determine whether statistically meaningful differences exist between the group means. A difference between two means is considered statistically significant when it is equal to or greater than the calculated LSD value; otherwise, it is deemed statistically insignificant. The results are presented in Table 4 using alphabetical grouping, where means sharing the same letter are not significantly different at the 0.05 probability level, while different letters indicate statistically significant differences between treatments.

Table 4. Statistical Examination of Marshall Properties, ITS, and SD of V and PP Mixtures.

Property	V	FL1	FL2	FL3	FL4
Marshall stability at 60°C, kN	**10.7±0.15 C**	**13.1±0.07 A**	**11.8±0.55 B**	**11.4±0.85 B**	**10.5±0.05 C**
ITS at 25°C, MPa	**4.5± 0.29 C**	**5.89±0.05 AB**	**5.93±0.33 A**	**5.54±0.06 B**	**5.09±0.53 BC**
ITS at 60°C, Mpa	**3.26±0.41 D**	**5.35±0.19 A**	**5.03±0.18 B**	**4.37±0.19 C**	**3.77±0.13 D**

SD at 60°C, Mpa	**2±0.22 A**	**2.9±0.12 AB**	**2.8±0.13 B**	**1.9±0.01 C**	**1.8±0.21 C**

N.B.: Means followed by different letters indicate statistically significant differences at $p < 0.05$ using Fisher's Least Significant Difference (LSD) test.

5.1 Marshall Stability

The impact of plastic fiber length on mixture stability (MS) is shown in Figure 7. Additionally, the graph displays the standard error, which is computed by dividing the standard deviation by the square root of the sample size. The stability of the control mix (V) initially increased, then decreased with longer polypropylene (PP) fibers. This decline occurs when the mixture can no longer compress, leading to reduced flexibility and, consequently, lower MS values. Compared to the control mix, stability increased for FL1, FL2, and FL3 by 23.3%, 10.5%, and 7.2%, respectively, before showing a downward trend in FL4 by 1.8%

However, unlike stability, the flow value of the V mix remains within the range of 2–4 mm (between the green lines) before increasing, which is still satisfactory for high-traffic conditions [39]. The higher flow values in PFR samples indicate superior resistance to crack initiation and propagation compared to the virgin mixture.

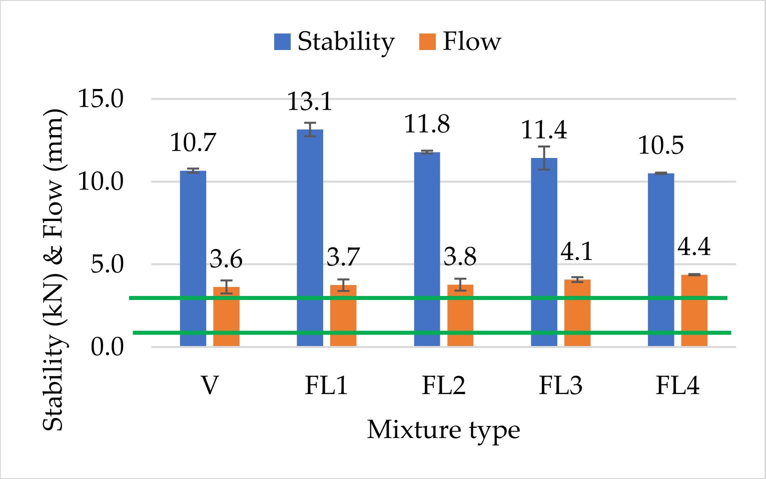

Figure 7. Effect Fiber length (FL) on Marshall Stability and Flow of Mixture

Figure 8 shows the Marshall stiffness of the virgin and PFR samples. Replacement of PFR in the virgin mix appeared to lead to less Marshall stiffness. Compared to V mix, FL1 and FL2 mixtures prepared at their OAC show 19.7% and 6.5% higher Marshall stiffness, respectively. But in FL3 and FL4 the mix shows 4.5% and 18% lower Marshall stiffness than the control one. PFR enhances the asphalt mixture by load transfer and stress distribution, limiting movement and improving load distribution, all of which increase stiffness and resistance to deformation.

However, excessively long plastic fibers, such as for FL3 and FL4, reducing stiffness could be due to their higher flow value, causing poor dispersion, increasing air voids, and reduced workability and compaction, which leads to a less dense and less uniform asphalt mixture.

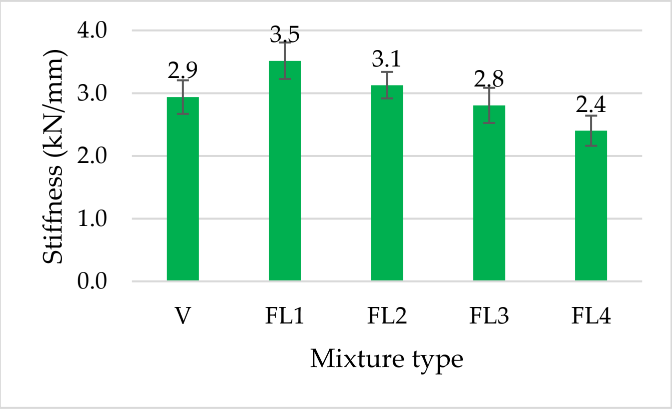

Figure 8. Effect Fiber length on Marshall Stiffness of Mixture

Nishant et al. [40] reported that paving combinations with Marshall stiffness values within 2 and 5 kN/mm exhibit satisfactory resistance to creep and rutting deformation. However, mixes with excessively high stiffness should be approached with caution, as they tend to develop cracks more easily if laid over weak foundations. In this study, virgin mixtures with all PP fiber lengths showed Marshall stiffness values above 2.0 kN/mm, indicating a rutting and creep resistance comparable to that of the virgin mixture.

Short fibers (1–2 cm) show better dispersion, increasing interlock between aggregates. They act as micro-reinforcement, bridging gaps and restricting deformation. But long fibers (3–4 cm) entangle and are poorly distributed, increasing air voids and reducing compaction efficiency.

5.2 Moisture Susceptibility

To evaluate the influence of moisture and temperature on mix tensile strength, the ITS test was conducted. Figure 9 presents the tensile strengths of both unconditioned and conditioned blends. The results show that PFR samples exhibited higher ITS values than the V samples, regardless of conditioning.

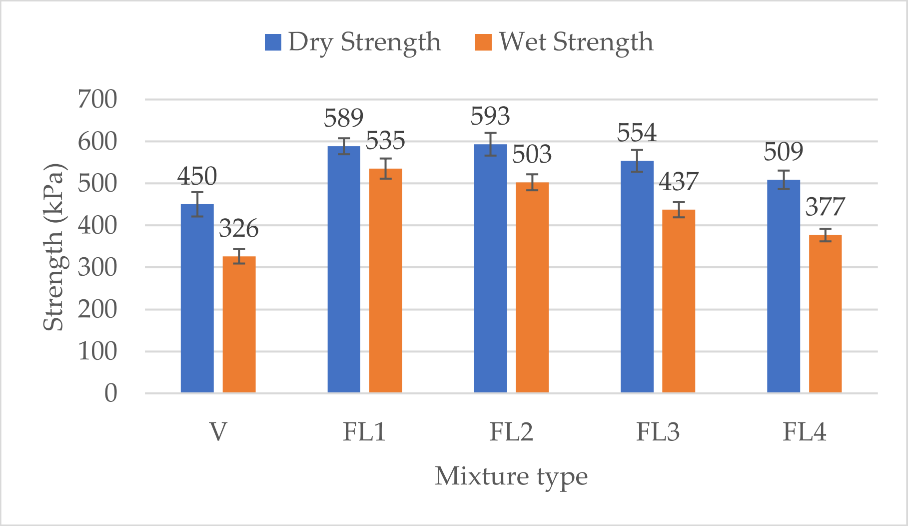

Figure 9. Effect Fiber length on ITS of Mixture with and Without PFR.

The ITS values that are presented in Figure 9 show that the performance of the PFR combinations was superior to the virgin combinations in the ITS, for both cases (conditioned and unconditioned) and for all combination lengths of the plastic fibers. For V, FL1, FL2, FL3, and FL4, average ITS values at 25°C are 450, 589, 593, 554, and 509 kPa, respectively; 326, 535, 503, 437, and 377 kPa, respectively, for ITS values at 60°C water conditioned.

Fibers increase binder–aggregate adhesion by acting as a mechanical anchor. Short fibers help form a dense, interlocked network that prevents moisture penetration. Longer fibers create micro-voids, inviting moisture intrusion to lower TSR.

The higher ITS values observed for PFR mixtures at all fiber lengths may be attributed to the existence of PFR, which reinforces the bonding interaction between the aggregate particles and asphalt binder. From these, % TSR values were established by V, FL1, FL2, FL3, and FL4. TSR for virgin and PFR mixtures are 26%, 18%, 9.7%, and 2.8%, respectively. Unlike the V, FL3, and FL4 samples, mixtures with fiber length FL1 (1 cm) and FL2 (2 cm) met the Asphalt Institute's minimum specification requirement of 80%. The greater ITS and TSR values for 1 and 2 cm fiber length at FL1 and FL2 may be related to better fiber dispersion, improved bonding between fibers and asphalt binder, and enhanced crack-bridging ability, all of which contribute to stronger and more moisture-resistant mixtures. In contrast, longer fibers (3–4 cm) exhibit reduced TSR values, which can be attributed to poor fiber dispersion and increased void content, facilitating moisture infiltration. This behavior highlights the importance of optimizing fiber geometry rather than only fiber content.

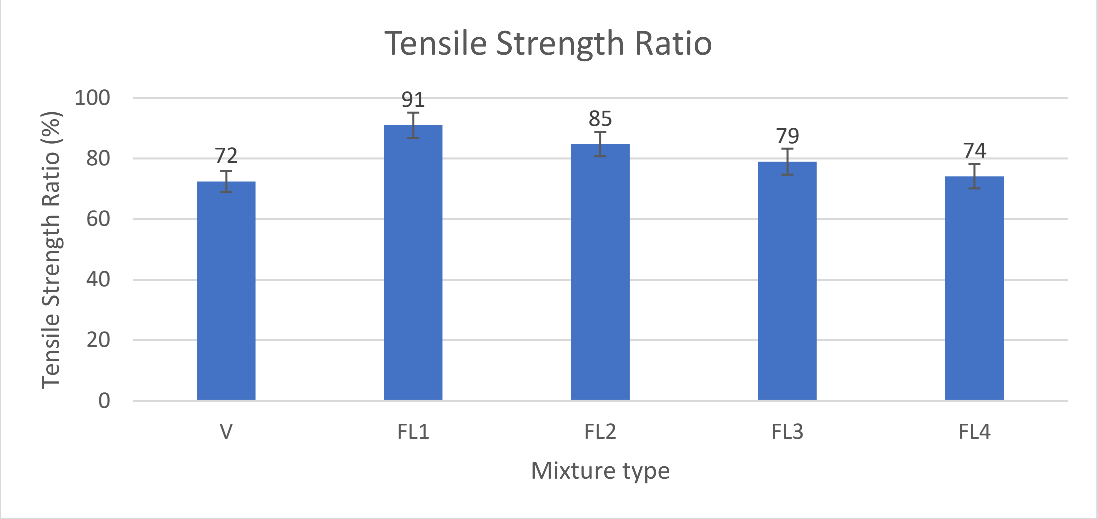

Figure 10. Effect Fiber length on TSR of Mixture with and Without PFR.

Figure 10 also shows that the FL1 and FL2 mixture has passed the minimum percentage of TSR, which is 80%, except V, FL3, and FL4 for the PFR mix. And thus, the mixes reinforced with 1 and 2 cm plastic fiber showed superior performance to virgin ones. Fibers enhance crack resistance by bridging micro-cracks and transferring tensile stress. At 1–2 cm, they provide a balance between flexibility and strength. Longer fibers reduce tensile resistance due to non-uniform orientation, weak spots, and poor coma actability. These results align with prior research, including [21], which observed that fiber reinforcement enhances tensile strength. Nevertheless, while previous work primarily focused on fiber volume, this research highlights fiber length as a decisive factor. The decline in effectiveness at greater lengths (FL3 and FL4) likely stems from inadequate fiber distribution and higher porosity—limitations that have received less attention in preceding literature.

5.3 Strength of Deformation

To evaluate rutting resistance, a strength of deformation test was executed, and the results are presented in Figure 11. The analysis shows that, in comparison to the virgin mix, FL3, and FL4, mixes with fibers of 1 cm and 2 cm length showed better deformation resistance. When the fiber length exceeded 2 cm, the rutting resistance decreased as the fiber length increased beyond 2 cm, with FL3 and FL4 showing 7% and 10.5% lower SD values, respectively, compared to the control mix. Compared to the virgin mix, FL1 and FL2 exhibited higher SD values of 43% and 40%, respectively.

The findings of these experiments show that at 60°C virgin mixtures with 1 cm long fiber (FL1) have significantly greater creep and rutting deformation resistance than the virgin mix, a result confirmed by their Marshall stiffness at the same temperature. Short fibers improve resistance to permanent deformation by limiting asphalt flow under load. Longer fibers interfere with compaction, resulting in less dense structures and lower rutting resistance.

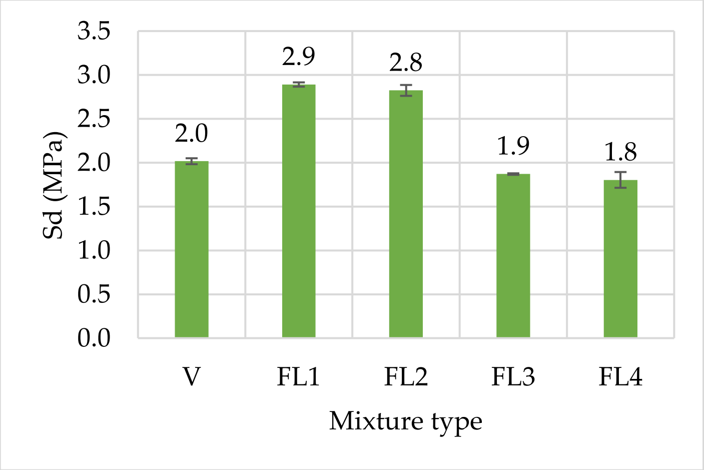

Figure 11. Impact of Fiber Length on Mixture Deformation Strength with and Without PFR.

Note that it should be remembered that the trends of this study are consistent with a robust set of data obtained through several complementary performance tests. All fiber lengths were tested using the same repeatable testing program (Marshall stability, Marshall stiffness, ITS, TSR, and deformation strength). This multi-indicator dataset allows the improvement patterns, notably those associated with stability, moisture resistance, and deformation performance, to be independent of a specific test outcome and to be consistently confirmed. This agreement among these performance indicators enhances the validity of their conclusions while confirming that reported effects of fiber reinforcement are supported by sound and sufficient experimental data.

6. Conclusions

In this work, the effects of four different polypropylene (PP) fiber lengths (FL1, FL2, FL3, and FL4) used as PFR in virgin mixes by 0.3% were examined. Laboratory tests—including Marshall properties, Marshall stiffness, indirect tensile strength, moisture sensitivity test, and deformation strength test—were performed on both virgin and fiber-reinforced mixes. Analysis of the outcomes led to the following conclusions:

1. Adding the plastic fiber to the mix in different lengths resulted in an increase and then a decrease in the values of stability. FL1, FL2, and FL3 mixes showed an increase of 23%, 10%, and 7% higher Marshall stability than the control mixes, respectively. But lower Marshall stability appears at FL4 by 1.8%.
2. Increasing the fiber length resulted in an increase in the values of TSR. The FL1, FL2, FL3, and FL4 mixes showed 26%, 18%, 10%, and 3%, respectively.
3. In terms of TSR, PFR mixtures outperformed virgin mixtures, with performance improving slightly as fiber length increased.
4. Plastic fibers demonstrated superior rutting resistance; however, rutting resistance decreased as fiber length increased, showing reductions of 63%, 42%, 28%, and 14% compared to the control mix.
5. The FL1 and FL2 fiber length displayed superiority at all performance tests (rutting and moisture damage).
6. The mechanisms governing performance clearly show that 1–2 cm fibers achieve the best balance between reinforcement efficiency, uniform dispersion, and mixture workability—resulting in superior mechanical performance across all tests.

The superior performance of FL1 and FL2 can be attributed to improved fiber dispersion within the mix. By bridging gaps, improving aggregate interlock, and minimizing deformation under stress, short fibers serve as micro-reinforcement. Longer fibers, on the other hand, have a tendency to entangle and form localized weak zones, which reduces compaction and increases the amount of air void. This explains the decrease in TSR, stiffness, and stability seen with FL3 and FL4.

Although the mechanical properties are encouraging, the long-term ecological impact of these materials warrants deeper scrutiny. Future inquiries should prioritize assessing the end-of-life characteristics of fiber-modified asphalt, with a specific focus on microplastic shedding resulting from mechanical abrasion and weathering. Furthermore, comprehensive Life Cycle Assessments (LCA) are essential to rigorously determine the net environmental advantages of utilizing recycled polypropylene fibers within paving infrastructure.

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Abbreviations

The following abbreviations are used in this manuscript:

Abbreviation	Full Form / Meaning
PP	**Polypropylene**
PPF	**Polypropylene Fibers**
PFR	**Plastic Fiber Reinforcement**
FR-AM	**Fiber Reinforcement Asphalt Mixture**
FR-AC	**Fiber-Reinforced Asphalt Concrete**
HMA	**Hot Mix Asphalt**
MS	**Marshall Stability**
ITS	**Indirect Tensile Strength**
TSR	**Tensile Strength Ratio**
SD	**Deformation Strength**
OAC	**Optimum Asphalt Content**
GF	**Glass Fiber**
FRAP	**Fine Reclaimed Asphalt Pavement**
SCB	**Semi-Circular Bending Test**
LDPE	**Low-Density Polyethylene**
HDPE	**High-Density Polyethylene**
PET	**Polyethylene Terephthalate**
PVC	**Polyvinyl Chloride**
ASTM	**American Society for Testing and Materials**
SCRB	**State Commission of Roads and Bridges**
SDGs	**Sustainable Development Goals**

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