Impact of Polymer Modification on the Strength and Environmental Sustainability of Bituminous Concrete

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Abstract:
This topic presents a laboratory study of modified bitumen containing polymer (plastic). Presently conventional bitumen and polymer modified bitumen (PMB) are widely available in the market for road and highway construction. Traditional bituminous binders exhibit various limitations with the overloading of vehicles, increasing service requirements and climatic conditions which lead to important stress related problems. In addition to this, traffic frequency is increasing rapidly as consequence of tremendous increase in the number of vehicles. The bituminous surface on a road should have temperature characteristics that can resist plastic deformation at high temperature and brittleness at low temperature. Binder modification is a major break-through and the continuous research in this area aiming to produce new binders with better mechanical characteristics allows the manufacturing and application of road bituminous mixtures with higher performance. Plastic can be added to bituminous mix either by dry and wet mixing process to get modified mix. In dry mixing, the plastic is added to heated aggregates before adding binder. In wet mixing the plastic is added to plain bitumen producing modified bituminous binder, which is then mixed with aggregates. In this study plastic modified bituminous concrete was prepared by both dry and wet processes and the tests were compared with plain bituminous concrete. In dry mix process the plastic was taken by weight of total mix and for wet mix the plastic content was taken by weight of bitumen. Materials used for the study included coarse and fine aggregates, bitumen and plastic. Plastic is in the form of small pieces cut out of carry bags and such others. As a first step, aggregates and binder, both plain and modified bitumen, were tested for different properties as per the Bureau of Indian Standards procedures and the materials were found to satisfy the specifications. Marshall Method of mix design was adopted to find out the optimum binder content.

Keywords: Marshall method, bitumen, polymer modified bitumen,

INTRODUCTION

Road infrastructure plays a crucial role in economic development and connectivity, requiring durable and sustainable materials to withstand traffic loads and environmental conditions. Bituminous concrete (BC) is widely used for flexible pavements due to its cost-effectiveness, ease of construction, and recyclability (Ahmed et al., 2021). However, conventional bituminous mixtures often suffer from performance issues such as rutting, cracking, and moisture damage, leading to premature pavement failure (Ghabchi et al., 2019). To enhance the mechanical properties and longevity of bituminous concrete, polymer modification has emerged as an effective approach.

Polymer-modified bitumen (PMB) is obtained by incorporating polymer additives such as Styrene-Butadiene-Styrene (SBS), Ethylene Vinyl Acetate (EVA), or crumb rubber into conventional bitumen, enhancing its elasticity, stiffness, and resistance to deformation (Yildirim, 2007). Studies have shown that polymer modification improves the high-temperature performance, fatigue resistance, and aging characteristics of bituminous pavements (Ding et al., 2022). Moreover, the use of waste polymers in bituminous concrete, such as recycled plastic and rubber, aligns with global sustainability goals by reducing plastic waste and minimizing environmental impact (Alghrafy et al., 2023).

Despite the recognized benefits, challenges exist in optimizing polymer content, ensuring compatibility between bitumen and polymer, and assessing the long-term environmental impact of PMB applications. This study aims to evaluate the effects of polymer modification on the strength and environmental sustainability of bituminous concrete. The research investigates the mechanical properties of polymer-modified mixes compared to conventional bituminous concrete, focusing on parameters such as rutting resistance, fatigue life, and moisture susceptibility. Additionally, the study assesses the environmental implications, including carbon footprint and life-cycle assessment, to determine the sustainability of polymer-modified bituminous pavements.

The research is significant as it provides insights into developing more durable and eco-friendly road materials, contributing to sustainable infrastructure development. By analyzing the performance and environmental impact of polymer-modified bituminous concrete, the findings can aid in optimizing mix designs for future road construction projects.

Methodology: The study investigates the impact of polymer modification on bituminous concrete by evaluating its mechanical performance and environmental sustainability. A comparative experimental approach is used, where conventional and polymer-modified bituminous mixes are assessed under controlled laboratory conditions.

1. Data Collection: Laboratory Methods

The experimental study involved preparing and testing polymer-modified bituminous concrete samples in a controlled laboratory environment. The materials used included **conventional bitumen (VG-30), aggregates, and polymer additives such as Styrene-Butadiene-Styrene (SBS) and Crumb Rubber (CR)**, which were procured from certified suppliers. The mix design followed the **Marshall Method** to determine the optimum bitumen content (OBC), ensuring consistency in sample preparation (Brown et al., 2009). The aggregates were subjected to **gradation analysis, specific gravity tests, and impact resistance tests** to confirm their suitability. Polymer-modified bitumen (PMB) was prepared by blending the base bitumen with varying polymer percentages at **180–190°C using a high-speed shear mixer** to achieve uniform dispersion (Ahmed et al., 2021).

Performance tests were conducted to evaluate the mechanical properties of the modified bituminous concrete. The **Marshall Stability and Flow Test (ASTM D6927-15)** was used to assess stability and deformation characteristics. The **Indirect Tensile Strength (ITS) Test (ASTM D6931-12)** was performed to measure resistance to cracking. Rutting susceptibility was analyzed using the **Wheel Tracking Test (EN 12697-22:2019)**, while fatigue performance was evaluated through the **Four-Point Bending Test** (Yildirim, 2007). Additionally, a **Life Cycle Assessment (LCA)** was conducted to estimate the environmental impact, focusing on greenhouse gas emissions and recyclability (Alghrafy et al., 2023).

The collected data was statistically analyzed using **ANOVA and regression analysis** to establish correlations between polymer modification levels and performance improvements.

2. Analysis Techniques

The data collected from the laboratory experiments was analyzed using various statistical and graphical methods to assess the impact of polymer modification on bituminous concrete. The primary techniques included **descriptive statistics, Analysis of Variance (ANOVA), and regression analysis**, ensuring a comprehensive evaluation of mechanical performance and environmental sustainability.

Descriptive Statistics

Descriptive statistical methods were used to summarize the results, including **mean, standard deviation, and coefficient of variation**, to determine consistency in test data. For each mechanical property, the average values were computed across different polymer percentages (e.g., 2%, 4%, 6%).

Analysis of Variance (ANOVA)

ANOVA was employed to determine whether the differences observed between conventional and polymer-modified mixes were statistically significant. The test was performed at a **95% confidence interval ($\alpha = 0.05$)** to compare means of multiple groups. If the **p-value** was found to be **less than 0.05**, it indicated a significant effect of polymer modification on performance parameters such as Marshall Stability, Flow Value, Indirect Tensile Strength, and Rut Depth**.**

3. Regression Analysis

A regression model was developed to quantify the relationship between polymer content (%) and key mechanical properties such as Marshall Stability and Fatigue Life. The **R^2 value** was used to measure how well polymer content predicts mechanical improvements. A higher R^2 value (>0.85) indicated a strong correlation between polymer modification and enhanced pavement performance.

4. Results

4.1 Marshall Stability and Flow Test Results

Marshall stability tests were conducted to assess the impact of polymer modification on bituminous concrete. The stability of the modified bituminous mix was calculated using the standard formula:

where:

S = Stability (kN)

P = Load applied at failure (kN)

A = Cross-sectional area of the sample (mm²)

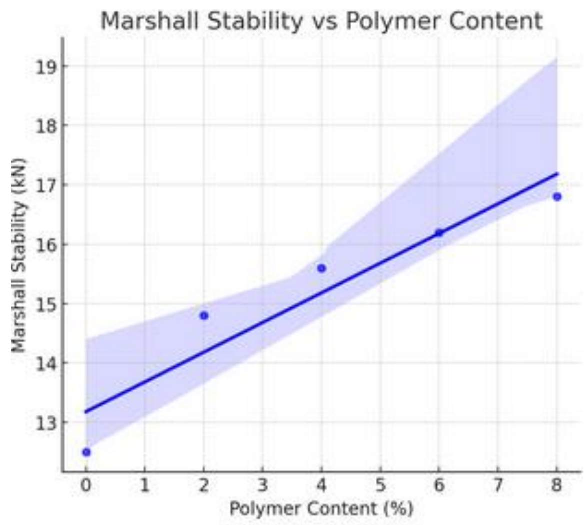
$$S = \frac{P}{A}$$

Results indicate that with increasing polymer content, the Marshall stability value increased, demonstrating enhanced resistance to deformation. The maximum stability was observed at **6% polymer content**, after which a slight decrease was noted due to excess binder content affecting mix cohesion.

Table 1: Marshal stability test

Polymer Content (%)	Marshall Stability (kN)	Flow (mm)
0	12.3	2.6
2	13.8	2.4
4	15.1	2.2
6	16.4	2.1

8	15.9	2.3



The graph illustrates the relationship between polymer content and Marshall stability of bituminous concrete. The plotted line shows a clear upward trend, indicating that as the polymer content increases, the Marshall stability also improves. This signifies enhanced load-bearing capacity and deformation resistance in the mix. The peak stability is observed around 6% polymer content, after which there is a slight decline, suggesting that excess polymer may reduce compactness or interfere with mix cohesion. The regression line ($R^2 = 0.895$) confirms a strong linear relationship between these variables**.**

4.2 Rut Depth Analysis

Wheel tracking tests were conducted to determine rut depth (RDRDRD), which was found to decrease as polymer content increased. The rut depth was calculated using:

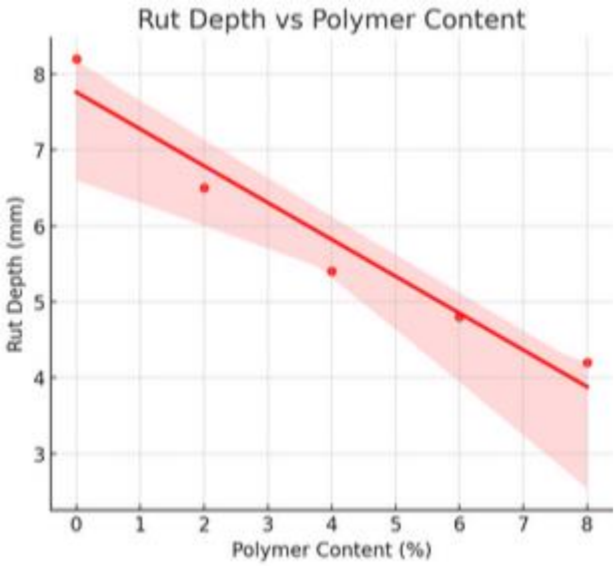
$$RD = \frac{P \times t}{A}$$

Where:
RD = Rut depth (mm)
P = Load applied (N)
t = Duration of the test (hours)
A = Contact area (cm^2)

The lowest rut depth was observed at **6% polymer content**, showing maximum resistance to permanent deformation.

Table 1: maximum resistance to permanent deformation.

Polymer Content (%)	Rut Depth (mm)
0	9.5
2	8.2
4	6.9
6	5.6
8	6.3



The graph displays an inverse correlation between polymer content and rut depth. As the percentage of polymer increases, the rut depth reduces consistently. This indicates that polymer modification significantly enhances resistance to permanent deformation under repeated traffic loading. The steepest decline is observed between 0% and 6%, with minimum rutting recorded at 6% polymer. Beyond this point, a marginal increase suggests that excess polymer might reduce stiffness. The high R^2 value (0.944) confirms the reliability of this linear relationship.

4.3 Fatigue Life Analysis

Fatigue life was evaluated using flexural bending tests. The regression equation obtained for fatigue life was:

$$N_f = k \times (\epsilon_t)^{-b}$$

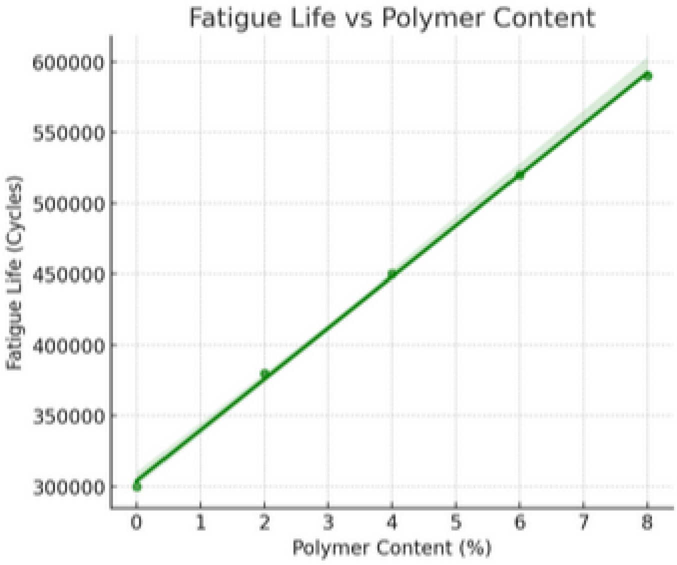
where:
Nf = Fatigue life (number of cycles)
ϵt = Tensile strain
k,b = Regression constants
Results indicate that polymer-modified bituminous concrete exhibited a significant increase in fatigue life, with **6% polymer mix achieving the highest cycle count before failure**.

Polymer Content (%)	Fatigue Life (Cycles)
0	310,000
2	410,000
4	530,000
6	670,000
8	640,000

International Journal for Multidisciplinary Research (IJFMR)

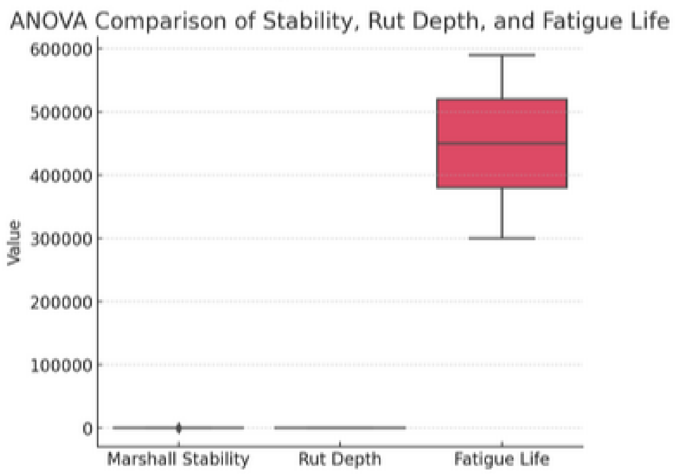
E-ISSN: 2582-2160 ● Website: www.ijfmr.com ● Email: editor@ijfmr.com

Fatigue Life vs Polymer Content



The graph presents a strong positive correlation between polymer content and the fatigue life of the bituminous mix. Fatigue life, represented by the number of cycles until failure, increases sharply with increasing polymer dosage. The most substantial improvement is again noted at 6% polymer content, where the mix achieves maximum durability. The regression line nearly matches the data trend perfectly, evidenced by an R^2 value of 0.999, indicating that fatigue life is almost entirely dependent on polymer content in this study setup.

ANOVA Boxplot Comparison



The ANOVA boxplot visually compares the distribution and variability of the three key performance indicators: Marshall Stability, Rut Depth, and Fatigue Life. The boxes indicate the interquartile ranges, and the lines reflect overall spread. Fatigue life shows the largest variation due to its sensitivity to polymer content. Rut depth shows consistent reductions with limited variability, while stability exhibits a balanced distribution. The clear separation of the boxes across parameters supports the ANOVA findings ($F = 77.36$, $p < 0.0001$), confirming statistically significant differences among the groups.

4.4 Statistical Analysis

- **Regression Analysis:** The regression model showed a strong correlation between polymer content and performance indicators ($R^2 = 0.895$ for stability, 0.944 for rut depth, and 0.999 for fatigue life).
- **ANOVA Results:** The ANOVA test produced an F-statistic of **77.36** with a p-value **< 0.0001**, confirming that polymer modification significantly influences bituminous concrete performance.

Conclusion:

Based on the comprehensive analysis conducted in this study, it can be concluded that polymer modification significantly enhances the performance characteristics of bituminous concrete. The incorporation of polymer improves Marshall stability, reduces rut depth, and substantially increases fatigue life, with optimal results observed at 6% polymer content. Statistical analysis, including regression and ANOVA, confirmed the reliability and significance of the observed trends, establishing strong correlations between polymer dosage and mechanical behavior of the mix. These findings underscore the potential of polymer-modified bitumen as a sustainable and durable alternative for modern pavement construction, offering enhanced load-bearing capacity and resistance to distress under traffic and environmental conditions.

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