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JIZPI XABARNOMASI

ILMIY-TEXNIK JURNAL

- 05.00.00 - Texnika fanlari
- 05.02.00 - Mashinasozlik va mashinashunoslik.
Mashinasozlikda materiallarga ishlov berish.
Metallurgiya. Aviasiya texnikasi
- 05.03.00 - Asbobsozlik, metrologiya va axborot-o'lchov
asboblari va tizimlari
- 05.04.00 - Radiotexnika va aloqa
- 05.05.00 - Energetika va elektrotexnika.
Qishloq xo'jaligi ishlab chiqarishini elektrlashtirish
texnologiyasi. Elektronika
- 05.06.00 - To'qimachilik va yengil sanoat materiallari
va buyumlari texnologiyasi
- 05.07.00 - Qishloq xo'jaligi ishlab chiqarishini
mexanizasiyalash texnologiyasi
- 05.08.00 - Transport
- 05.09.00 - Qurilish
- 05.10.00 - Inson faoliyati xavfsizligi

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Investigation of the strength properties of polymer-modified asphalt concrete mixtures

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Abstract — This study focuses on investigating the strength properties of polymer-modified asphalt concrete mixtures. The main objective is to evaluate the influence of polymer additives on the mechanical performance of asphalt concrete, including compressive strength, flexibility, and resistance to deformation. The methodology is based on laboratory testing, including Marshall stability analysis, deformation behavior under dynamic loading, and temperature-dependent strength evaluation. Specimens modified with different percentages of polymer additives were prepared and compared. The results demonstrate that polymer modification significantly enhances the load-bearing capacity of asphalt concrete and reduces its susceptibility to softening at elevated temperatures. Furthermore, improvements in crack resistance and overall service life were observed. The findings confirm the practical importance of polymer-modified asphalt concrete in modern road construction for producing durable, high-performance pavement materials capable of withstanding heavy traffic and harsh environmental conditions.

Keywords — *polymer-modified asphalt concrete, asphalt binder modification, mechanical properties of asphalt mixtures, Marshall stability, compressive strength, deformation resistance, rutting resistance, fatigue performance, temperature susceptibility, viscoelastic behavior, pavement durability, road construction materials, bitumen modification, high-performance asphalt mixtures, laboratory testing of asphalt concrete.*

INTRODUCTION

The performance, durability, and life-cycle cost of asphalt pavements are fundamentally governed by the mechanical and rheological properties of asphalt concrete mixtures. With the continuous growth of traffic intensity, axle loads, and speed, combined with increasingly variable and extreme climatic conditions, conventional asphalt materials are subjected to complex stress-strain states that accelerate structural deterioration. Typical distresses include rutting under high temperatures and heavy loads, thermal cracking at low temperatures, and fatigue cracking due to repeated traffic loading. These limitations significantly reduce pavement service life and increase maintenance costs, thereby necessitating the development of high-performance materials with enhanced mechanical stability and durability. One of the most promising approaches to improving asphalt mixture performance is the modification of bitumen using polymer additives. Polymer-modified asphalt (PMA) has gained widespread attention due to its ability to alter the internal structure and viscoelastic behavior of the binder. The incorporation of polymers—such as styrene-butadiene-

styrene (SBS), polyethylene (PE), and crumb rubber—leads to the formation of a three-dimensional network within the bitumen matrix. This network enhances elastic recovery, increases stiffness at high temperatures, and improves flexibility at low temperatures. Consequently, PMA mixtures exhibit superior resistance to permanent deformation (rutting), enhanced fatigue life, and reduced temperature susceptibility compared to conventional asphalt mixtures.

Recent studies have demonstrated that the performance of polymer-modified asphalt depends not only on the type of polymer used but also on its concentration, compatibility with the base bitumen, and mixing conditions. Despite significant progress in this field, several challenges remain unresolved. These include optimizing the dosage of polymer modifiers to achieve a balance between performance improvement and economic efficiency, understanding the physicochemical interactions between polymer and bitumen at the microstructural level, and ensuring long-term stability under aging and environmental impacts [1].

Furthermore, the increasing emphasis on sustainable infrastructure development has intensified interest in durable pavement materials that reduce resource consumption and environmental impact over their life cycle. In this context, polymer modification can contribute to sustainability by extending pavement lifespan and reducing the frequency of rehabilitation interventions.

Therefore, this study aims to conduct a comprehensive experimental investigation of the strength properties of polymer-modified asphalt concrete mixtures. The research focuses on evaluating key mechanical parameters, including stability, strength, deformation resistance, and fatigue performance, under controlled laboratory conditions. Additionally, the study seeks to identify optimal polymer content and assess its effectiveness in improving pavement performance. The findings are expected to provide both scientific insights and practical recommendations for the design and application of high-performance asphalt mixtures in modern road engineering.

METHODS

This study adopts a comprehensive controlled laboratory experimental framework aimed at systematically evaluating the strength-related and deformation characteristics of polymer-modified asphalt concrete mixtures. The methodology is structured into four interrelated stages: material selection and characterization, binder modification,

mixture design and preparation, and mechanical and statistical evaluation of performance. Each stage was designed to ensure reproducibility, consistency, and compliance with internationally recognized pavement engineering standards [2].

Materials and Binder Modification. A conventional penetration-grade bitumen was selected as the base binder due to its wide application in flexible pavement construction. The bitumen was modified using a thermoplastic polymer additive introduced at three dosage levels: 2%, 4%, and 6% by weight of the binder. The modification process was carried out using a high-shear mixing system to ensure uniform dispersion of polymer particles within the bitumen matrix. The mixing temperature was maintained within the range of 160–180°C, with controlled mixing duration and rotational speed to achieve optimal polymer–bitumen interaction and prevent phase separation.

Crushed mineral aggregates were selected based on standard grading requirements in accordance with ASTM D692 or equivalent EN specifications. The aggregates were thoroughly washed, dried, and classified into appropriate fractions to ensure consistent gradation, angularity, and surface texture. Filler material (mineral powder) was also incorporated to enhance mastic formation and improve mixture stability [3].

Mixture Design and Sample Preparation. Asphalt concrete mixtures were designed using the Marshall mix design method, which is widely adopted for evaluating medium- and heavy-traffic pavement structures. The optimal binder content was determined based on standard criteria, including maximum stability, acceptable flow values, and volumetric parameters.

Specimens were prepared using standardized cylindrical molds and compacted using a Marshall hammer with 75 blows per face to simulate field compaction conditions under traffic loading. After compaction, specimens were cooled at room temperature for 24 hours before testing to ensure structural stabilization.

Volumetric properties such as air voids (Va), voids in mineral aggregate (VMA), and voids filled with bitumen (VFB) were determined for each mixture. These parameters were used to verify compliance with design specifications and to ensure that polymer modification did not negatively affect mixture compactability or internal structure.

Mechanical Performance Testing. The mechanical behavior of both control and modified mixtures was evaluated through a series of standardized laboratory tests:

Marshall Stability and Flow Test: Conducted to determine load-bearing capacity and plastic deformation resistance under static loading conditions.

Uniaxial Compressive Strength Test: Performed at 20°C to evaluate structural strength and resistance to axial loading.

Dynamic Creep Test: Applied to assess permanent deformation behavior under sustained and repeated loading conditions.

Repeated Load Fatigue Test: Conducted under controlled stress or strain conditions to determine fatigue life and crack resistance.

Rutting Resistance Evaluation: Performed at elevated temperature conditions (typically 60°C) to simulate high-temperature field performance.

Temperature Susceptibility Analysis: Conducted at multiple temperature levels (5°C, 20°C, and 60°C) to assess performance variation under thermal fluctuations.

Statistical Analysis. To ensure the reliability and scientific validity of the results, statistical evaluation was performed using analysis of variance (ANOVA). This method was applied to determine the significance of differences between control and polymer-modified mixtures at different dosage levels. Standard deviation, mean values, and confidence intervals were also calculated to quantify data variability and ensure repeatability [4].

Methodological Reliability. All experimental procedures were repeated multiple times to minimize random errors and improve data accuracy. Calibration of testing equipment was performed prior to experiments, and standardized testing conditions were strictly maintained throughout the study. This methodological framework ensures high reliability, reproducibility, and scientific robustness of the obtained results while enabling meaningful comparison with existing literature in the field of pavement materials engineering.

RESULTS

Marshall stability exhibited a steady increase from 9.8 kN in the control mixture to 11.6 kN, 13.2 kN, and 14.1 kN for mixtures containing 2%, 4%, and 6% polymer additive, respectively, corresponding to an overall increase of approximately 44% at the highest modification level. Simultaneously, flow values decreased from 3.9 mm in the conventional mixture to 3.5 mm, 3.2 mm, and 3.0 mm, indicating enhanced stiffness and reduced plastic deformation under load.

Compressive strength at 20°C increased progressively from 3.2 MPa in the control sample to 3.8 MPa (2%), 4.4 MPa (4%), and 4.7 MPa (6%), representing an increase of up to 47%. Under dynamic loading conditions, permanent deformation decreased significantly by 12%, 21%, and 28% for 2%, 4%, and 6% polymer-modified mixtures, respectively, confirming improved resistance to repeated loading [5].

Rutting resistance at elevated temperature (60°C) also improved notably. Rut depth decreased from 7.5 mm in the unmodified mixture to 6.3 mm, 5.4 mm, and 4.8 mm, corresponding to a reduction of approximately 36% at the highest polymer dosage. Fatigue performance showed substantial enhancement, with fatigue life increasing from 18,000 cycles in the control mixture to 24,000 cycles (2%), 31,000 cycles (4%), and 36,000 cycles (6%), effectively doubling the service life under cyclic loading.

The temperature susceptibility index decreased from 0.92 to 0.81, 0.74, and 0.69, indicating improved thermal stability and reduced sensitivity to temperature variations. Despite these performance improvements, the air void content remained within the acceptable design range of 3.5%–4.2% for all mixtures, confirming that volumetric properties were not adversely affected by polymer modification.

DISCUSSION

The experimental findings clearly demonstrate that increasing polymer content leads to systematic improvements in the mechanical and functional performance of asphalt concrete mixtures. This trend is consistent with the fundamental principles of viscoelastic modification in bituminous materials, where the addition of polymers alters both the elastic and viscous components of the binder. The observed increase in Marshall stability and compressive strength indicates enhanced internal cohesion and structural stiffness of the asphalt matrix. This behavior can be attributed to the development of a three-dimensional polymer-bitumen network, which improves load transfer efficiency and stress distribution under both static and dynamic loading conditions.

The reduction in flow values and permanent deformation further confirms the enhanced resistance of polymer-modified mixtures to rutting. This effect is particularly significant at elevated temperatures, where conventional bitumen typically exhibits increased susceptibility to viscous flow. The results align with previously reported findings (Airey, 2004; Lu and Isacsson, 1997), which highlight that polymer-modified binders demonstrate higher elastic recovery and reduced temperature sensitivity. The decrease in rutting depth observed in this study quantitatively supports these conclusions [6].

The substantial improvement in fatigue life provides additional evidence of the beneficial role of polymer modification. The increased number of load cycles to failure suggests that the modified mixtures possess greater flexibility and improved energy dissipation capacity. This reduces stress concentration at microstructural defects and delays crack initiation and propagation, thereby enhancing the long-term durability of the pavement.

From a rheological standpoint, the results confirm that polymer addition shifts the behavior of asphalt binders toward a more elastic-dominant response, particularly under cyclic loading conditions. This transition is critical for maintaining structural integrity under repeated traffic loads. Moreover, the reduction in temperature susceptibility indicates improved performance across a wider range of climatic conditions, minimizing both high-temperature rutting and low-temperature cracking risks [7].

In practical terms, these improvements translate into extended pavement service life, lower maintenance and rehabilitation costs, and increased exploitation reliability, especially in regions with heavy traffic loads and significant temperature fluctuations. The performance gains observed at 4–6% polymer content suggest that this range represents an optimal balance between mechanical enhancement and material efficiency. However, beyond this range, the incremental benefits may diminish relative to the additional cost of polymer modifiers, necessitating further techno-economic evaluation.

Despite the positive outcomes, several limitations should be acknowledged. The study was conducted under controlled laboratory conditions, which may not fully replicate field exploitation environments. Additionally, only a single type of polymer modifier was considered, and the long-term effects of aging, oxidation, and moisture damage were not evaluated.

Future research should focus on long-term performance assessment, including aging resistance and moisture susceptibility, as well as full-scale field validation. Investigating alternative polymer types, recycled modifiers,

and hybrid modification systems could further enhance performance while improving sustainability. Such studies would contribute to the development of more resilient, cost-effective, and environmentally sustainable asphalt pavement technologies.

CONCLUSIONS

This study quantified the effect of polymer modification (2–6% by binder mass) on the strength-related performance of asphalt concrete. Key findings include a systematic increase in Marshall stability (from 9.8 kN to 14.1 kN), compressive strength at 20°C (from 3.2 MPa to 4.7 MPa), and fatigue life (from 18,000 to 36,000 cycles), alongside reductions in flow (3.9 mm to 3.0 mm), rutting depth at 60°C (7.5 mm to 4.8 mm), permanent deformation (up to –28%), and temperature susceptibility index (0.92 to 0.69). Air voids remained within the design range (3.5–4.2%), indicating that performance gains were not achieved at the expense of volumetric stability [8].

Scientifically, the results provide quantitative evidence that polymer addition strengthens the polymer-bitumen network, shifting the mixture toward a more elastic-dominant response and improving load distribution under static and cyclic loading. Practically, the identified performance gains translate into longer pavement service life, higher resistance to rutting in hot climates, and reduced maintenance frequency. The data indicate an effective modification window at 4–6%, balancing performance improvement and material efficiency.

Limitations include the laboratory-only scope, a single polymer type, and the absence of long-term aging, moisture susceptibility, and field validation.

Overall, polymer-modified asphalt concrete is confirmed as a high-performance pavement material; implementing 4–6% modification can deliver measurable durability gains under heavy traffic and elevated temperatures.

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