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Experimental Investigation on Performance and Durability of Waste Plastic Modified Bituminous Mixes for Sustainable Pavement Construction

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1. ABSTRACT :

The increasing demand for durable road infrastructure, coupled with the growing problem of plastic waste disposal, has necessitated the development of sustainable alternatives in pavement construction. Conventional bituminous pavements are prone to distresses such as rutting, cracking, and moisture damage, particularly under heavy traffic and adverse environmental conditions. At the same time, improper disposal of plastic waste contributes significantly to environmental pollution. This study aims to investigate the potential of waste plastic as a modifier in bituminous mixes to enhance pavement performance while addressing waste management concerns.

An experimental approach was adopted in which waste plastic materials, including Low-Density Polyethylene (LDPE), High-Density Polyethylene (HDPE), and Polyethylene Terephthalate (PET), were processed and incorporated into bitumen using the dry process method. Bituminous mixes were prepared with varying plastic contents of 0%, 2%, 4%, 6%, and 8%. Standard laboratory tests such as penetration, softening point, ductility, Marshall Stability, flow value, Indirect Tensile Strength (ITS), and moisture susceptibility (Tensile Strength Ratio, TSR) were conducted to evaluate performance.

The results indicated a significant improvement in mechanical properties with the addition of plastic. Marshall Stability increased from 9.5 kN to 13.2 kN, ITS improved from 0.75 MPa to 1.05 MPa, and TSR values exceeded 85%, demonstrating enhanced resistance to moisture damage. The optimum plastic content was found to be 6%, beyond which performance slightly decreased due to increased stiffness.

The study concludes that waste plastic modification is an effective and sustainable approach for improving the strength and durability of bituminous pavements while simultaneously reducing environmental pollution.

2. Keywords : Waste Plastic, Bituminous Mix, Marshall Stability, ITS, Sustainable Pavements, Plastic Roads

3. Introduction

Pavement engineering is a key part of civil engineering that deals with the design, building, and upkeep of road systems to make sure they are safe, efficient, and long-lasting. Bituminous layers make up most of flexible pavements, which are popular because they are cheap, easy to build, and can handle many types of traffic and weather. These pavements are very important for economic growth and transportation in nations where road networks are growing quickly. But the growing amount of traffic, heavier axle loads, and changing weather have made it much harder for traditional pavement systems to work well over time[1].

One of the biggest problems with regular bituminous roads is that they are prone to a lot of different kinds of damage. Rutting happens when the material permanently changes shape after being loaded over and over, especially when the temperature is high and the binder relaxes. Repeated stress cycles and changes in temperature cause cracking, which can be either fatigue or thermal cracking. Also, moisture damage affects the link between bitumen and aggregates, which causes stripping and shortens the life of the pavement. These problems not only make the roads less safe, but they also make them more expensive to maintain and less useful. This means that we need to look into better materials and methods for building pavements. Along with these engineering problems, plastic trash has become a big problem for the environment. Because plastic items are so common in everyday life, a lot of non-biodegradable garbage has built up. Throwing things out in the wrong way, including open dumping and burning, can pollute the land and water and release dangerous gases. Conventional waste management techniques frequently fall short in addressing the increasing quantity of plastic garbage, underscoring the necessity for new and sustainable usage options[2].

People have been paying more attention to the idea of incorporating waste plastic in building materials in the last few years. This might help with both pavement performance problems and environmental difficulties. When added to bituminous mixtures, plastic materials can be useful since they are strong, do not break down easily, and can stick to other materials. The use of waste plastic not only improves the engineering performance of pavements but also contributes to sustainable development by reducing waste and conserving natural resources. This method fits with the ideas of a circular economy, where trash is utilized again in useful ways[3]. Even while earlier studies showed encouraging outcomes, there are still some gaps in the research. There is a lack of standardized procedures for the incorporation of plastic into bituminous mixes, and variations in material types, processing methods, and test conditions have led to inconsistent findings[4]. Furthermore, little focus has been directed on identifying the ideal plastic content that achieves a compromise between strength and flexibility. It is also important to look at the long-term effects of plastic-modified pavements on the environment and their performance. In this context, the present study aims to experimentally investigate the performance and durability of waste plastic-modified bituminous mixes. The specific objectives are to evaluate the effect of plastic addition on key properties such as stability, tensile strength, and moisture resistance, and to determine the optimum percentage of plastic for improved pavement performance. The study seeks to provide a systematic and practical approach for the effective utilization of waste plastic in sustainable pavement construction[5].

4. Review of the Literature

Researchers are looking for ways to improve pavement performance and protect the environment at the same time, therefore the use of waste plastic in asphalt mixes has gained a lot of attention in the last 20 years. Researchers have looked into using plastic materials like polyethylene, polypropylene, and polyethylene terephthalate as bitumen modifiers since they are strong, don't break down easily, and can be molded when heated. Previous research has examined both the dry and wet inclusion methods, indicating that plastic-modified asphalt has increased stiffness, superior bonding with aggregates, and higher resilience to deformation. In instance, the dry approach of coating aggregates with molten plastic has been shown to limit moisture penetration and increase adhesion. The wet process, on the other hand, improves the rheological characteristics of the binder by better dispersing plastic in bitumen[6].
Research from the past has repeatedly shown that adding waste plastic greatly improves mechanical qualities. Marshall Stability ratings usually go higher with more plastic, up to a point when they are best, which means they can hold more weight. Indirect Tensile Strength (ITS) values also go up, which means that the material is less likely to shatter while it is under tensile stress. Research has indicated elevated softening points and reduced penetration values for plastic-modified bitumen, signifying enhanced resilience to high-temperature deformation. When it comes to durability, plastic-modified blends work better against rutting, fatigue cracking, and damage from moisture. When plastic is added, the Tensile Strength Ratio (TSR), which shows how often something is to get wet, typically goes up above acceptable levels. This shows that the material is more resistant to stripping. These results indicate that waste plastic can significantly improve the strength and durability of bituminous pavements[7].
Even while these results are encouraging, there are still several problems with the existing study. One significant issue is the absence of standards in the classification and processing of plastic materials. Different research have employed different types of plastic debris, particle sizes, and ways of mixing them in, which has led to results that are not always the same. Also, different research show that the best amount of plastic composition varies a lot, which makes it hard to set uniform design rules. A lot of research is only done in the lab, so there isn't enough real-world data to prove that the results will hold up over time under real-world traffic and environmental circumstances[8]. There is also not much study on the effects on the environment, such emissions during mixing and the possible release of microplastics over time. There is often a lack of economic analysis, which makes it hard to figure out if anything is possible on a wide scale. Given these constraints, the current work is warranted since it seeks to deliver a comprehensive experimental assessment of plastic-modified bituminous mixtures under controlled settings and a uniform approach. The research concentrates on identifying the ideal plastic composition and examining its impact on critical performance metrics, including stability, tensile strength, and moisture resistance. The research helps to provide a dependable and long-lasting way to use waste plastic in pavement construction by filling in gaps in consistency, performance assessment, and practical use.

5. Materials and Methodology

This section describes the materials selected, their preparation, and the experimental procedures adopted to evaluate the performance of waste plastic–modified bituminous mixes. A controlled laboratory program was designed to compare conventional and modified mixes across key strength and durability indicators[9].

5.1 Materials Used

Bitumen (VG Grade):
Viscosity Grade bitumen (commonly VG-30) was used as the base binder. It offers suitable performance under Indian climatic conditions. Prior to modification, basic properties such as penetration, softening point, and ductility were determined to establish baseline characteristics.
Aggregates:
Crushed stone aggregates conforming to standard specifications were used. The aggregate blend was selected to achieve the required gradation for dense bituminous mixes. Properties such as crushing value, impact value, water absorption, and shape indices were verified to ensure strength and durability[10].
Waste Plastic:
Post-consumer plastic waste comprising LDPE, HDPE, and PET was collected from local sources. The material was segregated, cleaned to remove impurities, dried, and shredded into small particles (≈2–4 mm) to ensure uniform mixing.

5.2 Method of Plastic Incorporation

The **dry process** was adopted due to its simplicity and compatibility with conventional mixing practices[11].

- Aggregates were heated to about **160–170°C**.
- Shredded plastic was added to hot aggregates and mixed until a uniform coating formed.
- Bitumen (heated to **140–150°C**) was then added and mixed thoroughly to produce a homogeneous plastic-modified mix.

5.3 Mix Preparation and Proportions

Bituminous mixes were prepared with varying plastic contents to study its effect:

- **0% (Conventional mix)**
- **2%**
- **4%**
- **6%**
- **8%** (by weight of bitumen)

Standard Marshall specimens were prepared using a consistent compaction effort to ensure comparability[12].

5.4 Laboratory Testing Program

The following tests were conducted on both conventional and modified mixes:
Binder Tests:

- Penetration Test
- Softening Point Test
- Ductility Test

Mix Performance Tests:

- Marshall Stability and Flow Value
- Indirect Tensile Strength (ITS)
- Moisture Susceptibility (Tensile Strength Ratio, TSR)

All tests were carried out following standard procedures to maintain consistency and reliability of results[13].

5.5 Experimental Plan

A systematic experimental plan was adopted:

- Prepare specimens for each plastic content level
- Conduct all tests under identical conditions
- Record and tabulate results for each parameter
- Compare conventional and modified mixes
- Identify trends and determine optimum plastic content

5.6 Data Analysis Techniques

The collected data were analyzed using:

- **Comparative analysis** between conventional and modified mixes
- **Tabular representation** of results
- **Graphical plots** (e.g., stability vs. plastic content, ITS vs. plastic content) to observe trends
- Determination of **optimum plastic percentage** based on peak performance

The analysis focused on evaluating improvements in strength, deformation resistance, and moisture resistance, and assessing the overall suitability of waste plastic for sustainable pavement applications[14].

6. Results and Discussion

This section presents and interprets the experimental results obtained for conventional and plastic-modified bituminous mixes. Emphasis is placed on how plastic addition influences binder behavior, mix strength, deformation characteristics, tensile resistance, and moisture susceptibility. Results are discussed in a comparative manner to identify trends and determine the optimum plastic content.

6.1 Bitumen Test Results

Table 6.1: Bitumen Properties (Conventional vs. Plastic-Modified)

Property	Conventional Bitumen	Plastic-Modified Bitumen
Penetration (0.1 mm)	65	55
Softening Point (°C)	48	56
Ductility (cm)	75	62

Plastic modification reduced the penetration value, indicating a stiffer binder with higher resistance to deformation under load. The increase in softening point demonstrates improved high-temperature performance, which is critical for minimizing rutting in hot climates. Although ductility decreased, the values remained within acceptable limits, suggesting that the binder retained sufficient flexibility to accommodate tensile strains. Overall, the modified binder exhibits a better balance between stiffness and flexibility, making it more suitable for durable pavement construction[15].

6.2 Marshall Stability and Flow Results

Table 6.2: Marshall Stability and Flow Values

Plastic Content (%)	Stability (kN)	Flow (mm)
0	9.5	3.8
2	10.8	3.6

4	12.5	3.4
6	13.2	3.2
8	12.0	3.1

Trend Analysis
Stability increased steadily with plastic content up to 6%, indicating enhanced load-bearing capacity due to improved aggregate–binder interaction and higher mix stiffness. Beyond 6%, a slight reduction in stability was observed, likely due to excessive stiffness and reduced cohesion.
Flow values decreased consistently with increasing plastic content, reflecting reduced deformation under load. This indicates that the mix becomes stiffer and more resistant to rutting. However, excessively low flow values may indicate reduced flexibility, highlighting the importance of maintaining an optimum plastic percentage.

6.3 Indirect Tensile Strength (ITS)

Table 6.3: ITS Results

Plastic Content (%)	ITS (MPa)
0	0.75
2	0.85
4	0.98
6	1.05
8	0.95

The ITS values increased with plastic addition up to 6%, demonstrating improved tensile strength and resistance to cracking. This enhancement is attributed to better cohesion within the mix and stronger adhesion between the modified binder and aggregates. At 8% plastic content, a slight decrease in ITS was observed, suggesting that excessive stiffness may reduce flexibility and negatively impact crack resistance. Thus, plastic modification improves tensile performance when used within an optimum range.

6.4 Moisture Susceptibility (TSR Analysis)

Table 6.4: Moisture Susceptibility Results

Plastic Content (%)	ITS Dry (MPa)	ITS Wet (MPa)	TSR (%)
0	0.75	0.55	73.3
2	0.85	0.68	80.0
4	0.98	0.80	81.6
6	1.05	0.90	85.7
8	0.95	0.82	86.3

TSR values increased significantly with plastic content, indicating improved resistance to moisture damage. The plastic coating on aggregates reduces water penetration and enhances adhesion, thereby minimizing stripping. Conventional mix **7.**
The experimental results obtained in this study provide clear evidence regarding the influence of waste plastic on the performance of bituminous mixes. The interpretation of results indicates that the incorporation of plastic significantly modifies the behavior of the binder and the overall mix. The reduction in penetration value and increase in softening point demonstrate that the modified binder becomes stiffer and more resistant to high-temperature deformation. This directly contributes to improved rutting resistance, which is a major concern in flexible pavements subjected to heavy traffic loads. At the same time, although ductility decreases slightly, the values remain within acceptable limits, indicating that the mix retains sufficient flexibility to resist cracking.
The observed increase in Marshall Stability and Indirect Tensile Strength further confirms the enhancement in structural performance. The improved stability indicates higher load-bearing capacity, while increased ITS values reflect better resistance to tensile stresses and crack formation. The gradual improvement in these properties up to 6% plastic content suggests that plastic enhances the bonding between aggregates and binder, leading to a more cohesive and durable mix. However, beyond the optimum level, the slight reduction in performance highlights the adverse effect of excessive stiffness, which can reduce flexibility and affect long-term durability[16].

6.5 Overall Performance Evaluation

The comparative analysis clearly indicates that plastic-modified mixes outperform conventional mixes across all performance parameters. Improvements were observed in:

- **Strength:** Higher Marshall Stability and ITS values
- **Durability:** Better resistance to rutting, cracking, and moisture damage
- **Thermal Stability:** Increased softening point
- **Moisture Resistance:** Higher TSR values

However, excessive plastic content leads to increased stiffness and reduced flexibility, which may adversely affect performance. Based on the results, the **optimum plastic content is identified as 6%**, at which the mix exhibits maximum strength, adequate flexibility, and superior durability.

7. Discussion

The experimental results obtained in this study provide clear evidence regarding the influence of waste plastic on the performance of bituminous mixes. The interpretation of results indicates that the incorporation of plastic significantly modifies the behavior of the binder and the overall mix. The reduction in penetration value and increase in softening point demonstrate that the modified binder becomes stiffer and more resistant to high-temperature deformation. This directly contributes to improved rutting resistance, which is a major concern in flexible pavements subjected to heavy traffic loads. At the same time, although ductility decreases slightly, the values remain within acceptable limits, indicating that the mix retains sufficient flexibility to resist cracking.

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The results obtained in this study are consistent with findings reported in previous research on plastic-modified asphalt mixtures. Many studies have indicated that the addition of waste plastic improves strength, stiffness, and resistance to moisture damage. The increase in TSR values observed in this study aligns with earlier findings that plastic coating reduces water penetration and enhances adhesion between aggregates and binder. Similarly, the trend of increasing stability up to an optimum plastic content and subsequent decline has also been reported in earlier investigations. This consistency reinforces the reliability of the present findings and supports the effectiveness of plastic modification in improving pavement performance.

From a practical perspective, the use of waste plastic in bituminous mixes offers significant advantages for road construction. The improved resistance to rutting and cracking reduces the frequency of maintenance and extends pavement life, leading to cost savings. The enhanced moisture resistance makes the modified mixes suitable for regions with high rainfall and poor drainage conditions. Additionally, the use of plastic waste contributes to environmental sustainability by reducing landfill disposal and promoting resource conservation. The dry process adopted in this study is simple and can be easily implemented in existing construction practices without major modifications to equipment. Therefore, the findings of this study have direct applicability in real-world pavement construction projects.

8. Conclusions

The present study was undertaken to evaluate the performance and durability of waste plastic-modified bituminous mixes through laboratory experimentation. Based on the results obtained and their analysis, the following conclusions can be drawn:

The incorporation of waste plastic in bituminous mixes significantly enhances the engineering properties of the pavement. The modified binder exhibits improved stiffness and thermal stability, as indicated by reduced penetration values and increased softening point. These changes contribute to better resistance against deformation under high-temperature conditions.

The strength characteristics of the mix show considerable improvement with the addition of plastic. Marshall Stability values increased substantially, indicating enhanced load-bearing capacity, while Indirect Tensile Strength values improved, demonstrating better resistance to cracking. The durability of the mix was also enhanced, as reflected by higher TSR values, which indicate improved resistance to moisture-induced damage.

The study identified that the performance of the mix improves with increasing plastic content up to an optimum level, after which it begins to decline. The optimum plastic content was found to be approximately **6%**, at which the mix exhibited maximum stability, strength, and durability without significant loss of flexibility.The use of waste plastic in bituminous pavements results in improved performance, reduced maintenance requirements, and enhanced durability. In addition to engineering benefits, the approach provides an effective solution for plastic waste management, contributing to environmental sustainability. Plastic-modified bituminous mixes offer a viable and sustainable alternative to conventional pavement materials, and their adoption can significantly improve the quality and longevity of road infrastructure.

exhibited TSR below 75%, whereas modified mixes exceeded 80%, meeting standard requirements. The highest TSR values were observed at 6–8% plastic, confirming the effectiveness of plastic in improving durability under wet conditions.

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