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Alleviating Permanent Deformation and Moisture Damage in Hot Mix Asphalt Using Polypropylene Fibers

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Abstract- The asphalt pavements in Pakistan suffer from various failures where rutting and fatigue cracking are significant. These failures may occur due to uncertainty in predicting actual traffic, material properties, poor construction methods, and poor mix design. As per existing literature, polypropylene fibers (PPF) have been extensively used in pavement engineering for many years to cope with the pavement failures. These PPF are effectively used in asphalt concrete due to the adequate adhesion between PPF, bitumen, and aggregate. Therefore, in the current study, the asphalt concrete specimens for Marshall Stability, Rut resistance, and Moisture damage, modified with PPF, ranging from 2% to 10% by weight of optimum binder content (OBC), were produced at a mixing temperature of 160^{o} C and tested as per ASTM D1559, ASTM D8292, and ASTM D6931 protocols, respectively. An OBC of 4.42% by weight of the Marshall specimen for the conventional mix was concluded in terms of Marshall Stability and flow. The PPF of 8%, by weight of OBC, used as per the wet method in the asphalt mixture, was concluded to be optimum in terms of Marshall Stability of 15.2 KN and flow value of 2.2 mm. The modified asphalt mixtures at PPF content of 8% leads to a least rut depth of 3.44 mm as compared to conventional specimens having rut depth of 7.35 mm, particularly due to the PPF's long-lasting integrity formed in the modified asphalt mixture at an 8% PPF content, supporting the asphalt mixture's ability to sustain repeated wheel loads. The values of TSR showed an increasing trend with the increase in PPF content from 2% to 8%, particularly due to the adequate mobility and dispersion of the PPF in the asphalt mixture and cohesion due to the optimum coating in the asphalt mixture. The TSR value of the asphalt mixture decreased at 10% PPF content as compared to conventional asphalt mixtures because of excessive rigidity or a lack of the required marginal flexibility in the asphalt mixture because of excessive PPF content. Therefore, the asphalt mixture modified with 8% PPF fibers as per wet method is recommended to be used in the construction industry to control permanent deformation and moisture damage in asphalt mixtures.

Keywords- Asphalt Mixture, Polypropylene fibers, Marshall Stability, Indirect Tensile Strength, Rut Resistance

I. INTRODUCTION

Pakistan's transport sector is primarily road-based, with around 96% of inland freight and 92% of passenger traffic carried by road. The annual growth rate of vehicle registration indicates a robust increase in traffic, with millions of vehicles contributing to the overall traffic load. The freight transport sector is a critical component of Pakistan’s economy. It includes road, rail, air, and sea transport, with road transport being the most prevalent. According to the Pakistan Economic Survey [1], road transport handles about 96% of the total freight, amounting to millions of tons annually. Railways handle a smaller portion, around 4%, focusing on bulk cargo such as coal, oil, and other heavy goods. Air freight, although smaller in volume, is significant for high-value and time-sensitive goods. The Pakistan Civil Aviation Authority reports detailed statistics on air freight traffic through various airports across the country. These figures highlight the critical role of road transport in Pakistan's economy, both for passenger mobility and freight logistics. Continued investment and improvements in road infrastructure are essential to accommodate the growing traffic demands. As of the latest available data, the total length of roads in Pakistan is approximately 263,775 kilometers [2]. This network includes motorways, highways, national roads, secondary or regional roads, and other types of roads. Regarding the condition of these roads, a significant portion is in need of maintenance and remedy. Pakistan's road network faces challenges such as wear and tear, lack of regular maintenance, and damage due to heavy traffic and climatic conditions. According to recent assessments, while the major highways and motorways are generally in better condition due to higher maintenance standards, many regional and local roads require substantial repairs and upgrades to improve safety and accessibility. Rutting and moisture damage primarily impair the comfort and safety of Pakistani roadways. Road surfacing frequently involves the use of hot mix asphalt. Crushed stone, stone dust as filler and bitumen serve as the binding agents in conventional HMA [3]. According to a study by Karim and Jawad (2021), pavement design needs special consideration to have a good design life and durability because highway networks have a significant impact on the growth and economics of any country [4]. HMA was modified with 20%, 30%, and 40% styrene-butadiene-styrene (SBS), and viscosity measurements, frequency sweep tests, and fluorescence microscopy were performed, respectively. It was discovered that the asphalt containing 30% SBS has the highest viscosity. Additionally, the asphalt with excessive styrene content is less vulnerable to shear stress [5]. The behavior of the asphalt mix prepared with gradation of 25mm, 19mm, and 12.5mm, where cellulose fibers were added to stone mastic asphalt (SMA), was studied. Tests Results showed that, in comparison to the control asphalt samples with aggregates of 12.5mm size, the mix with NMAS of 25mm has an excellent resistance to permanent deformation along with stiffness [6]. The design parameters, where voids in mineral aggregate are substantial, are the only factors that affect an HMA mixture's resistance against the environment. Different kinds of plastic fibers can help fill up openings in asphalt, improving its resilience to environmental factors and wheel stress [7]. The fibers can be employed in the restoration process of providing an asphalt dense overlay for improving the pavement's response against distresses such as rutting, fatigue, etc. with new asphalt [8].

In a research published in 2023, Khan et al. [9] assessed the effects of adding styrene-butadiene rubber (SBR) and crumb rubber (CR) additives, varying in weight of bitumen from 0% to 5%, on the performance of a bituminous concrete mixture utilizing the wet method. In the laboratory, tests such as the Marshall test were carried out to determine the OBC for the heated mixture. Finding the ideal ratios of CR and SBR to attain optimum strength is the main goal of the study. The findings demonstrate that increasing the amounts of both CR and SBR significantly increases strength; for a mix comprising 5% CR and 4% SBR, the maximum stability was measured at 16.14 KN and the flow was 1.23 mm. Polyolefin-aramid fibres were utilized to conduct an experimental investigation on the effects of fibres, loading rate, and temperature variation on the characteristics of asphalt concrete. Based on test results, it was determined that adding more fibres increased the fracture resistance of asphalt mixtures in service [10]. Shanbara (2018), employed four different kinds of fibres and looked at how they affected the performance of conventional HMA and cold mix asphalt (CMA). Based on the findings from testing, they reached to the conclusion that rut resistance enhanced for fiber modified CMA and HMA at various temperatures as compared to conventional HMA [11]. In order to check for high temperature cracking, master curves derived from dynamic modulus were employed instead of the rectangular beam bending test for low temperature. Results indicate that asphalt with fibres performs better in terms of low-temperature cracking. In a study on the combining of plastic waste with hot mix asphalt, came to the conclusion that it has a significant impact on the rheological characteristics of asphalt concrete and binder stiffness at high temperatures [12]. For the purpose of improving the behaviour of the asphalt binder, tests for crack propagation, indirect tensile strength (ITS), triaxial shear, and complex dynamic modulus were examined on polypropylene and aramid fibre mixtures. Results suggested that shear deformation and the complex modulus E* had greatly improved [13].

In order to examine the performance of asphalt mixture, aggregates from the quarries in Margalla, Burhan, and Karak, and plastic bottles (PB) were utilized as the polymeric waste. For each quarry, 48 samples were created for the PB modified asphalt mixture at different amounts of PB waste, and 12 samples were prepared for standard asphalt mixes. According to the wet procedure, the percentage of PB that was modified was 15%, 20%, 25%, and 30% by weight of the OBC. A 4.2% OBC was determined for traditional asphalt blends. The standard and modified asphalt mixtures' flow and stability properties were contrasted. When 15% PB was added to the modified Margalla asphalt mixes, their average stability was significantly higher than that of the regular asphalt mixtures. However, the Marshall stability indicated a declining tendency for Margalla aggregates, a rising trend for Karak aggregates, and a decreasing trend for Burhan aggregates when PB was employed above 15% [14]. Polypropylene fibers are a key component in asphalt pavements, enhancing rut resistance and moisture resistance. They act as structural reinforcement, creating a three-dimensional network that distributes loads more evenly across the pavement surface. They also bridge micro-cracks, reducing the likelihood of rutting under repeated traffic loading. The fibers also improve the cohesive strength of the asphalt binder, leading to better adhesion between the binder and aggregates. This increases the stiffness of the asphalt mix, making it more resistant to deformation or rutting. The fibers also improve load distribution by forming a reinforcing network, reducing stress concentrations and deformation. They also reduce moisture susceptibility by improving the bond between the asphalt binder and aggregates, reducing the potential for water infiltration. They also reduce the stripping potential, enhancing pavement durability and moisture resistance. Polypropylene fibers also help mitigate thermal cracking by enhancing the mix's flexibility and reducing thermal cracking. They also enhance rutting resistance by increasing shear resistance and reducing permanent deformation under repeated loading conditions. Overall, these fibers contribute significantly to the durability and longevity of asphalt pavements.

The literature mentioned above demonstrates that PPF effectively applied to asphalt enhances its performance. It is rather challenging to adhere to a certain PP fiber limit for usage in asphalt, nevertheless. Therefore, in order to determine a specific limit of its usage in asphalt in conjunction with the local characteristics of temperature, environment, and wheel load, PP fibers were imported from ZHONGSHI International Trade Company, Limited, China, and utilized in the current study.

II. Research Objectives

The main objectives of the study are,

1. To determine the optimum percentage of binder and Polypropylene fiber content for asphalt mixture using Marshall method of mix design,
2. To evaluate the effect of varying proportions of Polypropylene fibers on rutting resistance and Indirect tensile strength of asphalt mixture prepared as per wet method.

III. Materials and Methods

A. Asphalt Binder

Table 1 lists the physical characteristics of the 60/70 penetration grade asphalt binder used in current study.

Table 1: Description of the 60/70 Penetration Grade Asphalt Binder

Property	Reference	Value
Penetration (25°C, 1/10th of mm) [15]	ASTM D5	63
Softening point, (°C) [16]	ASTM D36	56
Ductility, (cm) [17]	ASTM D113	103
Flash and fire point, (°C) [18]	ASTM D 3143	305°C & 312°C
Viscosity, (Pa.s) [19]	ASTM D4402	0.412

B. Aggregate

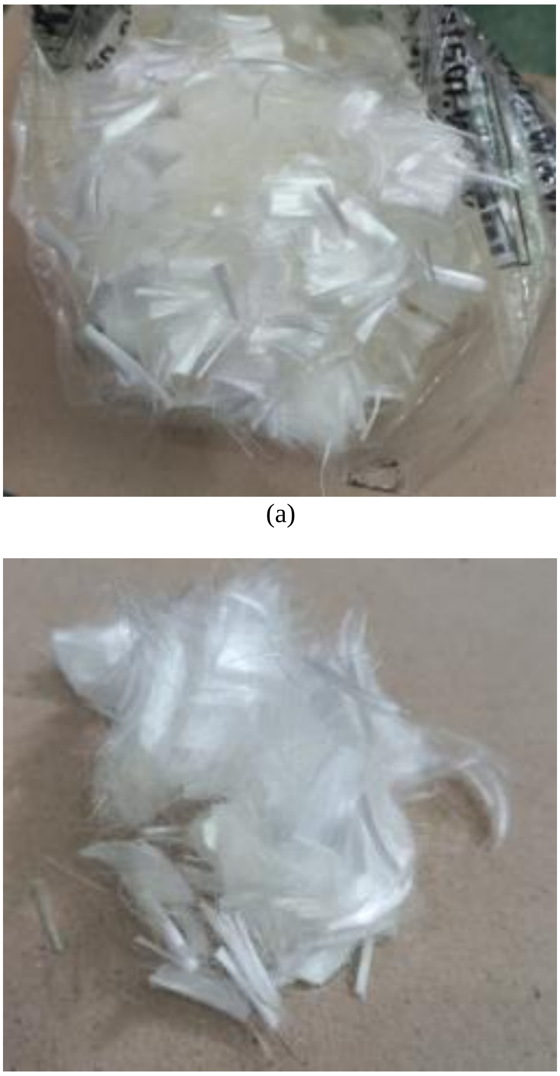
According to traditional index characteristics, the virgin aggregate used in the current investigation was described, as shown in Table 2.

Table 2: Consensus Properties of Aggregates

Property	Reference	Value
Los Angeles abrasion value, (%) [20]	ASTM C131	20.96
Water absorption, (%) [21]	ASTM C127	1.03
Specific gravity of Coarse aggregate [21]	ASTM C128	2.61
Flakiness index, (%) [22]	BS 933-3	12.6
Elongation index, (%) [23]	ASTM D4791	7.8
Soundness (%) [24]	ASTM C88	3.79
Impact Value, (%) [25]	BS-812	11.9

C. Polypropylene fibers

The Polypropylene fibers (PPF) were imported from the ZHONGSHI International Trade Company, Limited, China, as shown in Figure 1(a), and (b).



(a)

(b)

Fig. 1. Polypropylene Fibers

The complete characterization of the Polypropylene fibers is presented in Table 3.

Table 3: Physical Properties of Polypropylene Fibers

Property	Result	Property	Result
Fiber length (before use)	50 mm	Elastic Modulus	3.1 GPa
Fiber length (After Shredding)	12mm	Young's Modulus	3.2 KN/mm
Melting Point	155 – 165 ^oC	Softening point	145 – 165 ^oC
Specific Gravity	0.76 gm/cc	Alkali Resistance	High
Ignition Point	1100 ^oF	Geometry	Round
Diameter	75×10^{-6}m	Water Absorption	Nil
Density	0.71 gm/cc	Electrical Conductivity	Very low

IV. METHODOLOGY

The experiments were conducted at Sarhad University's highway engineering laboratory in Peshawar, Pakistan. In this investigation, 60/70 Penetration grade bitumen from Attock Refinery Limited (ARL) and aggregates from the Margalla quarry were used. Figure 2 describes the detailed technique.

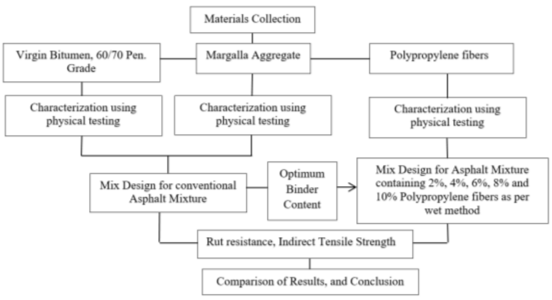


Fig. 2. Research Methodology

Ninety four specimens in all were prepared: Eighteen for rut resistance, thirty six for indirect tensile strength for both conditioned and unconditioned state, twenty Marshall Samples for modified asphalt with varying percentages of Polypropylene fibers, and twenty Marshall Samples for standard asphalt. The Marshall technique of mix design, which is detailed in ASTM D1559, was used to find the optimal binder content (OBC) for conventional asphalt. The observations made throughout this process are shown in Table 4, and 5 in the results and discussion section. According to the wet method, the modified asphalt mixture with 2%, 4%, 6%, 8%, and 10% PPF included the OBC that had already been established for the standard asphalt mixture, were prepared. As seen in Figure 3, the resulting aggregate blend was created in accordance with the Asphalt Institute grading. For three hours, the aggregate samples were heated to 180 degrees Celsius. The shredded PPF content was spread out in metal pans and then heated to 160°C for an hour. After being mobilized by mixing the melted PPF with the virgin bitumen at 160 degrees Celsius, the mixture was left to diffuse in the virgin binder for half an hour. At 160 degrees Celsius, mixtures of the virgin aggregate and binder were combined. The Marshall specimens were conditioned for 45 minutes at 60^{o}C in a water bath to mimic the critical temperature of pavement before testing. The mixing temperature of 160^{o}C, and compaction temperature of 130^{o}C for asphalt samples were determined as per Superpave viscosity – temperature relationship, and measured using a digital thermometer.

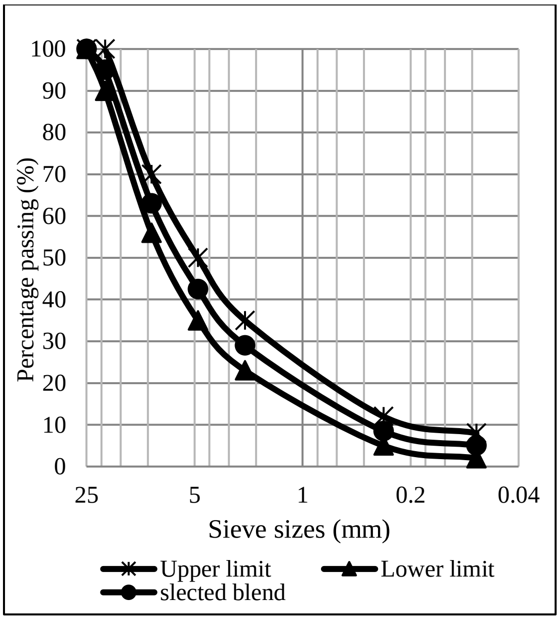


Fig. 3. Grain Size Distribution Curve

A cylindrical specimen was loaded across its vertical diametral plane at a deformation rate of 50 mm per minute at a test temperature of 25^{o}C to measure the indirect tensile strength (ITS) of bituminous mixtures. This was done to ascertain the moisture susceptibility of the asphalt specimens. The specimen's ITS was ascertained by taking note of the peak load at failure. Moisture damage was assessed after the specimens had been conditioned by being submerged in water at a pressure of 13–67 KPa for five to ten minutes. After the samples were saturated, they were placed in the freezer for 14 hours while sealed in a plastic bag with 10 cc of water. The samples were frozen and then stored for two to three hours at room temperature (25^{o}C) before spending a full day in a water bath at 60^{o}C. The samples were then placed into the testing apparatus. The ITS was determined using Equation (1), and the tensile strength ratio (TSR) was obtained using Equation (2).

$$S_t = {}^{2000P}/_{\pi t\, D} \quad (1)$$

where, S_t = Tensile strength (KPa), t = thickness of the ample (mm), D = diameter of the sample (mm), and P = load (N).

$TSR = S_{cond.}/S_{Uncond.}$ --------------------------- (2)

where, $S_{cond.}$ = Tensile strength of conditioned samples, and $S_{uncond.}$ = Tensile strength of unconditioned samples.

In order to determine rut resistance, each sample for the wheel tracking test consisted of 125 mm in height and 150 mm in diameter and was subjected to 160ºC mixing temperature. The samples were tested under carefully controlled circumstances at a temperature of 60°C, 10,000 revolutions of a standard wheel, and recording of the rut depth after 10,000 revolutions.

V. RESULTS AND DISCUSSION

Marshall Specimens at a mixing temperature of 160ºC and binder contents of 3.5%, 4%, 4.5%, 5%, and 5.5% by the weight of Marshall briquette for the conventional mix were prepared, tested, and the volumetric properties were recorded in Table 4. An OBC of 4.42% by weight of the Marshall briquette was determined for the data provided in Table 5 using ASTM D1559. The mixes fulfilled a minimum stability criterion of 8.0 KN with the prescribed flow under the design scenarios. According to the 14 percent (minimum), 65 to 75 percent, and 3 to 5 percent criteria, the VMA, VFA, and AV mostly achieved the prerequisite requirements.

Table 4: Volumetric Properties for Standard Mix Design

Symbol	Unit	Mix Design Results				
Pb	%	3.5	4	4.5	5	5.5
G_{mb}	-	2.327	2.360	2.393	2.390	2.380
G_{mm}	-	2.492	2.766	2.477	2.458	2.449
AV	%	6.64	4.67	3.39	2.76	2.81
VMA	%	14.47	13.69	14.10	14.21	13.85
VFA	%	54.17	65.86	73.83	79.55	80.45
S	KN	10.36	11.80	12.22	11.39	9.45
F	mm	2.13	2.49	2.90	3.42	4.33

Using the aforesaid OBC of 4.42% for the conventional asphalt mixture, the modified asphalt mixtures comprising of 2%, 4%, 6%, 8%, and 10% polypropylene fibers were produced, tested, and the results were recorded in Table 5.

Table 5: Mix Design Parameters of Marshall Specimen at Several Fiber Contents

OBC (%)	PPF (%)	VMA (%)	VFA (%)	AV (%)	Stability (KN)	Flow (mm)
4.42	2	13.37	68.44	4.8	12.39	3.8
	4	14.97	71.43	4.2	13.78	3.3
	6	15.77	73.86	3.6	14.94	2.7
	8	14.68	77.61	3.1	15.22	2.2
	10	13.78	66.44	5.7	11.74	4.3

While looking at the data provided in Table 5, it is clear that the modified sample's stability at various percentages of PPF showed an increasing trend as compared to the conventional asphalt specimens. PPF of 8 % showed better performance in terms of Marshall Stability of 15.22 KN as compared to that of conventional asphalt mixture. However, at other percentages of PPF, the asphalt mixture showed a declining trend. The improvement in performance of asphalt mixture at 8% PPF content is attributed to the improvement in interlocking and gripping action produced due to mobility and dispersion of the PPF fibers in asphalt binder in the asphalt sample. However, the stability declined at 10% PPF content because the specified PPF content declined the integrity among the aggregate in asphalt specimen. The flow values indicate that the stiffness of the modified asphalt mixtures at 8% PPF content is smaller than flow values at all other percentages of PPF.

Figure 4 shows how the PPF content affects the indirect tensile strength (ITS) in both the conditioned and unconditioned modes. The results of the moisture susceptibility test showed that the test parameters such as sample freezing and thawing and vacuum saturation accelerated the water damage. It is clear that when the PPF content rose to 8%, the TSR values also climbed. At 10% PPF content, the TSR value did, however, drop much further. When compared to the standard mix, the TSR values of the modified combination with the designated amounts of PPF produced much superior results. This is explained by the PPF's poor mobility and dispersion in the asphalt mixture as well as the cohesiveness brought about by the combination's ideal covering. However, the PPF content of 10% caused decline in integrity of the asphalt mixture.

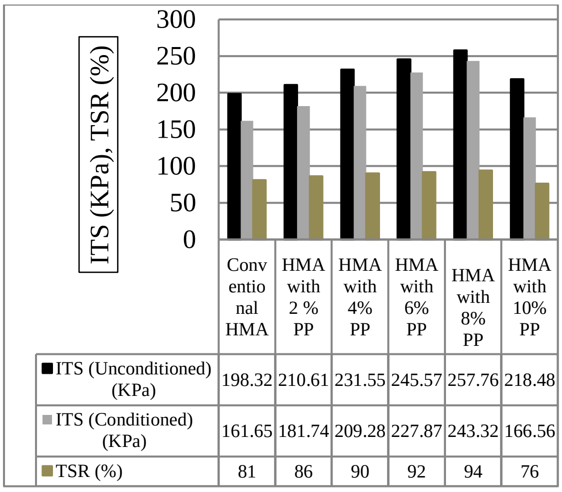
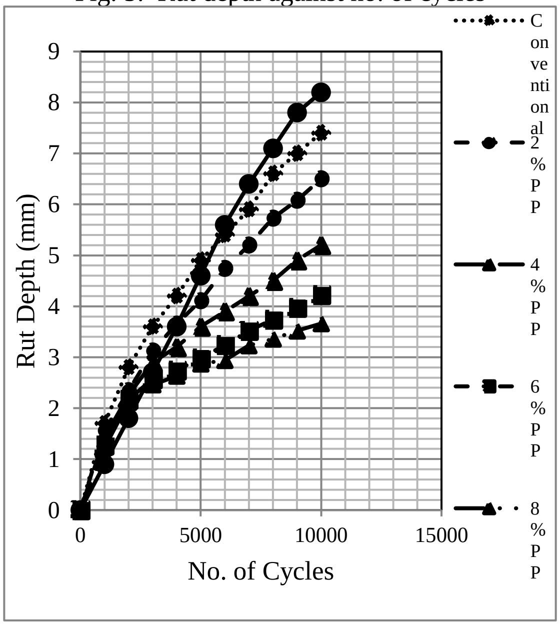


Fig. 4. Indirect tensile strength and tensile strength ratio

In order to measure the resistance of conventional and modified asphalt mixtures to permanent deformation at 55ºC against wheel loading, a total eighteen (18) samples, each of 7 kg, were prepared using the Marshal compactor at 2%, 4%, 6%, 8%, and 10% PP content, respectively, and subjected to a wheel tacking test for finding rut depth (mm) or rutting resistance. Figure 5 shows the average rut depth measurements for each of the six samples after 10,000 passes of the wheel tracking machine, respectively. All the asphalt samples met the criterion of a maximum rut depth of 12.5 mm. According to Figure 5, utilizing 8% PPF content leads to minimal rut depth as compared to conventional mixture against 10,000 passes of the wheel tracking machine. It is credited to the PPF's long-lasting integrity, which is formed in the modified asphalt mixture at 8% PPF content, for the asphalt mixture's ability to sustain repeated wheel loads. However, the asphalt mixture at 10% PPF content primarily showed the best result (2 mm rut depth), but the asphalt sample showed a gradual increase in rut depth as compared to the conventional asphalt mixture because of poor integrity and cohesion due to excessive fiber content, and thus the sample could not sustain wheel load.

Fig. 5. Rut depth against no. of cycles



The findings of the current study approve the findings of the study carried out by Sukrislistarto (2020) where the authors recycled Polypropylene (PP) waste in concrete asphalt mixtures. The study designed a concrete asphalt mixture with petroleum bitumen as the main binding material and PP waste, resulting in concrete asphalt with good resistance to environmental weather impact. The study used the Indirect Tensile Stiffness Modulus (ITSM) value to determine the effect of environmental weather on the stiffness properties of the mixture. The results showed that using waste PP in asphalt mixes with petroleum bitumen as the main binder produced a slightly stiffer mixture without negative effects [26]. The findings of the study partially coincide with the study conducted by Moubarak (207) where the authors suggested that reinforcing flexible asphalt with polypropylene fiber improves asphalt binder and mixture's performance. The study also reveals that the malleability, entrance, and relaxation properties of asphalt can be improved by incorporating polypropylene fiber, thereby enhancing service life [27].

Polypropylene fibers are being increasingly used in Hot Mix Asphalt (HMA) due to their potential to improve the mechanical properties of asphalt mixtures, particularly in terms of resistance to deformation and moisture damage. These fibers enhance the stiffness and strength of asphalt, reducing its susceptibility to rutting and fatigue cracking. They also enhance the binding properties of the asphalt matrix, reducing water ingress and moisture-induced damage [28]. However, they may lose some structural integrity at extremely high temperatures. Polypropylene fibers are encapsulated within the asphalt binder, reducing UV degradation over long periods. They have good chemical resistance to common chemicals found in asphalt pavements, preserving their structural integrity over time. They may contribute to increased surface wear resistance, reducing rates of surface degradation under traffic loads. Fibers also improve the fatigue life of asphalt, making it suitable for high traffic volumes and heavy loads. The initial cost of adding polypropylene fibers may be higher, but the extended service life and reduced maintenance needs offer a good return on investment.

Based on the aforesaid discussion of incorporating PPF in hot mix asphalt, where 8% PPF content showed adequate performance as compared to conventional HMA when subjected to traffic and environment, and therefore, recommended to be employed in the industry to produce durable pavements. WCO (Waste Control) can be blended with conventional asphalt binders, allowing for a seamless transition without significant changes in production processes. It can be integrated into performance-based design, promoting sustainability in design frameworks like Green roads and Envision. Standardization and guidelines for WCO use are crucial, including specifications for WCO quality, processing methods, and the allowable percentage of WCO in asphalt mixes. WCO-modified asphalt can lead to cost savings, extended pavement life, reduced maintenance costs, market creation, environmental cost reductions, and reduced reliance on virgin materials. This integration strategy can support sustainability and economic resilience in the industry, reducing the use of non-renewable resources and promoting recycling. Pilot projects and field trials can also help establish confidence in WCO-modified asphalt. The future research should focus on the use of various proportions of PPF in asphalt binder and asphalt mixtures. The binder should be subjected to DSR, BBR, and PAV tests. The asphalt mixtures should be subjected to Hamburg Wheel Tracking, and Fatigue resistance tests.

VI. Conclusion

The current study led to the following conclusions;

1. An optimum binder content of 4.42% by weight of the Marshall specimen for the conventional mix was concluded in terms of Marshall Stability and flow.
2. The Polypropylene fiber of 8%, by weight of optimum binder content, used as per wet method in the asphalt mixture, was concluded as optimum, in terms of Marshall Stability of 15.2 KN, and Flow value of 2.2 mm.
3. The modified asphalt mixture at Polypropylene fiber content of 8% lead to minimal rut depth of 3.44 mm as compared to conventional specimen with rut depth of 7.35 mm particularly due to the PPF's long-lasting integrity formed in the modified asphalt mixture at 8% PPF content, supporting the asphalt mixture's ability to sustain wheel loads.
4. The values of TSR showed an increasing trend with the increase of PPF content from 2% - 8% particularly due to the adequate mobility and dispersion of the PPF in the asphalt mixture, and cohesion due to optimum coating in the asphalt mixture.
5. The TSR value of the asphalt mixture decreased at 10% PPF content as compared to conventional asphalt mixture because of excessive rigidity or lack of required trifling flexibility in asphalt mixture because of excessive PPF content.

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