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Sustainable Road Infrastructure Using Plastic Waste-Modified Asphalt: Performance Evaluation and Life-Cycle Cost Analysis

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ABSTRACT

Sustainable infrastructure development requires innovative solutions that address both environmental challenges and economic efficiency. The increasing accumulation of plastic waste, coupled with the demand for durable construction materials, has encouraged the use of plastic-modified asphalt in road engineering. This study evaluates the mechanical performance and life-cycle cost benefits of bitumen mixtures incorporating varying percentages of plastic waste in Pakistan. Standard tests, including Marshall Stability and rutting resistance, were conducted to assess performance. Results indicate that a 9% plastic content significantly enhances stiffness, particle interlocking, and durability, with only 3.9 mm rutting observed after 10,000 load cycles, suggesting extended pavement life. Although higher plastic content (13%) shows moderate performance gains, optimal results were achieved at 9%. Life-cycle cost analysis reveals potential savings of approximately PKR 3.1 million per kilometre due to reduced maintenance and material replacement. The findings demonstrate that plastic-modified asphalt contributes to sustainable road construction by improving performance while mitigating plastic pollution, supporting environmentally responsible and cost-effective infrastructure development.

1. Introduction

The plastic waste is one of the most challenging environmental issues our planet faces. Every year, millions of tons of fresh plastic are produced, much of which escapes the recycling loop, heading straight to overcrowded landfills. This waste contributes to pollution and damages fragile ecosystems. Single-use plastics such as straws, Styrofoam containers, and over-packaged consumer goods are especially harmful due to their sheer volume and long-lasting environmental impact. These materials persist in the environment for centuries, and their accumulation disrupts ecosystems,

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contaminates soils, and harms marine life. The prolonged presence of plastic waste urgently calls for action to protect both the land and marine environments.

In Pakistan, the crisis is escalating, partly due to inadequate waste management systems and a lack of public awareness. Estimates suggest that the country adds nearly three million tons of disposable plastic to its waste stream annually. Much of this waste ends up in urban areas, along roads, and in rivers, especially during seasonal floods. The environmental and economic costs are borne by the communities involved in cleaning up these materials [1,2]. Meanwhile, Pakistan's road infrastructure is under immense strain due to rising vehicle numbers, extreme weather patterns, and budget constraints that limit access to durable materials. Conventional asphalt often fails to perform over time, resulting in premature wear and increased maintenance costs. To address both the challenges of road degradation and plastic waste accumulation, innovative solutions are necessary. One promising approach is the use of plastic waste in road construction, specifically by integrating it into asphalt mixtures. This method not only offers a potential solution to plastic pollution but also creates stronger, more durable roads. Research from countries like India, the UK, and South Africa demonstrates the effectiveness of plastic-modified asphalt, with India already constructing over 100,000 kilometers of plastic-based roads. These roads are more durable, require less maintenance, and are more cost-effective, particularly in busy cities where wear and tear is high [3, 4, 5, 6].

In the UK, trials have shown that plastic-modified asphalt resists rutting better and has a longer lifespan. Lifecycle assessments have also shown a significant reduction in carbon emissions, aligning with the UK's environmental goals [7]. South Africa has also adopted this method, applying it on rural roads with lower traffic, and has found that it reduces costs while maintaining road quality, especially when adapted to local aggregates and weather conditions. This highlights the importance of tailoring materials to meet local needs, ensuring project success [8].

Previous studies mainly focused on the general mechanical properties of plastic-modified asphalt. However, limited research has been conducted in the context of Pakistan considering both pavement performance and life-cycle cost analysis simultaneously. Given these global advancements, this study investigates the use of polyethylene terephthalate (PET) waste in asphalt mixtures, specifically under conditions relevant to Pakistan. The study focuses on how aggregate gradation influences the mechanical performance of these mixtures. Additionally, the research evaluates the economic feasibility and environmental benefits of PET-modified asphalt through lifecycle cost and sustainability analysis. By combining material performance with economic and environmental considerations, this research seeks to offer a practical and sustainable solution for road construction in Pakistan [9, 10].

The study is motivated by the increasing plastic waste problem and the need for sustainable and durable pavement materials in Pakistan. The main contributions of this research include:

- evaluation of the mechanical performance of asphalt mixtures with different plastic contents.
- identification of the optimum plastic percentage for enhanced pavement performance.
- assessment of long-term economic benefits through life-cycle cost analysis.

2. Literature Review

Asphalt mixtures are composite materials widely used in road construction due to their strong structural performance, flexibility, and cost-effectiveness. These mixtures typically consist of two main components: asphalt binder (bitumen), which acts as the binding agent, and mineral aggregates, which provide structural strength, durability, and resistance to traffic stresses. The overall performance and durability of asphalt pavements depend on various factors, including the properties of the binder, the type of aggregates (such as size, shape, and gradation), traffic loading, and external environmental conditions like temperature and moisture [8, 9].

Although they are commonly used, traditional asphalt mixtures often face challenges under higher traffic loads and harsh environmental conditions. Common issues include rutting, fatigue cracking, thermal cracking, and moisture stripping, all of which contribute to more frequent maintenance needs, reduced service life, and increased lifecycle costs. To address these problems, numerous modification technologies have been developed, such as the incorporation of polymers, rubber, and, more recently, plastic waste. These additives are used to improve the rheological and mechanical properties of asphalt mixtures, making them more resilient under extreme conditions [10].

Plastic waste, being polymeric in nature, enhances the properties of asphalt binder by improving stiffness, elasticity, and resistance to temperature fluctuations and moisture damage. This not only helps to extend the lifespan of the pavement but also promotes environmental sustainability by incorporating post-consumer plastic as a value-added material in infrastructure construction. The use of plastic waste in asphalt mixtures represents a dual benefit: reducing waste while enhancing the quality of road materials [11].

The use of plastic waste in asphalt mixtures is emerging as a promising solution for sustainable pavement construction. Materials such as low-density polyethylene (LDPE), high-density polyethylene (HDPE), polypropylene (PP), and polystyrene (PS) have properties that improve the performance of bitumen. These plastics enhance the stiffness, viscosity, and elasticity of the binder, making the asphalt more resistant to deformation and cracking [12, 13, 14].

Plastic-modified asphalt offers several performance and environmental advantages. One of the key benefits is its improved resistance to rutting and surface cracking. The added stiffness helps reduce permanent deformation under heavy traffic loads, while the increased elasticity allows the pavement to better withstand temperature fluctuations and fatigue, especially in regions with harsh climates [11].

This type of asphalt also demonstrates a higher load-bearing capacity, making it ideal for highways, industrial zones, and other high-traffic routes where durability and long-term performance are essential [16]. From a materials perspective, substituting part of the traditional petroleum-based bitumen with recycled plastic reduces reliance on virgin resources. This not only lowers construction and maintenance costs but also supports the use of locally available waste materials, contributing to more sustainable and circular practices [15, 16, 17].

Environmentally, the approach offers a dual benefit: it diverts plastic waste from landfills and oceans and reduces the greenhouse gas emissions throughout the pavement’s life cycle. As a result, plastic-modified asphalt stands out as an eco-friendly option for modern infrastructure development [18].

Despite the growing body of research on plastic-modified asphalt, several limitations remain in the existing literature. Most studies have focused on commonly used polymers such as polyethylene (PE) and polypropylene (PP), while comparatively fewer investigations have been conducted on polyethylene terephthalate (PET), particularly under conventional asphalt mixing conditions. Furthermore, many studies emphasize material performance without adequately considering the influence of aggregate gradation on mixture behavior.

In the context of Pakistan, research on plastic-modified asphalt is still limited, especially in terms of integrating locally applicable aggregate gradation standards, such as NHA Class A and B.

Additionally, there is a lack of comprehensive studies that combine mechanical performance evaluation with economic and environmental impact assessments. Therefore, this study aims to address these gaps by evaluating the performance of PET-modified asphalt mixtures using controlled aggregate gradation, while also incorporating rutting analysis, Marshall stability testing, and life cycle cost and environmental impact assessments relevant to Pakistan.

3. Methods

This study addresses the various challenges faced by asphalt pavements in both urban and rural areas across Pakistan. One of the most pressing issues is the heavy traffic load, particularly on highways and congested city roads, where continuous vehicular stress accelerates surface deterioration. In addition to this, Pakistan's sharp seasonal temperature fluctuations ranging from intense summer heat to cold winter conditions put further strain on pavement structures. These extreme conditions often lead to rutting, cracking, and a gradual loss of structural integrity in the asphalt.

To address these challenges, the experimental design of this study was specifically tailored to simulate real-world service conditions. It incorporates key variables such as heavy traffic loads, extreme temperatures, and exposure to harsh environmental elements. This comprehensive approach enables a thorough evaluation of plastic-modified asphalt's performance under the unique road infrastructure demands found in Pakistan.

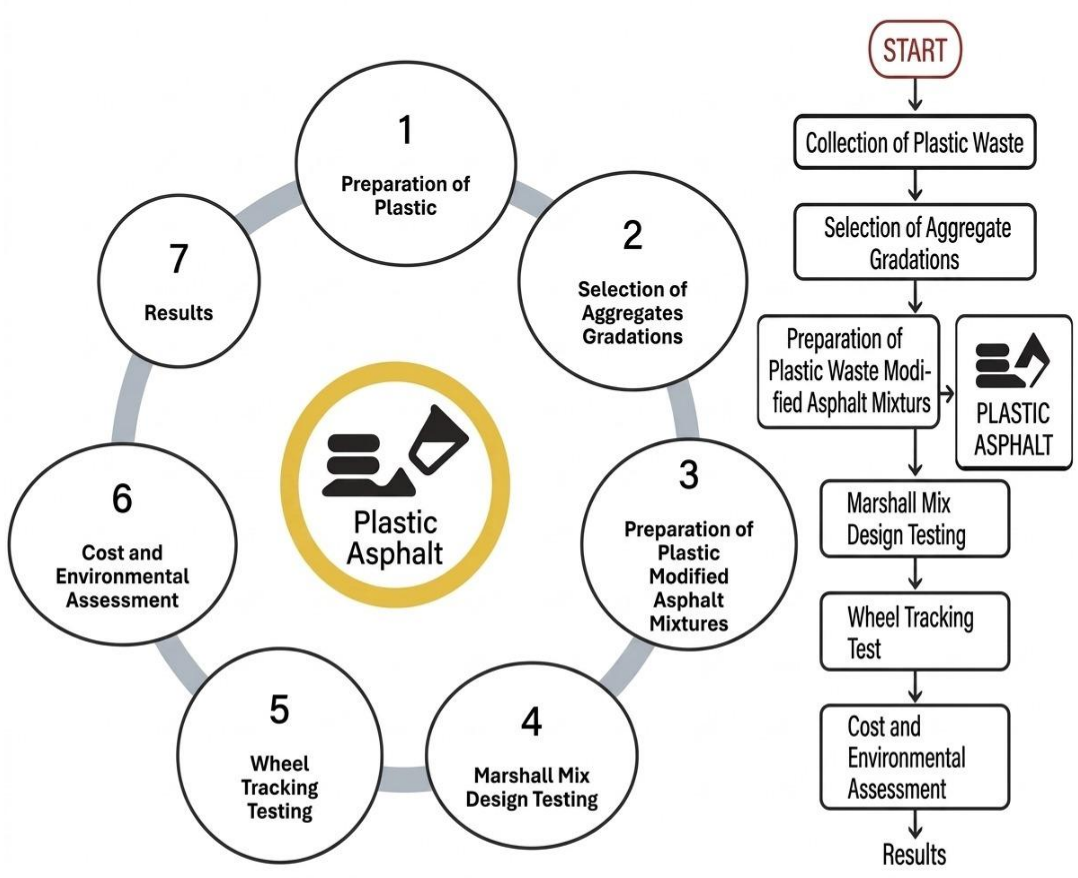

Fig. 1 Flowchart showing Methodology Steps

3.1 Sample Collection

Plastic Waste (PET): The plastic material used in this study was polyethylene terephthalate (PET), a polymer commonly found in beverage bottles and packaging products. PET was sourced from municipal solid waste through local waste management systems. It was selected for its wide availability, high strength, and proven ability in previous studies to enhance the properties of asphalt binders as presented in Figure 2.

Fig. 2 Plastic Waste particles

Aggregates: The aggregates used in this study were collected from nearby quarries to ensure they reflect the materials typically employed in road construction across Pakistan. Prior to their use, the aggregates were tested according to ASTM and AASHTO standards to ensure they met requirements for cleanliness, particle size distribution, and mechanical strength. These properties are essential for achieving strong interlocking and producing durable asphalt mixtures.

Asphalt Binder: A 60/70 penetration grade bitumen, commonly used in Pakistan, was chosen as the base binder for this study. This grade is well-suited to the local climatic conditions and traffic loads, making it an appropriate reference material for evaluating the improvements provided by PET modification.

3.2 Materials Preparation

Aggregate Preparation

Aggregates form the primary component of asphalt mixtures, and their particle size distribution plays a crucial role in determining the mixture’s density, air void content, and overall mechanical performance. Properly graded aggregates promote better interlocking between particles, which enhances load transfer efficiency across the pavement structure. This improved interlock not only strengthens the mixture but also boosts its resistance to deformation and moisture-related damage [19].

Aggregate gradation is regulated by standards set by various organizations, including ASTM, AASHTO, and Pakistan's National Highway Authority (NHA) [20]. To ensure dense-graded mixtures with the right amount of void filling, the Fuller-Thompson curve is commonly used. In this study, both NHA-A and NHA-B gradation types were adopted to evaluate their influence on the performance of asphalt modified with plastic waste.

Table 1
NHA Class A Gradation

Sieve Size (mm)	NHA Class A% Passing
37.5	100
25	95
9.5	63
4.75	42.5
2.36	29
0.075	5
Pan	0

The relationship between plastic additives and aggregate gradation is vital for the overall performance of asphalt pavements. The gradation pattern dictates how the mixture will behave under varying environmental conditions and traffic load. Coarse gradation helps improve the interlocking of particles, which enhances the mixture's resistance to rutting and provides greater structural stability. This is particularly beneficial for roads that experience heavy traffic. However, this type of gradation can lead to higher air voids, which may reduce the mixture's durability and make it more vulnerable to moisture-related damage [21, 22].

Conversely, fine gradation improves the mixture's workability and facilitates easier compaction during construction. It provides a smoother surface finish and improves performance in colder climates. However, fine-graded mixtures can lose structural integrity at higher temperatures and are more susceptible to deformation under heavy loads. Achieving the right balance between coarse and fine gradation is crucial. This balance ensures that the pavement can meet specific traffic demands and endure varying climatic conditions while maintaining long-term durability.

- Well-Graded: This mix contains a balanced amount of fine and coarse particles, ensuring proper packing and good workability.
- Coarse-Graded: This mix includes predominantly large particles that enhance load-bearing capacity and reduce deformation.
- Fine-Graded: This mix has more fine particles, improving workability and surface finish, although it may reduce rutting resistance.
- Washing: The aggregates were thoroughly washed to remove dust and fines that could interfere with bonding to the binder.

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Stockpiling: Clean aggregates were stored separately by gradation type for easy use during mix preparation.

Incorporation of PET in Asphalt Mixture: In this study, polyethylene terephthalate (PET) waste was incorporated into the asphalt mixture using a modified blending approach. Shredded PET plastic was added during the mixing stage at temperatures ranging between 160°C and 170°C, which are typical for asphalt production in Pakistan.

Addition of PET: It is important to note that PET has a relatively high melting temperature (approximately 250°C). Therefore, at the selected mixing temperatures, PET was not expected to fully melt and chemically blend with the bitumen. Instead, it behaved as a thermoplastic additive within the asphalt mixture, contributing to improved mechanical performance through physical interaction, particle reinforcement, and partial softening [23, 24, 25].

Mixing Process: The PET particles were uniformly distributed within the hot mix using mechanical mixing to ensure consistent dispersion throughout the aggregate-binder matrix. This approach is consistent with the dry or semi-dry process reported in previous studies, where plastic materials act as reinforcing modifiers rather than fully dissolved polymers [26, 27, 28].

In this context, the main role of PET in the mixture is to increase the stiffness, enhance resistance to permanent deformation, and improve the overall structural stability when subjected to loading conditions.

3.3 Mix Design & Preparation

Selection of Mix Design Method: This study used the Marshall Mix Design method, which is widely recognized and commonly used in Pakistan for designing asphalt mixtures. The method is highly regarded for its reliability in evaluating mixture stability and overall performance, making it ideal for assessing the influence of PET waste and variations in aggregate gradation. It focuses on key parameters such as stability, flow, and binder content, offering a comprehensive evaluation of the mixture's suitability for practical field use.

It is important to note that this study does not include a direct comparison between PET-modified asphalt mixtures at different plastic contents. A conventional control mixture without plastic was not part of the experimental program, which is acknowledged as a limitation of the study. However, the analysis comparing different PET content levels provides useful insights into how varying plastic dosages affect mixture performance.

Although a conventional control mixture was not included, the evaluation of different PET content levels offers valuable insights into performance trends. For future studies, including a control mix would be beneficial for direct benchmarking.

Heating Aggregates: The aggregates were preheated to a temperature range of 160–170°C, which is considered optimal for proper integration with the asphalt binder. Maintaining compatible temperatures for both the aggregates and the binder helps reduce the risk of segregation and ensures adequate bonding. The aggregates were heated to this range to ensure proper bonding with the hot binder during mixing.

Mixing Process: Shredded PET plastic was added to the hot aggregate–binder mixture during the mixing process to ensure uniform distribution.

The PET-modified binder was then thoroughly mixed with the preheated aggregates to produce a uniform and consistent asphalt mixture.

Sample Molding: The prepared hot mix was compacted using a Marshall hammer into cylindrical molds measuring 100 mm in diameter and 63.5 mm in height. These molded specimens were then used for laboratory performance testing.

Plastic Content Variations: The selection of PET content in this study was based on ranges reported in previous research, where plastic waste is typically incorporated between 5% and 15% by weight of the binder. Based on preliminary observations and literature trends indicating improved performance at moderate plastic contents, three dosage levels 9%, 11%, and 13% were chosen for detailed evaluation.

These percentages were selected to represent low, intermediate, and relatively high plastic contents, enabling an assessment of how increasing PET dosage affects the mechanical performance and rutting resistance of asphalt mixtures.

Marshall Stability and Flow Test: Each cylindrical specimen is placed in the Marshall testing apparatus and subjected to compression until failure. The highest load sustained before failure is recorded as the stability value, and the corresponding deformation is noted as the flow value. Together, these results provide an indication of how the mixture will perform under traffic loads.

Each specimen was compacted according to standard Marshall compaction procedures, following ASTM/AASHTO guidelines.

Rutting Resistance Test: Specimens are tested in a wheel-tracking device at 60°C, where a moving wheel applies a load repeatedly. The depth of the rut formed is measured over time. These results help assess the pavement's potential for rutting, which is directly related to its service life.

For each test condition, multiple specimens were prepared and tested to ensure consistency in the results, with the reported values representing average measurements.

4. Results & Discussions

4.1 Marshall Mix Design Test

The Marshall Mix Design method is one of the most widely used procedures for designing and evaluating asphalt mixtures, and it remains a standard practice in Pakistan's road construction industry. Developed in the 1940s by Bruce Marshall, this method determines the optimal asphalt binder content by analyzing two key parameters: Marshall stability, which measures the mixture's load-bearing capacity, and flow, which reflects the potential for the mixture to deform under applied stress.

The Marshall method was chosen for this study because of its reliability and relevance. It provides a comprehensive framework for assessing how the incorporation of plastic waste into asphalt binder along with variations in aggregate gradation (such as well-graded, coarse, and fine) affects the strength, durability, and overall performance of asphalt mixtures.

Given the real-world conditions of Pakistan's road network, which include heavy traffic loads, extreme temperature fluctuations, and inconsistent maintenance practices, the Marshall test offers valuable insights into how plastic-modified asphalt is likely to perform under local service conditions.

The improved performance observed at 9% PET content can be attributed to enhanced stiffness and better load distribution within the asphalt mixture. The presence of PET particles likely improves internal friction and aggregate interlocking, leading to higher stability values.

At higher PET contents (11% and 13%), the performance begins to decline. This may be due to the excessive plastic content disrupting the aggregate-binder matrix and reducing mixture homogeneity. The increased presence of unmelted PET particles can lead to poor bonding, making the mixture more susceptible to deformation under load. These findings suggest that there is an optimal PET content, beyond which the mixture's mechanical performance is negatively impacted.

The observed trend suggests that PET acts as a reinforcing filler at lower contents, while excessive amounts may lead to particle agglomeration and reduced mixture cohesion.

Testing of Specimens

1. Prior to testing, the specimens are immersed in a water bath maintained at 60 °C for a period of 30–40 minutes to ensure uniform temperature distribution throughout the sample.

2. Perform Marshall Stability Test

- Placed specimen in Marshall Testing Machine.
- Applied load at a constant rate of 50 mm/min until failure.
- Recorded Stability (maximum load before failure, in kN).
- Measured Flow (deformation in 0.25 mm units during loading).

The graphs show the effect of asphalt content on air voids, density, and stability for mixtures with 9% plastic. Air voids increase steadily with asphalt content, indicating reduced compaction at higher levels. Density rises and reaches a peak at 4% asphalt content, then slightly decreases, suggesting optimal compaction at this point. Stability also increases with asphalt content and peaks at 4%, after which it declines, showing reduced strength. According to Table 1 trends suggest that 4% asphalt content provides the best balance of compaction, strength, and durability for plastic-modified asphalt.

The air void values obtained in this study are relatively low compared to typical ranges reported in standard specifications. This may be attributed to the presence of fine PET particles, which tend to occupy void spaces within the aggregate structure, resulting in a denser and more compact mixture. Additionally, the compaction process may have contributed to reduced air void content. Although these values fall below conventional limits, similar trends have been observed in other studies where plastic materials are used as fillers in the asphalt matrix. However, more research is needed to fully understand the long-term effects of plastic on pavement performance.

These results emphasize the importance of optimizing plastic content in the mixture, as both insufficient and excessive amounts can negatively impact the pavement's performance.

Figure 3 shows that stability reaches its peak at a moderate asphalt content. However, as the asphalt content increases further, strength begins to decline due to the excess binder. Air voids decrease as more binder is added, suggesting an improvement in durability. Additionally, the density increases consistently with higher asphalt content, which strengthens the overall structural integrity.

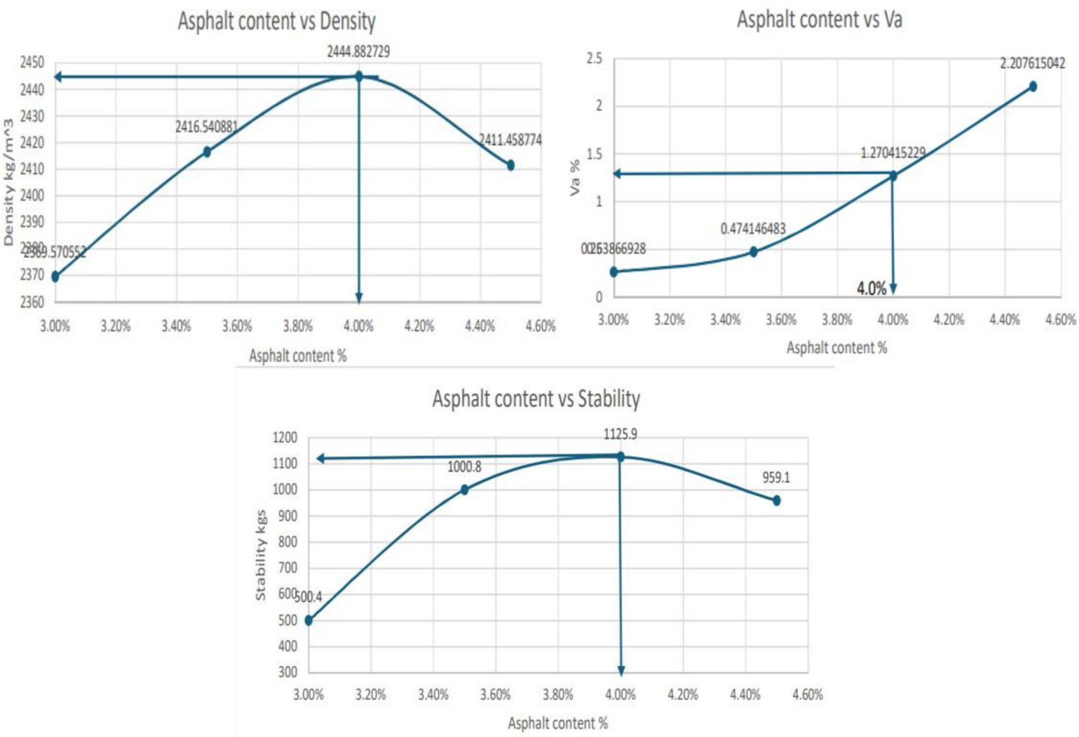

Fig. 3 Effect of Asphalt Content on Va, Density, and Stability at 9% Plastic

The results from Table 2 indicate that the best asphalt performance is achieved with approximately 9% plastic content and 4.0% asphalt content. At this point, the VMA reaches its lowest value (10.6%), while the VFA begins to decrease significantly. Stability flow peaks at 8.4 (0.01 in), suggesting a well-balanced mixture in terms of compaction, durability, and strength.

Table 2
Results of Marshall Stability Test with 9% Plastic

3.00%	48.28	1158.72	673	1162	2.369571	2369.571	1170.79	6357
3.50%	54.315	1152.69	680	1157	2.416541	2416.541	1170.79	6359
4.00%	60.35	1146.65	693	1162	2.444883	2444.883	1170.79	6370
4.50%	66.385	1140.62	670	1143	2.411459	2411.459	1170.79	6370

Wg. of Container + Sample + Water (W2) (gm)	Specific Gravity Gmm (Wm / (Wm + W1 - W2))	Stability (Kg/Lbs.) Dial Reading	Stability(kg/Lbs.) Measured	Flow (mm/0.01")	Gsb	V.M.A = (100 -%age * Gmb / Gsb)	Va = 100* (Gmm-Gmb) /Gmm	V.F.A = 100 *(VMA - VA) / VMA
7035	2.37854	120	500.4	8	2.65	13.711106	0.263867	98.07563
7048	2.429053	240	1000.8	8.3	2.65	12.001044	0.051747	96.04295
7053	2.476433	270	1125.9	9	2.65	10.969936	1.270415	88.41852
7066	2.465896	230	959.1	9.5	2.65	12.1865	2.207615	81.88475

Figure 4 shows that stability reaches its peak at a moderate asphalt content. However, as the asphalt content increases further, strength begins to decline due to the excess binder. Air voids decrease as more binder is added, suggesting an improvement in durability. Additionally, the density increases consistently with higher asphalt content, which strengthens the overall structural integrity.

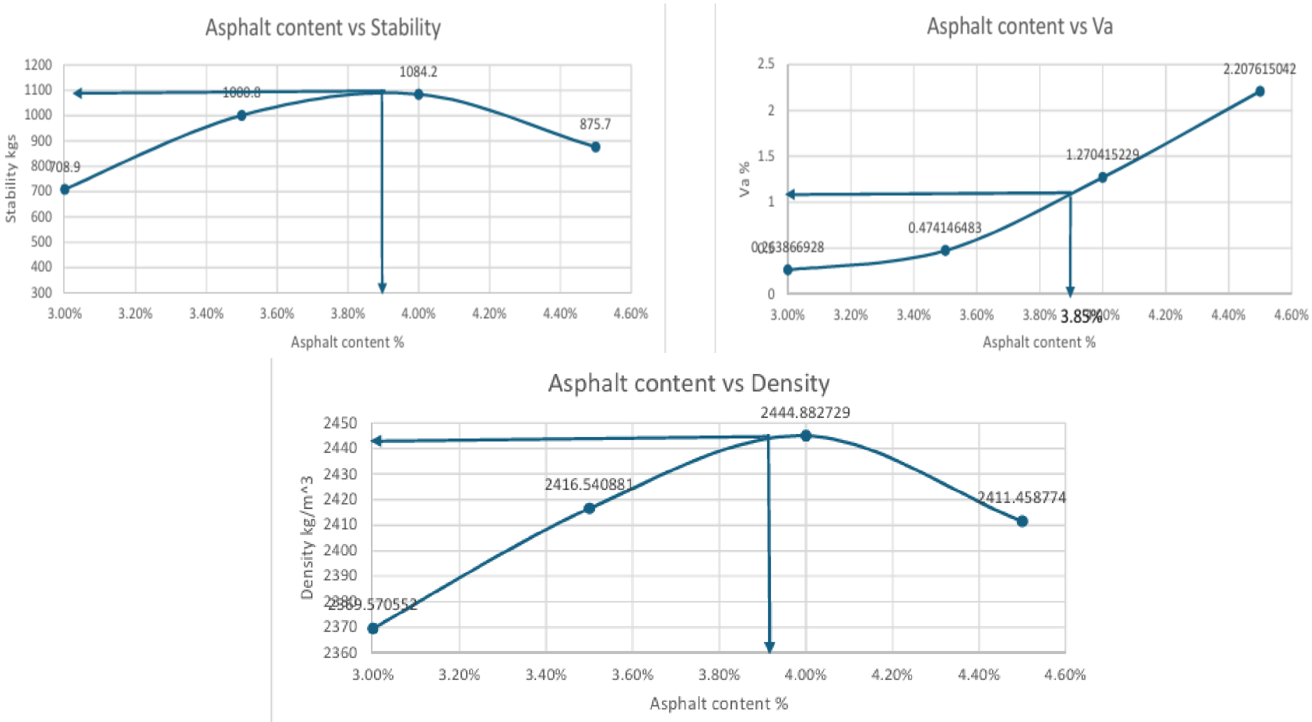

Fig. 4 Effect of Asphalt Content on Va, Density and Stability at 11% Plastic

The results from Table 3 indicate the asphalt performance at 11% plastic content and 4.0% asphalt content. At this point, the VMA reaches its lowest value (10.969%), while the VFA begins to decrease significantly. Stability flow peaks at 1084 Kg/Lbs, suggesting a well-balanced mixture in terms of compaction, durability, and strength.

Table 3
Results of Marshall Stability Test with 11% Plastic

% Binder	Wt. of Bitumen (g)	Wt. of Sample (Agg. + Plastic) in Air (g)	Wt. of Sample in Water (g)	Saturated Surface Dry Wt. (g)	Gmb (A/C-D)	Unit Weight (kg/m³)	Wt. of Loose Mix (Wm) (g)	Wt. of Container + Water (W1) (g)
3.00 %	48.28	1158.72	673	1162	2.369571	2369.571	1170.79	6357
3.50 %	54.315	1152.69	680	1157	2.416541	2416.541	1170.79	6340
4.00 %	60.35	1146.65	693	1165	2.444883	2444.883	1170.79	6370
4.50 %	66.385	1140.62	670	1143	2.411459	2411.459	1170.79	6370

Wt. of Container + Sample + Water (W2) (g)	Gmm (Wm/Wm+W1 - W2)	Stability (Kg/Lbs.) Dial Reading	Stability (Kg/Lbs.) Measured Reading	Flow (mm/0.01")	Gsb	V.M.A (%)	Va (%)	V.F.A (%)
7035	2.37584	170	708.9	8	2.65	13.71186	0.26386	98.07563
7048	2.428053	240	1000.8	8	2.65	12.001044	0.47144	96.07134
7068	2.476343	260	1084.2	8	2.65	10.96936	1.27062	88.41852
7066	2.465896	210	875.7	8	2.65	12.1865	2.20765	81.88475

Figure 5 illustrates that stability decreases at 13% plastic content, signaling a reduction in the mix's ability to bear load. The air voids are very low, which raises concerns about potential pavement flushing and a shorter service life. While density increases, this may indicate that the mix is over-compacted, leading to reduced stiffness. It is recognized that these values are below the standard recommended limits, which could impact durability. This limitation emphasizes the need for further optimization of the mix.

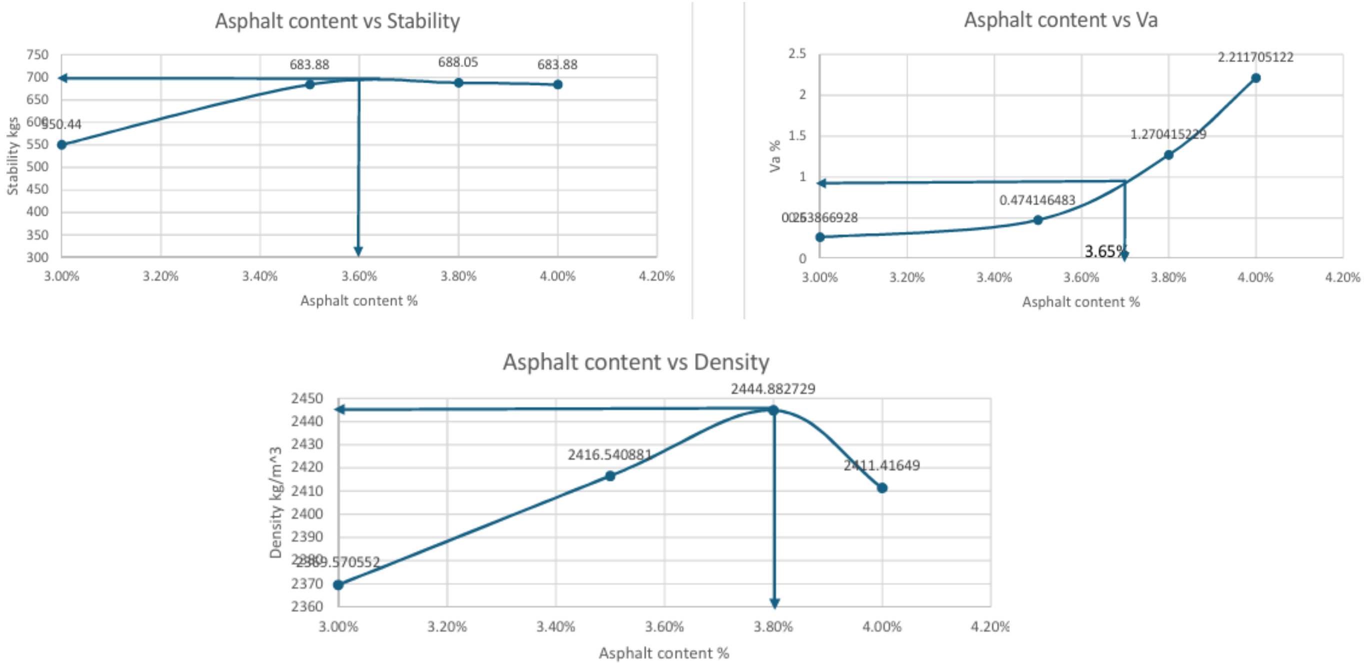

Fig. 5. Effect of Asphalt Content Va, Density & Stability at 13% Plastic

Table 4
Results of Marshall Stability Test with 13% Plastic

% Binder	Wt. of Bitumen (g)	Wt. of Sample (Agg. + Plastic) in Air (g)	Wt. of Sample in Water (g)	Saturated Surface Dry Wt. (g)	Gmb (A/C-D)	Unit Weight (kg/m³)	Wt. of Loose Mix (Wm) (g)	Wt. of Container + Water (W1) (g)
3.00 %	48.28	1158.72	673	1162	2.369571	2369.571	1170.79	7035
3.50 %	54.315	1152.69	680	1157	2.416541	2416.541	1170.79	7048
3.80 %	60.35	1146.65	693	1162	2.444883	2444.883	1170.79	7068
4.00 %	66.385	1140.6	670	1143	2.414116	2411.416	1170.77	7070

Wt. of Container + Sample + Water (W2) (g)	Gmm (Wm/Wm+W1 - W2)	Stability (Kg/Lbs) Dial Reading	Stability (Kg/Lbs) Measured Reading	Flow (mm/0.01")	Gsb	V.M.A (%)	Va (%)	V.F.A (%)
7035	2.37584	132	550.44	8.2	2.65	13.71186	0.26386	98.07563
7048	2.428053	164	683.88	8.3	2.65	12.00414	0.47414	96.04925
7068	2.476343	165	688.05	8.4	2.65	10.9692	1.27041	88.41852
7070	2.465956	164	683.88	8.2	2.65	12.18084	2.21170	81.85348

4.2 Rutting Resistance Test

Rutting is one of the most significant forms of distress in flexible pavements, typically caused by permanent deformation in the asphalt layers due to repeated traffic loading, especially under high-temperature conditions. This results in longitudinal depressions along wheel paths, which severely impact ride quality, safety, and the overall lifespan of the pavement. This study assesses the rutting resistance of asphalt mixtures modified with plastic waste to determine their ability to withstand such deformation. It is hypothesized that the inclusion of plastic enhances the stiffness and viscoelastic properties of the mixture, improving its resistance to rutting. To evaluate these factors, the Hamburg Wheel Tracking Test was conducted under controlled laboratory conditions. This approach allows for a comparative analysis between conventional and plastic-modified asphalt mixtures.

The findings provide valuable insights into the potential of plastic waste as a sustainable modifier, particularly for pavements exposed to Pakistan's diverse climatic conditions and heavy traffic demands. The Rut Resistance test was carried out at UET Taxila.

Test Procedure:

- Load Repetition: The specimen was subjected to repeated wheel movements, either for a set number of passes (e.g., 10,000–20,000) or for a specified time duration (e.g., 1 hour).
- Measurement: Rut depth (in mm) was continuously measured at regular intervals.
- Rut Depth vs. Number of Passes: A graph was generated showing the change in rut depth with respect to the number of wheel passes.
- Maximum Rut Depth: The final rut depth was recorded to assess the specimen's performance.
- Comparison of Results: The rutting resistance of conventional and plastic-modified mixtures was compared.
- Evaluation of the Effect of Gradation: The test also analyzed how different aggregate gradations influence rutting behavior.

The rut depth graphs in Figure 6 show that the mixture with 9% plastic content demonstrates excellent resistance to deformation, with very little rutting even after 10,000 passes. At 11% plastic, moderate rutting is observed, but it stays within acceptable performance limits. However, with 13% plastic, the rut depth exceeds the allowable limits, indicating poor performance and reduced resistance to permanent deformation.

The rutting resistance results further support the trend observed in the Marshall stability tests. The mixture containing 9% PET exhibited the lowest rut depth, indicating superior resistance to permanent deformation. This behavior is likely linked to the increased stiffness and improved ability to resist shear deformation under repeated loading.

In contrast, the 13% PET mixture showed significantly higher rut depth, suggesting that excessive plastic content weakens the structural integrity of the mixture. The reduced performance may be due to inadequate bonding and increased voids caused by the presence of non-melted plastic particles.

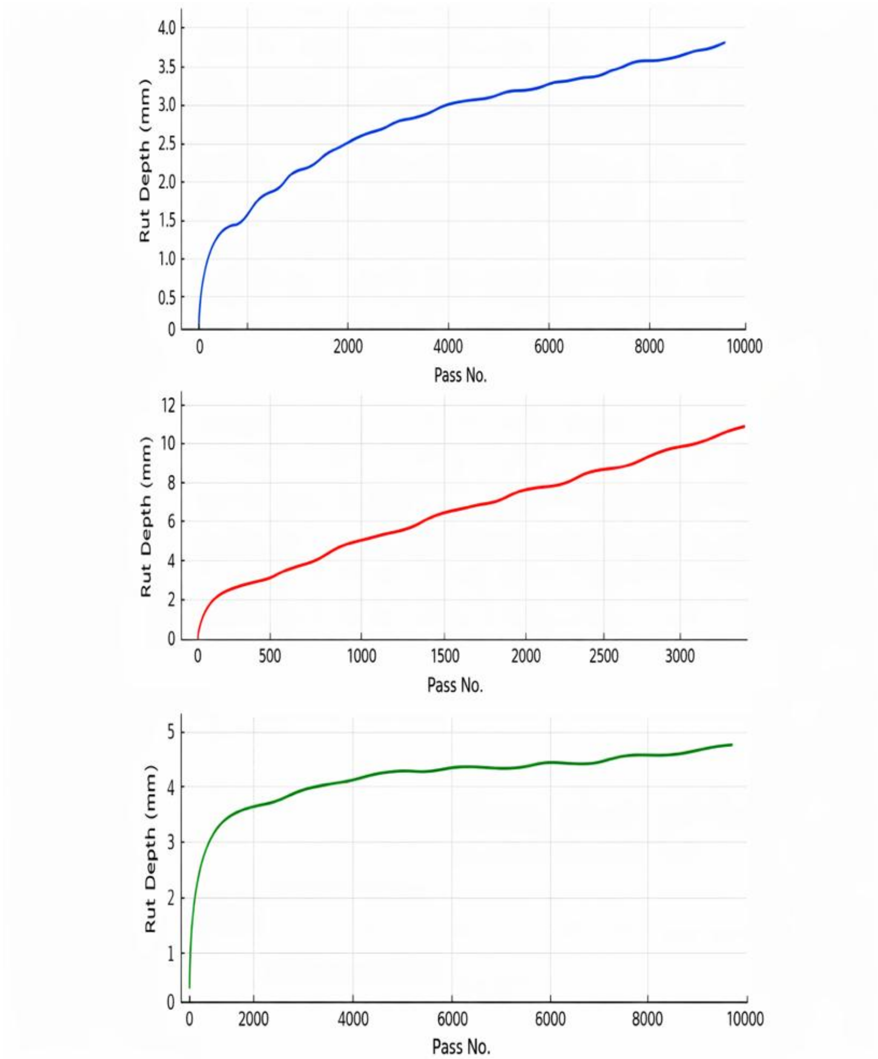

Fig. 6 Effect of 9%, 11% and 13% Plastic on Rut Depth and Pass No

The comparative rut depth progression clearly shows that the mixture with 9% plastic outperforms the 11% and 13% mixtures in rut resistance, maintaining the lowest deformation throughout the loading cycles (Fig.7). Average rutting trends confirm that the 9% plastic-modified mix exhibits the slowest deformation rate among all tested samples, indicating superior resistance to permanent de formation (Fig.8).

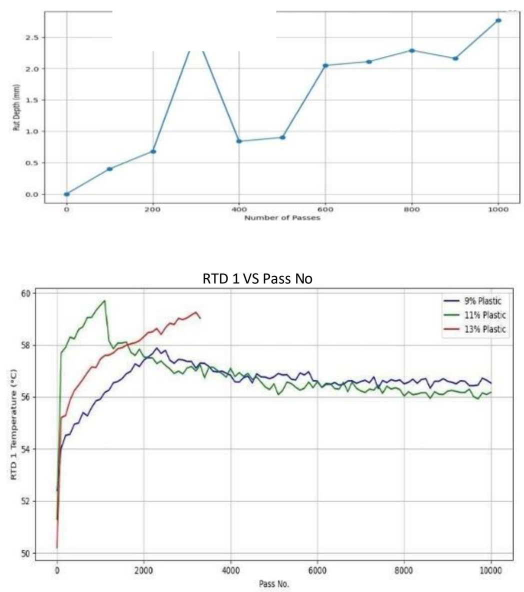

Fig. 7. Rut Depth Progression Over Wheel Passes

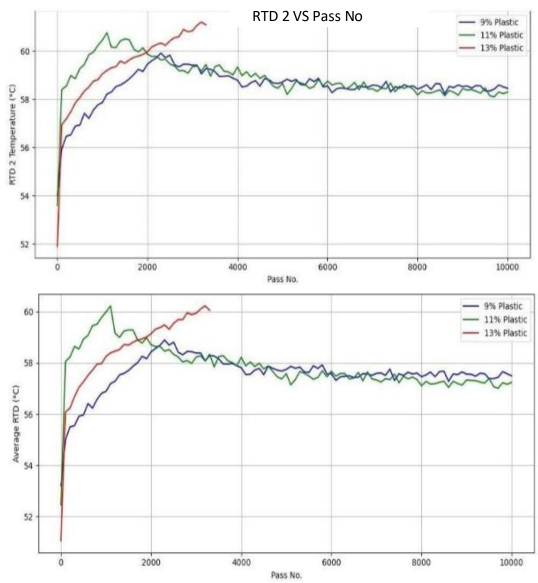

Fig. 8. Average Rut Tracking Depth (RTD) vs Pass No

Average rutting trends confirm that the 9% plastic mix has the slowest deformation rate, indicating the best rutting resistance among the tested samples (RTD 1 vs Pass No). In contrast, the rut depth progression in (RTD 2 vs Pass No) shows a consistent increase across all passes, with the steepest slope observed in the 13% plastic mix, reflecting its poor resistance to deformation as shown in figure 9.

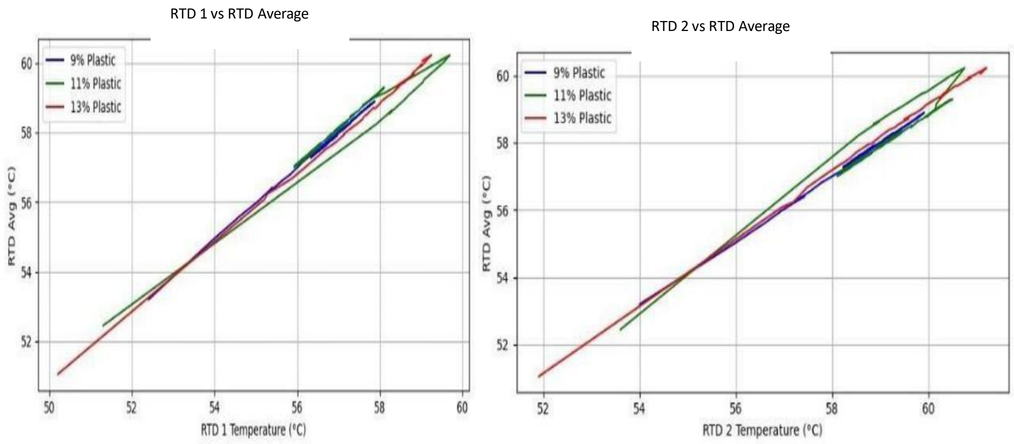

Fig. 9. Average Rut Tracking Depth (RTD 1 and RTD 2) vs Pass No

The graphs in Figure 10 show a strong correlation between RTD 1 and the average rut depth, suggesting consistent test performance and reliable accuracy in rut measurements. Similarly, RTD 2 correlates well with the average, further supporting the overall stability and repeatability of rut measurements across different samples.

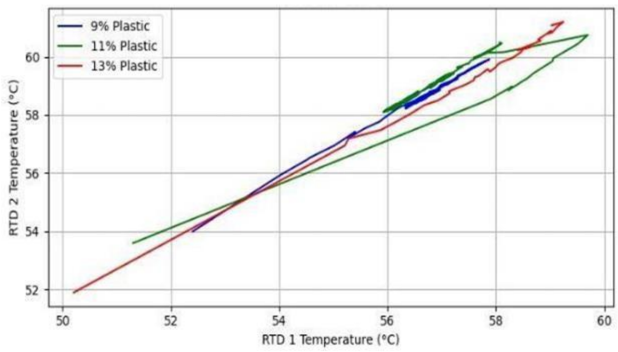

Fig. 10. Average Rut Tracking Depth (RTD 1 and RTD 2)

4.3 Plastic Waste Modified Flexible Pavement Cross-Section

A conventional flexible pavement cross-section consists of multiple layers, including the surface course, binder course, base course, sub-base, and subgrade. In sustainable road construction, the plastic waste-modified flexible pavement cross-section provides an innovative solution to enhance performance while addressing environmental challenges. This design maintains the conventional layered system but replaces the surface course with a plastic-modified bitumen mix to improve durability, deformation resistance, and overall lifespan.

The pavement structure includes the surface course, binder course, base course, sub-base, and subgrade, each playing a crucial role in load distribution, drainage, and structural integrity. By incorporating plastic waste into the top layer, the design aims to reduce rutting and other distresses commonly seen under Pakistan's climatic and traffic conditions, while also helping to reduce plastic pollution. The following report presents the cost and sustainability impact of plastic-modified asphalt roads in Pakistan.

Fig. 11. Plastic waste-modified samples

Material Composition and Costs

Part 1: Cost Comparison (Per 1 KM Road, 1,680,000 kg Total Mass) Material Prices:

The material composition and cost comparison indicate that incorporating plastic waste slightly increases the initial construction cost compared to conventional asphalt. The conventional mix consists of 5% bitumen and 95% aggregate, resulting in a total cost of PKR 12,982,920 per kilometer. When plastic waste is introduced at 9%, 11%, and 13%, the bitumen content decreases accordingly. However, the total material cost only increases modestly due to the adjusted material proportions, despite plastic being cheaper than bitumen. The cost increase ranges between PKR 654,472 and PKR 1,014,489 per kilometer compared to conventional pavement as presented in Table 5.

Table 5
Material Composition and Costs

Mix Type	Bitumen (%)	Plastic (%)	Aggregate (%)	Bitumen Cost (PKR)	Plastic Cost (PKR)	Aggregate Cost (PKR)	Total Cost (PKR)
Conventional	5.0%	0%	95.0%	8,400,0	0	4,582,92	12,982,92
Plastic (9%)	4.0%	9%	87.0%	6,720,0	2,721,6	4,195,79	13,637,39
Plastic (11%)	3.8%	11%	85.2%	6,384,0	3,326,4	4,107,00	13,817,40
Plastic (13%)	3.6%	13%	83.4%	6,048,0	3,931,2	4,018,20	13,997,40

Although the upfront cost is slightly higher for plastic-modified mixes, this increase is relatively small when compared to the long-term economic and environmental benefits. The cost values used in this analysis are based on approximate market rates for bitumen, plastic waste, and aggregates in Pakistan. These values may vary depending on location, time, and project-specific conditions. The analysis is therefore intended to provide a comparative estimation of economic feasibility rather than an exact cost prediction.

Part 2: Sustainability Impact (Annual Estimate for 100 KM Road Construction)

The environmental benefits of plastic-modified roads are significant. For 100 km of annual road construction, large quantities of plastic waste can be diverted from landfills.

Plastic Waste Recycled from Landfills

This demonstrates that higher plastic content significantly increases landfill diversion capacity. In addition to reducing waste, carbon emissions are saved by using less bitumen and recycling plastic as shown in Table 6.

Table 6
Plastic Waste Diverted from Landfills

Plastic %	Plastic Used per KM (kg)	Total Plastic Used (100 KM)
9%	151,200	15,120,000 kg (15,120 tons)
11%	184,800	18,480,000 kg (18,480 tons)
13%	218,400	21,840,000 kg (21,840 tons)

Carbon Emission Reduction

From a sustainability perspective, the environmental benefits are significant. For an annual construction target of 100 km, plastic-modified roads can divert between 15,120 tons and 21,840 tons of plastic waste from landfills, depending on the percentage of plastic used. Additionally, replacing bitumen helps reduce carbon emissions, as bitumen production emits 3.78 kg of CO_2 per kg. With 9%, 11%, and 13% plastic content, the CO_2 savings from reducing bitumen range from 6.35 million to 8.89 million kg annually. Further environmental benefits come from recycling plastic, as each kilogram of plastic reused saves about 6 kg of CO_2. This results in total annual carbon reductions of 97,070 tons, 118,500 tons, and 139,930 tons, respectively. These figures highlight the significant environmental advantages of plastic-modified asphalt, which go beyond waste management as shown in Table 7 and Table 8.

Table 7
Bitumen Replacement Savings (Bitumen CO2 Emission: 3.78 kg CO2/kg)

Plastic %	Bitumen Reduced (kg)	CO2 Saved (kg)
9%	1,680,000	6,350,400
11%	2,016,000	7,622,000
13%	2,352,000	8,894,560

Table 8
Plastic Recycling Savings (Each kg plastic reused = 6 kg CO2 saved)

Plastic %	Plastic Reused (kg)	CO2 Saved (kg)
9%	15,120,000	90,720,000
11%	18,480,000	110,880,000
13%	21,840,000	131,040,000

The environmental impact assessment is based on generalized emission factors found in existing literature. Actual environmental benefits may vary depending on the methods used for processing, transportation, and local implementation practices.

Part 3: Life Cycle Cost Analysis (20-Year Span Assumptions)

The life cycle cost analysis over a 20-year period strengthens the case for plastic-modified roads. While the initial construction cost is slightly higher, maintenance costs are significantly lower. Conventional asphalt requires PKR 700,000 per kilometer per year for maintenance, whereas plastic-modified asphalt requires only PKR 400,000 per kilometer per year. Using a 5% discount rate, the net present value (NPV) of maintenance over 20 years is PKR 8,745,000 for conventional roads and PKR 4,997,000 for plastic-modified roads. Consequently, the total life cycle cost per kilometer is much lower for plastic roads, resulting in savings of approximately PKR 2.9–3.1 million over 20 years. This shows that although plastic-modified roads may have slightly higher upfront costs, they are more economical in the long term.

The cost estimates used in this analysis are consistent with commonly reported construction cost data and previous studies on asphalt pavement materials.

Part 4: Performance Evaluation Based on Wheel Tracking Test

Performance evaluation through the wheel tracking test provides valuable insights into durability. A rut depth below 6 mm at 10,000 passes indicates good rutting resistance. The 9% plastic mix performed the best, with a rut depth of 3.9 mm, demonstrating excellent resistance to deformation. The 11% mix recorded 5.4 mm, which remains within acceptable limits for durability. However, the 13% mix showed a rut depth of 13.72 mm, exceeding acceptable standards and indicating a high risk of rutting under heavy traffic loads. This suggests that excessive plastic content can negatively affect the structural performance of the pavement as shown in Table 9.

Table 9
Wheel Tracking Test Analysis

Plastic %	Final Rut Depth @10,000 Passes	Performance Interpretation	Reference / Standard Criteria
9%	3.9 mm	Excellent – High rut resistance	**Routinely below typical rutting limits**; ≤ ~5 mm indicates very low permanent deformation (EN 12697-22 based rutting performance used in Pakistani pavement research)
11%	5.4 mm	Acceptable – Durable and compliant	5–12.5 mm **within acceptable range** per adopted EN 12697-22/Cooper Wheel Tracking criteria (limit ~12.5 mm at 10 000 passes)
13%	13.72 mm	Poor – Exceeds limits, risk of rutting	**Exceeds max accepted rut depth (~12.5 mm)** under Pakistan's adopted EN 12697-22 criteria, indicating unacceptable rutting potential at design conditions.

It should be noted that the experimental results are based on laboratory-scale testing, and some variation in the measured parameters may occur due to material handling and testing conditions. To confirm the observed trends, further validation through repeated testing and field-scale implementation is recommended.

5. Conclusions

This study demonstrates that incorporating polyethylene terephthalate (PET) plastic waste into asphalt mixtures, combined with optimized aggregate gradation, improves mechanical performance, enhances environmental sustainability, and offers cost-effectiveness for road infrastructure in Pakistan.

The 9% PET-modified asphalt mixture showed the best overall performance, with rutting depth limited to 3.9 mm after 10,000 load repetitions, showing high durability under simulated heavy traffic conditions. It maintained good structural performance when mixed with properly graded aggregates. The 11% PET mixture stayed within acceptable deformation limits (5.4 mm rut depth), but it showed a slightly reduced load-bearing capacity compared to the 9% mixture. The 13% PET mixture exhibited significant issues, with excessive rutting (13.72 mm), indicating that higher plastic content can negatively impact mix performance under heavy traffic loading.

Proper aggregate gradation, following NHA Class-A specifications, was essential for improving inter-particle locking and enhancing structural densification. This improved vertical load distribution throughout the pavement layers, reducing surface distress and improving long-term performance.

The 20-year life cycle cost analysis confirmed that 9% PET-modified pavements offer significant economic benefits, reducing overall costs by PKR 3.1 million per kilometer due to lower maintenance requirements. The analysis also highlighted reduced consumption of virgin bitumen. Environmental impact assessments indicated that approximately 15,120 tons of PET plastic waste could be diverted from landfills per 100 kilometers of roadway. This would result in an annual reduction of 97,070 tons of CO_2 emissions through polymer reuse, alongside decreased dependence on fossil fuels.

Structural evaluation confirmed that both 9% and 11% PET-modified mixtures can safely withstand axle loads from high-capacity commercial vehicles (e.g., 22-wheeler trucks), provided proper layer thickness and sub-base conditions are maintained. This supports the transition toward more sustainable infrastructure, aligning with global environmental and development goals.

Further research, including field trials and detailed material characterization, is recommended to validate the long-term performance of PET-modified asphalt mixtures.

Further research involving field trials and detailed material characterization is recommended to validate the long-term performance of PET-modified asphalt mixtures, moreover, artificial intelligence tools can be adopted to improve the outcome.

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