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Plastic Bottle Waste as a Sustainable Material in Reclaimed Asphalt Pavement Production

M. Anas[1], F. Karim[2]

[1,2]*Department of Civil Engineering, Sarhad University of Science and Information Technology, Peshawar 25000, Pakistan*

[2]engr_fazli@yahoo.com

Abstract- Plastic degradation is an important sustainability problem since it cannot be easily recycled and leads to land pollution. Plastic bottles waste (PBW), which are non-biodegradable, pose significant environmental risks. This study investigates how to enhance the performance of recycled asphalt blends in Pakistan's hot weather by combining rejuvenators and recycled Polyethylene-based Plastic Bottles with reclaimed asphalt aggregate. The current research aims to optimize the incorporation of 5 - 25% PBW and 15% recycled asphalt mixture, rejuvenated with 2 – 10% Waste Engine Oil (WEO) in Hot Mix Asphalt to assess the environmental benefits of using PBW and recycled materials by evaluating its impact on rut resistance, Marshall stability, flow, and volumetric properties to ensure a sustainable and high-performance mix and reduce plastic waste accumulation, and potential carbon footprint. Overall, ninety samples were created and the optimum binder content (OBC) for the conventional mix was determined using Marshall Mix technique, as per ASTM D1559 protocols. The study revealed that the asphalt mix comprising 15% recycled materials, 15% PBW at 8% WEO contents showed the least rutting (highest rut resistance), suggesting that PBW significantly enhances the structural integrity of the asphalt when subjected to traffic. Plastic modification strengthens asphalt, reducing rutting and extending pavement life. The study recommends that using PBW in asphalt not only strengthens the pavement but also helps tackle plastic pollution, making it an eco-friendly solution.

Keywords- Sustainability, Plastic Bottle Waste in Asphalt, Asphalt modification, Reclaimed asphalt, and Rejuvenators

I. INTRODUCTION

Nowadays, plastic waste bottles and their disposal pose a serious risk to the ecosystem. Global warming and pollution are the consequences of this. Similarly, roads in Pakistan are becoming a nuisance for people because they develop potholes, corrugation, ruts etc. after a short interval post-completion. The roads when milled, in form of RAP, are disposed to the environment as waste. There is an easy fix for these two issues: using plastic trash bottles in bituminous mixtures. This will additionally enhance road properties but also environment could be saved the ecosystem by utilizing the plastic waste. A complete waste management system must be implemented to control this problem which may include reuse, recycle, source reduction etc. The problem here is that plastic cannot be easily reused or recycled. Plastic is not a substance that breaks down biologically, and according to several studies' Trash made of plastic can linger on Earth for up to 4500 years. Pakistan produces 55 billion single-use non-biodegradable plastic bags and bottles every year, most which somehow find its way to the garbage dumps, landfill site etc. (RAP) has been extensively recognized as a sustainable alternate for pavement construction materials, providing both environmental benefits and economic. Reusing RAP mitigates the need for fresh aggregates and bitumen, thereby conserving natural resources and reducing emissions associated with their production [1-5].

However, RAP materials are often aged and exhibit inferior performance compared to fresh asphalt mixtures, particularly in terms of durability and their mechanical properties under heavy traffic loads and exciting temperatures. To address this, rejuvenators have been introduced to restore the characteristics of aged bitumen, allowing for improve flexibility and durability in reclaimed asphalt mixtures [6]. Waste plastic, particularly in the form of discarded plastic bottles, has been identified as a most important environmental pollutant. In the modern era, researchers have explored the potential of incorporating plastic waste into asphalt blend as a means of reducing both the environmental footprint of road construction and the capacity of plastic waste [7]. The addition of plastic waste in asphalt mixtures can enhance the mechanical properties of the pavement by improving its resistance to rutting and cracking [8].

However, pavement paving is the most practical way to recycle plastic bottles. It is already becoming popular in numerous countries because roads created with plastic particles outperform conventional ones. Most used plastic is polyethylene which we use every day in the form of shopping bags and water bottles. When heated at 100-150°C, the waste softens and binds effectively to polyethylene, polypropylene, and polystyrene. Following that, the rubbish is coarsely cut and put into the aggregates at a certain temperature. Plastic bottle waste improves the road's binding characteristics, making it more durable and stronger. As a result, plastic roads benefit countries such as Pakistan, which has sections exposed to both highly hot and severely cold weather.

Researchers discovered that combining plastic, bitumen, and aggregates improves road qualities. Specifically, rutting is considerably reduced, and pothole formation is avoided. According to the findings, Plastic rubbish can sustain high traffic and is more resilient than flexible pavement. Furthermore, employing plastic trash can lower bitumen usage by 10% [9]. Researcher's researched the viscoelastic nature of binders and discovered that estimating the phase angles and complex modulus of the binders at various temperatures and loading rates is critical for accurately simulating varied climatic and loading circumstances [10].

Researcher's research on the usage of plastic trashes in pavement building. They adjusted the blend by adding up to 20% plastic filler. The amended concrete mix, which used plastic filler as a 10% replacement for coarse aggregate, met the IS specification. However, replacing 20% of the coarse aggregate with plastic filler reduced the density of the concrete [11]. Researcher's research on the reprocess of plastic trashes in asphalt mixtures discovered that RPE from silo bags increases mixture performance. The results show that adding 2% SBF improves the mixture's performance. Properly adding plastic trash can improve the mechanical and physical properties of the asphalt blend while also helping to dispose of significant amounts of plastic waste [12].

A research focussed on the usage of waste plastic in the building of roads and developed a kilometer-long test track that was tested in Karnataka using plastic trash as a modifier. They observed that the durability of the plastic roads are more than the conventional ones, they last longer because of the binding properties of the plastic, they also observed that the rainwater does not enter the road because of the plastic in the tar, similarly the other physical properties were observed to be enhanced [13].

A study investigated the utilization of plastic trash in pavement construction. They assessed mix qualities such as bulk density, Marshall Stability, voids, and flow. They also looked at how different soaking conditions affected the combination. Their findings revealed that the combination had the highest Marshall Stability, with an Optimum Binder Content (OBC) of 8% plastic. The optimal plastic concentration for 80/100 grade bitumen was found to be 8%. The researchers discovered that blending bitumen with plastic wasn't possible in the wet procedure due to the greater melting point of plastic. However, combining waste plastic to 80/100-grade bitumen resulted in a 10%-15% increase in stability. The water sensitivity test findings indicated a decline in stability values. Unsoaked specimens had good stability values, however, soaked specimens showed a reduction [14].

The study compared the impact of PCA-modified Bituminous Asphaltic Concrete (BAC) and PMB-modified BAC on pavement. Tests have been carried out on mix designs that included 60/70 penetration grade asphaltic concrete (5%), 6% fine aggregate, and aggregate compositions of 68% coarse aggregate, and 21% filler. It was discovered that both PCA and PMC resulted in greater Marshall Stability with increasing plastic content. Air gaps increased with increasing plastic waste for PCA, however reduced for PMB. In PMB-modified BAC, adding PET plastic waste decreased penetration value while increasing the softening point, plasticity index, and ductility. In contrast, increasing plastic content in PCA-modified BAC led to lower density and increased air spaces, VMA, and Marshall Stability. The study used plastic trash in pavement construction and discovered that plastic waste pavement had increased water resistance, minimizing bitumen peeling from aggregates [15].

The possibility of using plastic trash in bituminous pavement construction was investigated. The study showed that adding plastic improves bitumen's rheological qualities. The qualities of AC-20 bitumen may be achieved by introducing 2% polymer content into AC-10 bitumen. This modification not only improves Marshall's stability, additionally, it also increases the design life, strength, and other desired characteristics of asphalt concrete pavements. Simultaneously, bitumen use is lowered [16]. (Patel, Popli, & Bhatt, 2014), Emphasizing the urgent need for reconsidering and developing new standards and building of roadways in India using plastic bottle waste. This strategy not only lowers the cost of road building but also eliminates practically all maintenance costs. Furthermore, the roads have greater strength, as demonstrated by higher Marshall Stability ratings, improved resistance to precipitation and water stagnation, and reduced concerns such as stripping and potholes. Furthermore, the mix's binding and bonding have been shown to improve, resulting in lower aggregate porosity and, as a result, less rutting and raveling [17]. (Amit Gawande, 2012), established a systematic approach to using plastic trashes as a bitumen modifier for pavements with flexible characteristics. Extensive research with various percentages of plastic waste revealed that integrating between 5 and 10% plastic waste by the amount of bitumen considerably improves strength, Marshall Stability, fatigue life, and other desired pavement attributes [18]. (Bale, 2011), Over the past few years, a notable rise has occurred in interest in employing plastic trash in road building, particularly in underdeveloped nations. Heating polymers like polyethylene, polypropylene, and polystyrene to 100-160°C softens them and improves their binding qualities. When these softened polymers are combined with bitumen, the resultant material is appropriate for road paving. This technology promises to build sturdy, durable, and environmentally friendly roadways, potentially reducing the environmental impact of plastic trash in the future [19]. (Hayat, Rahim, Khan, & Rehman, 2020), Umar Hayat investigated the efficacy of asphalt mixes with 30% (RAP) binder and 4% polyethylene terephthalate (PET) for road building. Their study shows that using recycled non-biodegradable plastics to build roads is a cheap, easy and sustainable way to support sustainability. The study encourages additional investigation into the complex behavior of binders modified with RAP and PET, particularly regarding fatigue resistance, permanent deformation, and low-temperature cracking [20].

In the context of Pakistan's road network, which is subject to high temperatures and heavy traffic loads, the combination of RAP, plastic waste, and rejuvenators could offer a sustainable and effective solution for improving road durability and reducing the environmental impact of road construction. The application of these materials could lead to pavements that are more resistant to common forms of distress, such as rutting, cracking, and moisture damage, while also addressing the pressing issue of plastic waste management.

Given the potential benefits, this study seeks to investigate the combined effect of waste plastic bottles and rejuvenators on the performance of recycled asphalt mixtures. Specifically, the research will focus on optimizing the percentage of plastic waste and rejuvenator content to maximize the mechanical performance of the asphalt, particularly in terms of resistance to permanent deformation, rutting, and cracking. By doing so, this study aims to contribute to the growing body of knowledge on sustainable road construction practices and offer practical solutions for reducing the environmental impact of asphalt pavements. We concurrently address two issues.

A. Research Significance

Our possible approach is to employ recycled plastic debris (shredded) in pavements. Therefore, the research significance of this project is:

- Every year, lots of tons of plastic waste are disposed of by utilizing them as binder in asphalt.
- Construction of durable and sustainable pavements.
- Environmental Friendly in nature.

II. RESEARCH OBJECTIVES

The key objectives of the research project are as follows:

To optimize the incorporation of 5-25% plastic bottle waste and 15% recycled asphalt mixture, rejuvenated with 2–10% Waste Engine Oil (WEO) in Hot Mix Asphalt to assess the environmental benefits of using plastic bottle waste and recycled materials by evaluating its impact on Marshall stability, flow, and volumetric properties to ensure a sustainable and high-performance mix and reduce plastic waste accumulation, conservation of natural aggregates, and potential carbon footprint reduction.

III. MATERIALS & METHODS

A. Aggregates

Aggregate, Bitumen, and Reclaimed Asphalt Pavement (RAP) were gathered from Peshawar. Because aggregate resists deformation in pavements, it should have sufficient strength and texture to withstand its purpose in pavement. Pavements' strength and longevity are largely determined by their aggregate content, which takes the maximum load. The texture and shape of the aggregate have a significant impact on its strength-related properties.

Table 1: Properties of Aggregate

Description	References	Values
Water absorption	ASTM C127 [21]	1.0%
Impact value	BS-812 [22]	12%
Sp. Gravity of C.A.	ASTM C127 [21]	2.6
Soundness	ASTM C88 [23]	3.81

B. Plastic

Plastic waste originates from different plastic materials and there are different types of polymers but here we use Polyethylene-based plastic bottle waste (PBW), which we obtain from packaging films, and plastic-bottles. The plastic materials, which are made of this type of plastic, are recycled by shredding them into pieces, cleaning them through a process and then modified them into grains, resulting into Polyethylene-based plastic bottle waste (PBW) i.e. (water bottles grains) as shown in Figure 1. During this process, the PBW waste was cleaned, shredded into flakes, and then melted and blended with bitumen. PBW enhances asphalt performance and helps reduce environmental plastic waste.

C. Reclaimed Asphalt Aggregate

The term "reclaimed asphalt aggregate" refers to aggregate and asphalt-containing pavement materials that have been removed and/or recovered. These materials are produced during the reconstruction, resurfacing, or removal of asphalt roads. When "RAP" is crushed and screened correctly, it produces fine, well-graded aggregates that are coated with asphalt [24].

Fig. 1. Polyethylene Terephthalate (PET) Grains (Shredded)

D. Bitumen

It was obtained from NHA (National Highway Authority); Peshawar. It was the ARL 60/70. Bitumen is a binder used in paving and roofing works. 85% of all bitumen is used as an asphalt binder on roads, runways, parking lots and sidewalks. The road is then spread with a mixture of crushed stone, gravel, and thick bitumen for retention. Several tests are performed as per ASTM to check the properties of bitumen affecting pavement.

Table 2: Characteristics of Bitumen

S. No.	Properties and References	Average Values
1	Penetration (ASTM D5) [25]	60.66 or 6.06mm
2	Softening point (ASTM D36) [26]	56°c
3	Flash and fire point (ASTM D3143) [27]	270°c and 290°c
4	Ductility test (ASTM-D113) [28]	115
5	Viscosity (ASTM D4402) [29]	0.40 Pa-s

IV. RESEARCH METHODOLOGY

The experiment was conducted at SUIT, Peshawar. Bitumen with an evaluation of 60/70 was gathered from Peshawar, while plastic was gathered from Peshawar Saddar. The necessary quantity of plastic, bitumen, and aggregates were gathered from sites that were easily accessible locally. I used materials that were readily available to me locally for this project. The study's methodology is illustrated in Figure 2, which outlines four phases. 27 samples were created. Seven samples were prepared for rutting testing, while the remaining ten samples were examined to see how different percentages of waste plastic affect asphaltic mixes. The ten samples were examined to determine the OBC on Marshal Procedure, as shown in the result analysis section. 5 weight percentages (i.e., 5, 10, 15, 20, and 25%) of plastic bottle waste were investigated, along with rejuvenating agents such as waste vegetable oil and waste engine oil, at doses of 6-10%, respectively.

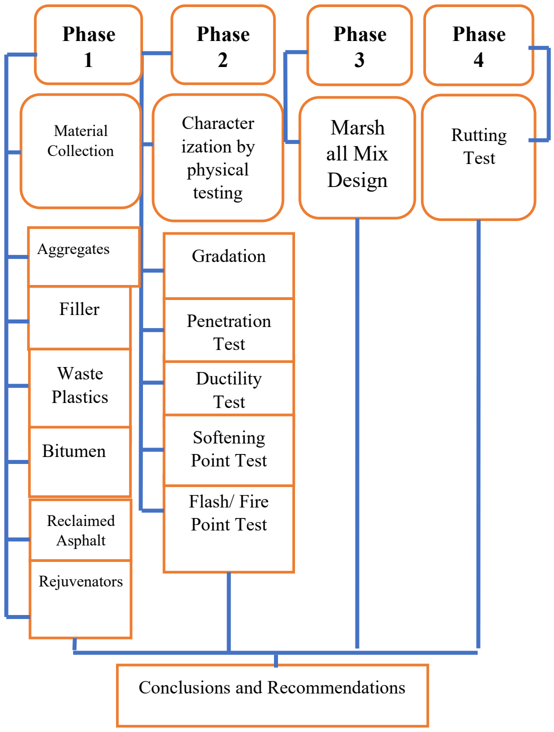

Fig. 2: Research Flow Chart

There will be a thorough breakdown of the steps used and techniques employed to carry out this examination. I initially performed a sieve analysis (ASTM C 136-04) [30] on the aggregates to separate the aggregates into different sizes for use in creating Marshall Mix sample preparation. To assess compliance with design, verification, and production control parameters, the sieve analysis analyzes the gradation, which is the size-wise distribution of aggregate fragments inside a sample. By graphically representing gradation curves, one can establish the relationship between various aggregates or aggregate blends, evaluate their compliance, and predict production patterns. I collected coarse aggregates and filler; the sieve analysis was done for both types of aggregates. The equipment used for the gradation was Asphalt Institute specified sieves combination according to Marshall Mix Design (1″, 3/4″, 3/8″, # 4, # 8, # 50, # 200, Pan), and Sieve Shaker. The sieve combinations are as shown in Figure, placed combination of sieves in an electric sieve shaker then put the dried Aggregates of about 2 kg which is a mixture of aggregates below 25mm size on the top sieve (1″), and then start the sieves shaker for about

15 minutes and then after 15 minutes I stopped the sieves shaker and get the different sizes of aggregates from different sieves and then save it in separate bags or plastic containers for the use in Marshall Mix design. According to (ASTM D6927) [31], making Marshal Mix Design ready is what this phase entails. Different-sized aggregates (Course and Fine) were blended to provide the gradation required by the standards. 4.5%, 5%, 4%, and 3.5% of the bitumen were added. Mixing was done at 140°C–160°C to ensure proper melting and blending of PBW with bitumen. For every mix, the value of G_{mb}, G_{mm}, stability, flow, and volumetric was extracted. During this phase, tests were conducted to verify the G_{mb}, G_{mm}, stability, flow, and volumetric properties of the plastic substituted for bitumen in the asphalt mix at varied percentages. After analyzing the data, it was determined how the outcomes of the modified and conventional samples differed. Standard bitumen tests were carried out for additional testing, including the penetration test, softening point, fire and flash point test, and ductility test. The recovered bitumen was examined using a centrifuge, solvent dissolving, and subsequent filtering according to standards. For rutting, samples were prepared with the help of the OBC that we had found. Then five (05) rutting samples were prepared in a mix having plastic content of 5%, 10%, 15%, 20%, and 25%. The sample mixes were compacted with the help of a Marshall Compactor.

. Thus, the samples were compacted and put forward for the rutting test. All specimens were examined under controlled conditions at 60 degrees Celsius, maintaining constant confining pressure, and were made to complete ten thousand (10,000) passes on each sample and the data was recorded.

Table 3: Marshall Sample Blend

Total Weight of Sample = 1200 gms				
Maximum Aggregate Size = 19 mm				
Trial Mixes	Bitumen Content	Biutmen	Aggregate Content	Aggregates
	%	gm	%	gm
1	3.5	42	96.5	1158
2	4	48	96	1152
3	4.5	54	95.5	1146
4	5	60	95	1140
5	5.5	66	94.5	1134

V. RESULTS ANALYSIS

This section covers the findings from the laboratory study in three stages. To begin, the asphalt binder course gradation curve is calculated by combining aggregates. In the second stage, the Marshall test is carried out with various bituminous percentages (3.5%, 4%, 4.5%, 5%, and 5.5%) and volumetric properties were recorded in below tables. The data are then evaluated to investigate the (OBC). An OBC of 4.2% Following the formation of the OBC, the next step was to investigate the effects of adding various amounts of waste plastic (5%, 10%, 15%, and 20% by weight of OBC) on the quality of the asphalt mix. The Marshall Test results for these modified asphalt mixes are being analyzed to determine the optimal amount of plastic waste as a modifying ingredient. Then the rutting test was implemented on samples by passing ten thousand (10,000) passes and results were noted as shown in Fig. 8 [32-33]. The study utilized asphalt prepared with Margalla aggregated due to its adequate performance as a control sample [34] in order to see the effect of PBW and rejuvenator content on RAP. As shown in Figure 3, the aggregate blend for the asphalt mix was prepared following the NHA grading.

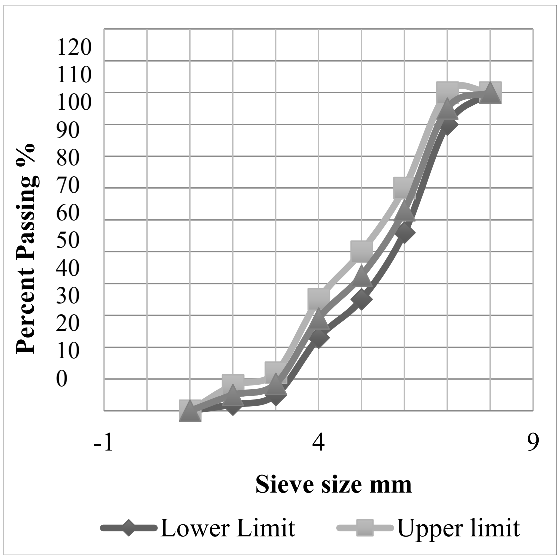

Fig. 3. Grain Size Distribution

A. Marshall Mix Design

Samples of Marshall Mix were made in order to determine the ideal proportion of plastic bottle waste by weight of OBC and the ideal bitumen content (OBC).

There are two stages to it.

To figure out the ideal bitumen content (OBC), several samples weighing 1200 g were made with four distinct bitumen levels (ranging from 3.5 to 5% with 0.5% incrimination). The results for Marshall Stability, Va, VFA, Flow, G_{mb}, VMA, and G_{mm} are displayed below.

Table 4: Marshal Test Report for Conventional Sample

Asphalt Content (%)	Stability (KN)	Flow (mm)	Density (Kg/m^3)	G_{mb}	G_{mm}	AV (%)	VMA (%)	VFA (%)
3.5	10.3	2.13	2335.1	2.31	2.51	6.82	14.16	51.8
4	11.80	2.49	2362.0	2.33	2.48	4.88	13.62	64.1
4.5	12.20	2.90	2385.6	2.32	2.49	3.32	13.10	73.4
5	11.30	3.42	2391.4	2.35	2.47	3.21	13.21	76.1
5.5	9.40	4.33	2392.0	2.34	2.46	2.74	13.85	80.3

A.1. Determination of OBC

- Bitumen content with highest stability = 4.2 %
- Bitumen content at the median of allowable proportion of air voids is 4.0%

Optimum Bitumen Content = $\frac{5.0+4.5+4}{3}$ = 4.2 percent.

A.2. Marshall Mix Design for Optimum Modifier Content (RAP)

After obtaining the OBC, 1200 gram weight samples were made using Rejuvenator and 5 different plastic Polyethylene Terephthalate (PET) contents (from 5 to 25% with 5% incrementation) to acquire the optimal modifier (plastic) contents by weight of OBC. For Marshall Stability and Flow, Va, VMA, VFA. The reclaimed blend was made using the same gradation as the virgin gradation illustrated in Figure 3.

Table 5: Marshall Test Report for Rejuvenated Rap Samples

PBW (%)	Recycled Mixture (%)	Rejuvenator (%)	Stability (KN)	Flow (mm)	Density (Kg/m^3)	A.V (%)	VMA (%)	VFA (%)
5	15	6	15.50	3.2	2335	5.1	14.20	66.00
10		7	16.10	3.5	2365	5.0	13.70	67.80
15		8	16.41	3.8	2390	4.2	13.30	69.00
20		9	14.70	4.0	2395	3.5	13.00	77.00
25		10	12.50	4.2	2385	3.8	14.00	77.50

It is clear that the asphalt mixture comprising of 15% recycled materials, 85% virgin materials showed better performance at PBW of 15% and WEO of 8%.

B. Rutting Test

The Rutting Test was implemented on samples prepared at optimum rejuvenator content (WEO) of 8% and OBC of 4,2% by passing ten thousand (10,000) passes of the wheel tracking machine, and results were presented in figure 4, with main highlights as under;

- X-Axis: Number of passes (loading cycles), representing traffic load.
- Y-Axis: Rut depth measurement (in mm), indicating permanent deformation in asphalt.
- Legend: Different percentages of plastic bottle waste (PBW) are compared to a virgin (unmodified) asphalt sample.
- Virgin Sample (No PBW): Exhibits the highest rut depth, showing the most significant deformation as loading cycles increase.
- 5–10% PBW: Shows noticeable improvement, with reduced rut depth compared to the virgin sample.
- 15–20% PBW: Further reduces rutting, indicating better resistance to permanent deformation.
- 20–25% PBW: Displays the lowest rut depth, suggesting the best performance in resisting rutting.
- As the plastic content increases, rut depth decreases, meaning the modified asphalt is more resistant to deformation.
- The difference becomes more pronounced after 4,000–6,000 passes, indicating improved long-term performance with PBW modification.
- The 15% PBW modified mix at WEO of 8% performs best, showing the least rutting, suggesting that plastic bottle waste significantly enhances the structural integrity of the asphalt.
- Plastic modification strengthens asphalt, reducing rutting and extending pavement life.
- Higher PBW content (up to 25%) also yields the best rut resistance. However, excessive stiffness might increase cracking risks.

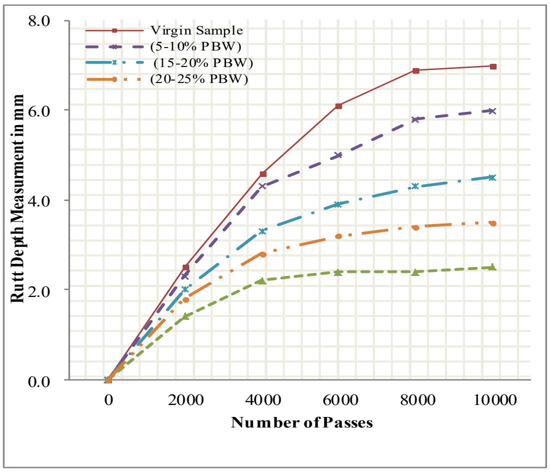

Fig. 4. Rut Depth Against the Number of Cycles.

The rut depth in combinations with 5-10% PBW was 4.75 mm; however, in mixtures with 15-20% PBW, the amount of rut depth was reduced to 2.2 mm, exhibiting good rutting resistance within the appropriate limits.

However, research shows that 15% PBW provides the most effective blend of integrity and resistance, making that levels the most effective for usage. The optimum rejuvenator as per performance is 9%. These findings are consistent with the study conducted by Diyar, (2023) [35] where various percentage of RAP were evaluated, and findings of the study conducted my Karim (2024) where Polypropylene fibers were employed in asphalt [36]. Various studies were conducted by Mufti, (2024) [37], Arif, (2020) [38], Nawaz, (2019) [39], and Akbar, (2019) [40] where RAP was explored in terms of rutting. Their findings were exactly comparable to the findings of the current study.

The study recommends long-term field performance of asphalt modified with plastic bottle wastes for future research.

VI. Conclusion

The following conclusions were drawn:

1. Using plastic bottle waste in asphalt not only strengthens the pavement but also helps tackle plastic pollution, making it an eco-friendly solution.
2. The asphalt mix comprised of 15% recycled materials showed best results in terms of Marshall parameters at Optimum binder content of 4.2%, PBW of 15%, and WEO of 8%.
3. As the plastic content increases, rut depth decreases, meaning the modified asphalt is more resistant to deformation. The difference in rut resistance becomes more pronounced after 4,000–6,000 passes, indicating improved long-term performance with PBW modification.
4. The 15% PBW modified mix at WEO of 8% and 15% recycled materials performs best, showing the least rutting, suggesting that plastic bottle waste significantly enhances the structural integrity of the asphalt.
5. Plastic modification strengthens asphalt, reducing rutting and extending pavement life.
6. Higher PBW content (up to 25%) also yields the best rut resistance. However, excessive stiffness might increase fatigue cracking risks.

Future Work: While plastic reduces rutting, it might increase the risk of fatigue cracking over time. Future studies should focus on fatigue performance and test different plastic types (HDPE, PET) in varying amounts to further refine pavement durability.

VII. Author Contributions

Investigations were carried out by F.K. and M.A. Methodology was developed by M.A. and F.K. The original draft was put together by M.A., F.K. Writing, review, editing, and supervision were managed by F.K., M.A. The final version of the manuscript was reviewed and approved by all the authors.

VIII. Acknowledgments

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IX. Conflicts of Interest

The authors have disclosed that they have no conflicts of interest to report.

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