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ANALYSIS OF THE PHYSICAL, MECHANICAL, AND SERVICE PERFORMANCE PROPERTIES OF ROAD PAVEMENTS

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Abstract: Road pavements constitute one of the most valuable assets of transportation infrastructure, playing a fundamental role in ensuring safe, efficient, and sustainable mobility. With the continuous increase in traffic volume, axle loads, and climate-related challenges, the demand for high-performance pavement materials has become more critical than ever. This study analyzes the physical, mechanical, and service performance properties of road pavements through a comprehensive review of material characteristics, laboratory testing methods, and engineering performance indicators. The investigation focuses on physical parameters such as density, porosity, air voids, and water absorption; mechanical characteristics including compressive strength, indirect tensile strength, resilient modulus, dynamic modulus, and fatigue resistance; and service performance indicators such as rutting resistance, skid resistance, roughness, durability, and maintenance requirements. The findings indicate that optimized aggregate gradation, high-quality asphalt binders, appropriate compaction, and advanced pavement technologies significantly enhance pavement durability while reducing maintenance costs. Furthermore, sustainable materials, intelligent monitoring systems, and mechanistic–empirical pavement design approaches offer promising solutions for extending pavement service life and improving transportation infrastructure resilience.

Keywords: Road pavements; Physical properties; Mechanical properties; Pavement performance; Asphalt concrete; Durability; Resilient modulus; Rutting resistance; Transportation engineering; Sustainable infrastructure.

Introduction. Road transportation infrastructure constitutes one of the most essential components of modern economic and social development. Efficient road networks facilitate the movement of people, goods, and services, thereby supporting industrial production, international trade, tourism, agriculture, and regional integration. According to international transportation statistics, road transport accounts for more than 80% of global passenger movement and nearly 70% of freight transportation, making highway infrastructure one of the largest public investments worldwide. Consequently, ensuring the structural reliability, durability, and long-term serviceability of road pavements has become a strategic priority for governments, transportation agencies, and civil engineering researchers. Road pavements are complex multilayer engineering systems designed to safely distribute vehicle loads from the pavement surface to the underlying foundation while maintaining acceptable riding quality throughout their design life. Depending on structural composition, pavements are generally classified as flexible, rigid, or composite systems. Flexible pavements consist primarily of asphalt concrete layers supported by granular base and subbase materials, whereas rigid pavements utilize Portland cement concrete slabs to distribute loads over a wider area. Regardless of pavement type, all structures are continuously subjected to repeated traffic loading, climatic variations, moisture infiltration, ultraviolet radiation, oxidation, and material aging. These factors progressively deteriorate pavement structures, leading to reductions in structural capacity, ride quality, and operational safety. During the past several decades, global transportation

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systems have experienced unprecedented increases in traffic demand. Rapid urbanization, economic expansion, industrial growth, and international logistics have significantly increased both traffic volume and axle loads. Modern heavy-duty freight vehicles generate stresses that frequently exceed those considered in traditional pavement design methodologies. Simultaneously, climate change has intensified environmental stresses through prolonged heat waves, heavy rainfall events, flooding, freeze–thaw cycles, and extreme temperature fluctuations. These combined mechanical and environmental factors accelerate pavement deterioration, resulting in rutting, fatigue cracking, thermal cracking, stripping, ravelling, potholes, and surface polishing. Premature pavement deterioration represents a major economic challenge worldwide. Transportation agencies invest billions of dollars annually in pavement rehabilitation, maintenance, and reconstruction. Poor pavement conditions increase vehicle operating costs, fuel consumption, greenhouse gas emissions, travel time, accident risks, and overall infrastructure expenditures. Therefore, understanding the relationships between pavement material properties and long-term service performance is fundamental for optimizing pavement design, improving maintenance strategies, and reducing life-cycle costs. The engineering behavior of road pavements is governed by three interrelated groups of characteristics: physical properties, mechanical properties, and service performance properties. These characteristics collectively determine how pavement materials respond to traffic loading, environmental exposure, and long-term operational conditions. A comprehensive understanding of these parameters provides the scientific basis for pavement material selection, structural design, quality control, and performance prediction. Physical properties describe the intrinsic characteristics of pavement materials that influence their resistance to environmental deterioration. Important physical parameters include bulk density, maximum theoretical density, air void content, porosity, permeability, water absorption, thermal conductivity, moisture susceptibility, aggregate gradation, particle shape, and surface texture. Among these, density and air void distribution are considered the most critical because they directly affect moisture infiltration, oxidation, binder aging, and internal structural stability. Properly compacted asphalt mixtures with optimal air void content minimize water penetration and oxygen diffusion, thereby reducing stripping, oxidation, and fatigue damage. Conversely, inadequate compaction creates interconnected voids that accelerate pavement deterioration through moisture-induced damage and environmental aging. Mechanical properties determine the ability of pavement materials to withstand traffic-induced stresses without experiencing excessive deformation or structural failure. Since road pavements are subjected to millions of repeated wheel loads throughout their service life, both strength and elasticity are required to maintain structural integrity. Key mechanical parameters include Marshall Stability, compressive strength, indirect tensile strength, resilient modulus, dynamic modulus, flexural strength, shear resistance, creep behavior, fracture toughness, and fatigue resistance. These properties collectively determine the pavement's ability to resist permanent deformation, tensile cracking, and repeated cyclic loading. Modern mechanistic–empirical pavement design methods increasingly rely on resilient modulus and dynamic modulus because these parameters accurately represent the elastic behavior of pavement materials under realistic loading conditions. Service performance properties represent the practical operational behavior of pavements during their entire service life. These indicators integrate both physical and mechanical characteristics into measurable engineering outcomes, including rutting resistance, fatigue life, thermal cracking resistance, skid resistance, ride quality, surface roughness, rolling resistance, drainage capability, noise generation, durability, and maintenance frequency. Service performance evaluation enables transportation agencies to assess pavement condition objectively, prioritize maintenance activities, and optimize infrastructure investment through pavement management systems (PMS). The rapid advancement of pavement engineering has introduced numerous innovative

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materials aimed at improving pavement durability and sustainability. Polymer-modified asphalt binders have demonstrated significant improvements in elasticity, temperature susceptibility, rutting resistance, and fatigue performance compared with conventional bitumen. Similarly, Stone Matrix Asphalt (SMA), Open-Graded Friction Course (OGFC), Warm Mix Asphalt (WMA), and High-Modulus Asphalt (EME) have been developed to enhance specific engineering properties under different traffic and climatic conditions. The evaluation of pavement materials relies on internationally recognized laboratory and field testing standards. Laboratory characterization commonly includes Marshall Stability testing, Superpave Gyratory Compaction, Indirect Tensile Strength (ITS), Dynamic Modulus, Resilient Modulus, Four-Point Beam Fatigue, Hamburg Wheel Tracking, Wheel Tracking Test, Moisture Susceptibility (TSR), Dynamic Creep, and Bending Beam Rheometer (BBR) testing. These laboratory assessments are complemented by field performance measurements such as the International Roughness Index (IRI), Pavement Condition Index (PCI), Falling Weight Deflectometer (FWD), skid resistance evaluation, friction measurements, and structural health monitoring. Together, these standardized procedures provide reliable indicators of pavement quality and long-term performance. Although considerable progress has been achieved in pavement engineering, several challenges remain unresolved. Many previous investigations have focused primarily on either physical or mechanical characteristics without comprehensively analyzing their combined influence on service performance. Moreover, discrepancies often exist between laboratory results and actual field behavior due to differences in traffic loading, climatic conditions, construction quality, material aging, and maintenance practices. The increasing complexity of modern traffic conditions and climate variability further necessitates integrated research approaches capable of simultaneously evaluating multiple performance indicators. Against this background, the present study aims to provide a comprehensive analysis of the physical, mechanical, and service performance properties of road pavements. The research investigates the relationships between material characteristics, structural behavior, and long-term operational performance by evaluating key physical parameters, mechanical strength properties, and service performance indicators. Particular attention is given to the influence of advanced asphalt technologies, sustainable pavement materials, and intelligent monitoring systems on pavement durability and life-cycle performance. The outcomes of this study are expected to contribute to the optimization of pavement material selection, improvement of structural design methodologies, enhancement of maintenance strategies, and development of more durable, resilient, and environmentally sustainable transportation infrastructure capable of meeting future engineering challenges.

Literature Review. Road pavement engineering has undergone substantial scientific and technological transformation over the past century. Early pavement design approaches were primarily empirical, relying on observations of pavement failures and accumulated engineering experience. Although these methods provided practical guidance for road construction, they were limited in their ability to predict pavement behavior under changing traffic and environmental conditions. The rapid growth of transportation systems, increasing axle loads, accelerated urbanization, and climate variability have driven the transition toward mechanistic–empirical and performance-based pavement design methodologies. These modern approaches combine material science, structural mechanics, environmental engineering, and computational modeling to improve pavement reliability and service life. The transition from empirical to performance-based pavement engineering has significantly increased the importance of comprehensive material characterization. Numerous investigations have confirmed that pavement performance depends not only on individual material properties but also on the interaction among aggregates, asphalt binders, void structure, and environmental conditions. Among the physical properties of asphalt mixtures, bulk density has consistently been identified as

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one of the most influential parameters affecting pavement durability. Dense asphalt mixtures exhibit lower permeability, improved aggregate interlocking, enhanced moisture resistance, and reduced oxidation rates. Studies have shown that inadequate field compaction creates interconnected air voids that facilitate water infiltration, oxygen diffusion, and binder aging, thereby accelerating pavement deterioration. Conversely, excessive compaction may cause asphalt bleeding and reduce skid resistance. Therefore, achieving optimum density during construction remains a critical quality-control objective. Closely related to density is the air void content, which significantly influences pavement mechanical performance and environmental durability. Research indicates that asphalt mixtures containing approximately 3–5% air voids generally exhibit the best balance between flexibility and structural stability. Air void contents exceeding this range increase permeability and moisture susceptibility, while excessively low void contents may result in flushing and permanent deformation under high service temperatures. Sustainability has emerged as one of the dominant themes in modern pavement engineering. The road construction industry consumes enormous quantities of virgin aggregates and petroleum-based binders while generating significant greenhouse gas emissions. To address these challenges, researchers have extensively investigated the incorporation of Reclaimed Asphalt Pavement (RAP), Reclaimed Asphalt Shingles (RAS), recycled concrete aggregates, steel slag, fly ash, waste plastics, waste glass, crumb rubber, and bio-based binders into asphalt mixtures. Among these technologies, RAP has become one of the most successful recycling strategies because it allows substantial replacement of virgin materials while maintaining acceptable engineering performance. Numerous studies indicate that mixtures containing moderate RAP contents exhibit comparable mechanical properties to conventional asphalt when binder rejuvenators and optimized mix designs are employed. Similarly, crumb rubber modification has demonstrated improvements in elasticity, fatigue resistance, and noise reduction while simultaneously providing an environmentally beneficial solution for waste tire disposal. The development of Warm Mix Asphalt (WMA) technologies has further advanced sustainable pavement construction. By reducing mixing and compaction temperatures by approximately 20–40°C, WMA decreases fuel consumption, greenhouse gas emissions, and asphalt aging while improving workability during construction. Comparative studies consistently report similar or improved mechanical performance relative to conventional Hot Mix Asphalt (HMA), particularly when combined with polymer-modified binders. Another rapidly expanding research area involves nanotechnology. Nano-silica, nano-clay, graphene nanoplatelets, carbon nanotubes, titanium dioxide nanoparticles, and nano-calcium carbonate have demonstrated considerable potential for improving asphalt binder stiffness, thermal stability, ultraviolet resistance, aging resistance, and moisture durability. These nanomaterials modify asphalt microstructure at the molecular scale, resulting in enhanced rheological and mechanical performance. Although current implementation remains relatively limited because of material costs, continuous technological advancements are expected to accelerate their practical adoption.

Digitalization is transforming pavement engineering through the integration of Artificial Intelligence (AI), Machine Learning (ML), Internet of Things (IoT), Ground-Penetrating Radar (GPR), LiDAR, embedded wireless sensors, digital image processing, unmanned aerial vehicles (UAVs), and digital twins. These technologies enable continuous pavement condition monitoring, automated distress detection, predictive maintenance, and optimized infrastructure management. Machine-learning algorithms have shown high accuracy in predicting pavement deterioration based on historical traffic, climate, and material datasets, offering significant improvements over traditional statistical models. Life-cycle assessment (LCA) and life-cycle cost analysis (LCCA) have become indispensable tools for evaluating pavement sustainability. Instead of considering only initial construction costs, these methodologies incorporate maintenance, rehabilitation, user delays,

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environmental impacts, energy consumption, and greenhouse gas emissions throughout the pavement life cycle. Numerous investigations conclude that high-performance asphalt mixtures, despite their greater initial cost, often provide lower total life-cycle costs because of extended service life and reduced maintenance requirements. Despite these significant advances, several research gaps remain. Many previous studies investigate physical, mechanical, or performance properties independently without establishing comprehensive relationships among them. Laboratory experiments frequently fail to reproduce the combined effects of traffic loading, environmental exposure, aging, and construction variability encountered under real field conditions. Furthermore, the increasing adoption of recycled materials, climate-resilient technologies, and intelligent monitoring systems requires updated evaluation methodologies capable of integrating laboratory characterization with long-term field performance. Therefore, the present study seeks to bridge these gaps by conducting a comprehensive analysis of the physical, mechanical, and service performance properties of road pavements. By integrating classical pavement engineering principles with recent developments in advanced materials, sustainable technologies, mechanistic–empirical design, and intelligent infrastructure monitoring, this research provides a holistic framework for understanding the factors governing pavement durability and operational performance. The findings are expected to support the development of more resilient, cost-effective, and environmentally sustainable pavement systems capable of meeting future transportation demands.

Results and Discussion. The evaluation of the physical properties of road pavement materials demonstrates that these characteristics play a decisive role in determining pavement durability, structural integrity, and long-term operational performance. Physical parameters such as bulk density, air void content, porosity, water absorption, and moisture susceptibility directly influence the internal structure of asphalt mixtures and their resistance to environmental deterioration. The laboratory evaluation showed that asphalt mixtures possessing higher bulk densities exhibited lower permeability and improved aggregate interlocking. The average bulk density measured in the investigated mixtures reached 2.42 g/cm³, indicating an adequately compacted pavement structure. Proper compaction reduced interconnected air voids and minimized moisture penetration, thereby decreasing the risk of oxidation and stripping.

Table 1. Physical Properties of the Investigated Asphalt Mixtures

Property	Standard Requirement	Experimental Result	Performance Evaluation
Bulk Density (g/cm³)	2.30–2.50	2.42	Excellent
Air Void Content (%)	3–5	4.1	Excellent
Water Absorption (%)	<2.0	1.38	Excellent
Porosity (%)	4–8	5.4	Good
Moisture Susceptibility (TSR, %)	>80	89	Excellent

The obtained air void content of 4.1% lies within the recommended engineering range for dense asphalt mixtures. This balance provides sufficient flexibility while maintaining adequate structural stability. Air voids exceeding 6% generally increase permeability and accelerate oxidation, whereas excessively low air void contents may lead to asphalt flushing during hot weather conditions. Water absorption remained well below the accepted engineering limit of 2%, confirming that the asphalt binder effectively coated the aggregate particles and minimized moisture ingress. Consequently, improved moisture resistance contributes to longer pavement service life and reduced maintenance requirements.

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Mechanical Performance of Asphalt Pavements. Mechanical properties determine the structural capacity of pavement materials to withstand repeated traffic loading without excessive deformation or cracking. Marshall Stability testing demonstrated excellent structural performance, with an average value of 15.1 kN, considerably exceeding the minimum specification for heavy-traffic pavements.

Table 2. Mechanical Characteristics of the Pavement Mixtures

Mechanical Property	Specification	Measured Value
Marshall Stability (kN)	≥8	15.1
Flow (mm)	2–4	3.0
Indirect Tensile Strength (MPa)	>0.80	1.29
Resilient Modulus (MPa)	2000–8000	5780
Dynamic Modulus (MPa)	3000–12000	8050
Fatigue Life (cycles)	>1,000,000	1,560,000

The measured Marshall Stability confirms that the asphalt mixtures possess excellent resistance against permanent deformation under heavy wheel loads. The indirect tensile strength reached 1.29 MPa, demonstrating strong adhesive bonding between aggregate particles and asphalt binder. Improved tensile strength delays crack initiation and increases resistance to fatigue damage. The resilient modulus averaged 5780 MPa, indicating efficient elastic recovery after repeated loading cycles. Higher resilient modulus values reduce tensile strain at the bottom of asphalt layers while minimizing compressive deformation within the subgrade. Dynamic modulus testing further demonstrated that the investigated asphalt mixtures maintained stable mechanical behavior over a wide range of loading frequencies and service temperatures. The present investigation demonstrates that pavement performance is governed by the combined interaction of physical characteristics, mechanical properties, environmental conditions, and construction quality rather than by any single engineering parameter. Among the investigated variables, resilient modulus, air void content, moisture susceptibility, rutting resistance, and fatigue life exhibited the strongest influence on long-term pavement performance. The findings further indicate that achieving an optimal balance between stiffness and flexibility is essential for maximizing pavement durability. Excessively stiff mixtures are vulnerable to fatigue and thermal cracking, whereas overly flexible mixtures become susceptible to rutting and permanent deformation. The incorporation of polymer-modified binders, optimized aggregate gradation, recycled asphalt pavement (RAP), fiber reinforcement, and intelligent quality-control technologies substantially enhances pavement performance while supporting sustainable infrastructure development. From an engineering perspective, these results strongly support the adoption of mechanistic–empirical pavement design methodologies integrated with advanced laboratory characterization and digital pavement monitoring systems. Such approaches enable transportation agencies to optimize material selection, improve structural design, reduce maintenance costs, and extend pavement service life under increasingly demanding traffic and climatic conditions. Overall, the study confirms that comprehensive evaluation of physical, mechanical, and service performance properties provides a scientifically reliable framework for designing durable, safe, cost-effective, and environmentally sustainable road pavement systems capable of meeting future transportation requirements.

Conclusion. The comprehensive analysis conducted in this study demonstrates that the long-term performance of road pavements is governed by the combined interaction of physical, mechanical, and service performance characteristics rather than by any individual engineering parameter. Pavement durability, structural reliability, and operational efficiency are strongly influenced by material quality, mixture design, construction practices, environmental exposure, and traffic loading conditions. The evaluation of physical properties revealed that bulk density, air void content, porosity,

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water absorption, and moisture susceptibility are among the most influential factors affecting pavement durability. Asphalt mixtures exhibiting optimal density and air void contents between 3% and 5% provided improved aggregate interlocking, reduced permeability, enhanced resistance to moisture damage, and lower oxidation rates. Proper field compaction was identified as one of the most critical construction factors for extending pavement service life. Mechanical characterization confirmed that the investigated asphalt mixtures possess excellent structural capacity. Marshall Stability, indirect tensile strength, resilient modulus, dynamic modulus, and fatigue resistance all exceeded commonly accepted engineering requirements for medium- and heavy-duty highways. The resilient modulus proved to be a particularly important indicator because it reflects the elastic recovery of asphalt mixtures under repeated traffic loading, thereby improving load distribution and reducing structural deformation. Similarly, higher tensile strength delayed crack initiation and enhanced resistance to fatigue failure. The assessment of service performance demonstrated excellent resistance to rutting, moisture-induced deterioration, thermal damage, and long-term traffic loading. The investigated mixtures achieved low rut depths, high skid resistance, satisfactory ride quality, and an estimated service life exceeding twenty years under normal operating conditions. These findings confirm that service performance is strongly dependent upon the interaction between physical characteristics and mechanical behavior throughout the pavement life cycle. Furthermore, recent advances in intelligent infrastructure technologies—including pavement management systems (PMS), artificial intelligence (AI), machine learning, digital image processing, embedded wireless sensors, unmanned aerial vehicles (UAVs), ground-penetrating radar (GPR), and digital twin technologies—provide powerful tools for continuous pavement monitoring and predictive maintenance. The integration of these technologies with mechanistic–empirical pavement design approaches is expected to improve maintenance planning, optimize infrastructure investment, and enhance pavement reliability throughout its operational life. Overall, the findings of this research confirm that comprehensive evaluation of the physical, mechanical, and service performance properties of road pavements provides a reliable scientific foundation for improving pavement material selection, structural design, quality assurance, maintenance planning, and long-term infrastructure management. The implementation of optimized mixture design, advanced materials, sustainable construction practices, and intelligent monitoring technologies will contribute significantly to the development of safer, more durable, cost-effective, and environmentally sustainable highway systems. The implementation of these research directions will further strengthen sustainable pavement engineering practices and support the development of resilient transportation systems capable of meeting future mobility demands.

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