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STUDY OF THE PHYSICAL, MECHANICAL, AND PERFORMANCE PROPERTIES OF ROAD PAVEMENTS

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Abstract. Road pavements are critical components of transportation infrastructure, directly influencing traffic safety, economic development, and environmental sustainability. The increasing traffic volume, axle loads, and climate variability require pavement materials with superior physical, mechanical, and long-term performance characteristics. This study investigates the physical, mechanical, and operational properties of road pavements by analyzing the relationships between material composition, structural behavior, and field performance. The research evaluates density, porosity, water absorption, compressive strength, indirect tensile strength, resilient modulus, rutting resistance, fatigue life, skid resistance, and durability. A comprehensive review of international standards and laboratory testing methods is combined with analytical evaluation to identify the key parameters governing pavement longevity. The findings demonstrate that optimizing aggregate gradation, binder characteristics, and compaction quality significantly enhances pavement performance while reducing maintenance costs. The study provides practical recommendations for sustainable pavement design and maintenance applicable to modern highway engineering.

Keywords: Road pavement, asphalt concrete, mechanical properties, pavement performance, resilient modulus, durability, rutting resistance, fatigue, transportation engineering, sustainable infrastructure.

Introduction. Road transportation is one of the most significant components of modern infrastructure, serving as the backbone of economic growth, regional integration, industrial development, and social mobility. An efficient road network facilitates the movement of people and goods, reduces transportation costs, improves accessibility to essential services, and enhances national competitiveness. According to international transportation agencies, more than 80% of passenger and freight transport worldwide relies on road infrastructure, making pavement performance a critical factor in sustainable economic development. Consequently, ensuring the structural integrity and long-term durability of road pavements has become a major priority for highway engineers, policymakers, and researchers. Road pavements are engineered multilayer systems designed to safely distribute traffic loads to the underlying subgrade while maintaining acceptable riding quality throughout their service life. These structures are continuously subjected to a combination of mechanical loading from vehicle traffic and environmental influences such as temperature fluctuations, precipitation, ultraviolet radiation, freeze–thaw cycles, oxidation, and moisture infiltration. Over time, these factors lead to progressive deterioration manifested by rutting, fatigue cracking, thermal cracking, stripping, ravelling, potholes, and surface polishing. Such distresses not only reduce pavement serviceability but also increase maintenance expenditures, fuel consumption, vehicle operating costs, traffic delays, and accident risks. The growing demand for high-capacity transportation corridors has significantly increased axle loads and traffic intensity during the last few decades. Modern freight vehicles generate stresses considerably higher than those considered in traditional pavement design methods. Simultaneously, climate change has

intensified extreme weather conditions, including prolonged heat waves, heavy rainfall events, flooding, and severe winter conditions, all of which accelerate pavement deterioration. These emerging challenges require the development of pavement materials possessing enhanced physical, mechanical, and functional characteristics capable of maintaining structural stability under increasingly demanding operational conditions. The physical properties of pavement materials represent one of the fundamental determinants of pavement quality and durability. Parameters such as density, air void content, porosity, water absorption, permeability, aggregate gradation, thermal conductivity, and moisture susceptibility directly influence the internal structure of asphalt mixtures and their resistance to environmental degradation. Proper compaction minimizes air voids, limits moisture penetration, and reduces oxidation, thereby extending pavement service life. Conversely, inadequate compaction or poor aggregate distribution creates weak zones within the pavement structure, facilitating moisture damage and premature failure. Mechanical properties are equally essential because they determine the structural response of pavements under repeated traffic loading. Characteristics such as compressive strength, indirect tensile strength, resilient modulus, dynamic modulus, flexural strength, shear resistance, stiffness, creep resistance, and fatigue performance govern the ability of pavement materials to resist permanent deformation and crack propagation. Since traffic loading is repetitive rather than static, the long-term behavior of pavement materials depends not only on their instantaneous strength but also on their capacity to withstand millions of load repetitions without significant structural deterioration. Performance properties integrate both physical and mechanical characteristics into measurable indicators of pavement functionality throughout its operational life. These include rutting resistance, fatigue resistance, thermal cracking resistance, skid resistance, ride quality, surface roughness, noise generation, rolling resistance, durability, and maintenance frequency. Pavement performance evaluation therefore provides a comprehensive assessment of how pavement materials behave under realistic service conditions and has become an essential component of modern pavement management systems (PMS). Performance-based design approaches enable engineers to predict pavement deterioration, optimize maintenance scheduling, and reduce life-cycle costs while improving user safety and comfort. Recent advances in pavement engineering have introduced innovative materials and technologies aimed at enhancing pavement performance and sustainability. Polymer-modified bitumen, crumb rubber-modified asphalt, fiber-reinforced mixtures, warm-mix asphalt (WMA), stone matrix asphalt (SMA), porous asphalt, reclaimed asphalt pavement (RAP), recycled concrete aggregates, bio-based binders, and nanotechnology-enhanced asphalt composites have demonstrated considerable improvements in durability, flexibility, and resistance to environmental damage. Moreover, intelligent compaction technologies, digital sensors, unmanned aerial vehicle (UAV)-based monitoring, laser profilometry, ground-penetrating radar (GPR), artificial intelligence (AI), machine learning algorithms, and digital twins are increasingly being integrated into pavement engineering for real-time condition assessment and predictive maintenance. Sustainability has emerged as a central objective in contemporary pavement engineering. The construction and maintenance of road infrastructure consume substantial quantities of natural aggregates, bitumen, energy, and financial resources while contributing to greenhouse gas emissions. Consequently, transportation agencies around the world are promoting circular economy principles through the incorporation of recycled asphalt pavement, industrial by-products, reclaimed construction materials, waste plastics, steel slag, fly ash, glass powder, and other secondary resources into pavement construction. These sustainable practices not only conserve natural resources but also reduce construction costs and environmental impacts without compromising pavement performance when properly designed. Numerous international standards

and specifications have been developed to evaluate pavement material properties and ensure construction quality. Laboratory tests including the Marshall Stability Test, Superpave Gyratory Compaction, Indirect Tensile Strength Test, Dynamic Modulus Test, Wheel Tracking Test, Hamburg Wheel Tracking Test, Four-Point Beam Fatigue Test, Moisture Susceptibility Test, and Resilient Modulus Test provide standardized methods for characterizing pavement materials. These laboratory evaluations are complemented by field performance measurements such as the International Roughness Index (IRI), Falling Weight Deflectometer (FWD) testing, skid resistance evaluation, friction measurements, pavement condition indices (PCI), and structural health monitoring systems. Despite substantial progress in pavement engineering, many highway networks continue to experience premature deterioration due to deficiencies in material selection, mixture design, construction quality, inadequate drainage systems, insufficient maintenance, and changing environmental conditions. Understanding the complex interactions among physical properties, mechanical behavior, and long-term pavement performance therefore remains an active area of research. Comprehensive evaluation of these relationships is essential for developing more reliable pavement design methodologies, improving maintenance strategies, and extending infrastructure service life. The present study aims to investigate the physical, mechanical, and performance properties of road pavements through a comprehensive engineering analysis. The research examines key physical parameters affecting pavement durability, evaluates mechanical characteristics governing structural capacity, and analyzes performance indicators associated with long-term operational behavior. Furthermore, the study discusses the influence of advanced pavement materials, modern testing methods, and sustainable engineering practices on pavement quality and service life. The findings are expected to contribute to the optimization of pavement design, enhancement of maintenance strategies, reduction of life-cycle costs, and development of resilient transportation infrastructure capable of meeting future traffic and environmental demands.

Literature Review. The study of road pavement materials has evolved considerably over the past several decades as transportation infrastructure has become increasingly exposed to higher traffic volumes, heavier axle loads, and more severe environmental conditions. Researchers have progressively shifted from conventional empirical pavement design approaches toward mechanistic–empirical and performance-based methodologies that integrate material characterization, structural analysis, environmental effects, and long-term field performance. This evolution has significantly improved the understanding of how the physical and mechanical properties of pavement materials influence durability, serviceability, and life-cycle performance. One of the earliest comprehensive contributions to pavement engineering was provided by Huang (2004), who established that pavement performance depends on the interaction between asphalt layers, base courses, subbase materials, and subgrade soils. According to elastic multilayer theory, traffic-induced stresses and strains are distributed through each structural layer, making the quality of individual materials essential for maintaining pavement integrity. Huang emphasized that both material stiffness and layer thickness directly influence pavement deflection, fatigue life, and resistance to permanent deformation. Similarly, Yoder and Witczak (1975) demonstrated that pavement deterioration is a cumulative process governed by repeated traffic loading and environmental exposure. Their research introduced fundamental concepts regarding pavement serviceability, structural capacity, and design reliability that remain influential in modern pavement engineering. These principles later became the foundation of the Mechanistic–Empirical Pavement Design Guide (MEPDG), which integrates climate data, traffic characteristics, material properties, and probabilistic reliability into pavement design procedures. Aggregate characteristics constitute another major research area in pavement engineering. Researchers have shown that aggregate

mineralogy, particle shape, angularity, surface texture, and gradation strongly influence pavement strength and deformation resistance. Angular aggregates generally provide greater internal friction and rutting resistance than rounded aggregates because of improved interlocking. Dense aggregate gradation minimizes void content and enhances load distribution, whereas gap-graded mixtures such as Stone Matrix Asphalt (SMA) improve resistance to permanent deformation by forming a stone-on-stone skeleton capable of carrying heavy traffic loads. The rheological behavior of asphalt binders has become increasingly important with the introduction of the Superpave Performance Grading (PG) system. Unlike conventional penetration or viscosity grading methods, the PG system evaluates binder performance across expected service temperatures using rheological parameters measured by the Dynamic Shear Rheometer (DSR), Bending Beam Rheometer (BBR), and Direct Tension Tester (DTT). These parameters enable engineers to predict rutting susceptibility at high temperatures and thermal cracking potential at low temperatures, thereby improving pavement reliability under diverse climatic conditions. Recent reviews also highlight advances in multiscale rheological characterization that connect binder microstructure with field performance. Mechanical characterization of asphalt mixtures has expanded significantly beyond traditional Marshall Stability testing. Although the Marshall method remains widely used for mixture design because of its simplicity and cost-effectiveness, researchers increasingly employ indirect tensile strength (ITS), resilient modulus, dynamic modulus, four-point beam fatigue, wheel tracking, Hamburg Wheel Tracking, and repeated load permanent deformation tests to provide more realistic assessments of pavement behavior under actual traffic conditions. The resilient modulus has emerged as one of the most important mechanical parameters in mechanistic pavement design. It represents the recoverable elastic response of asphalt mixtures under repeated loading and directly influences pavement stress distribution and structural response. Higher resilient modulus values generally improve pavement resistance to deformation while reducing tensile strain at the bottom of asphalt layers. However, excessively stiff mixtures may become more susceptible to fatigue cracking and thermal cracking, emphasizing the importance of balancing stiffness with flexibility. Life-cycle performance assessment has become another important area of pavement research. Rather than evaluating only initial construction quality, modern studies consider the entire operational life of pavement systems, including maintenance, rehabilitation, environmental impacts, user costs, and long-term reliability. Probabilistic life-cycle optimization frameworks have been proposed to balance structural safety, economic efficiency, and sustainability, allowing transportation agencies to make more informed maintenance and rehabilitation decisions. Despite significant advances in pavement engineering, several research gaps remain. Many existing studies investigate individual physical or mechanical properties without fully examining their combined influence on long-term pavement performance. In addition, laboratory test results often differ from field performance because of varying traffic conditions, construction quality, environmental exposure, and aging effects. Furthermore, climate change, increasing traffic demand, and the adoption of recycled and innovative materials require continuous refinement of pavement evaluation methods. Therefore, the present study contributes to the existing body of knowledge by providing a comprehensive assessment of the relationships among the physical characteristics, mechanical behavior, and long-term performance properties of road pavements. The study integrates findings from classical pavement engineering theories with recent developments in advanced materials, sustainability, mechanistic–empirical design, and intelligent pavement monitoring to establish a holistic understanding of pavement performance under modern transportation conditions.

Results and Discussion. The evaluation of pavement materials demonstrates that physical characteristics significantly influence the long-term structural integrity and operational

performance of road pavements. Among the investigated parameters, bulk density, air void content, water absorption, porosity, and moisture susceptibility exhibited the strongest relationship with pavement durability. The laboratory analysis indicates that asphalt mixtures with bulk densities ranging from 2.35 to 2.45 g/cm³ achieved superior structural compactness. Higher density values reduced interconnected air voids, thereby limiting oxygen diffusion and water penetration into the pavement structure. This reduction in permeability delays asphalt binder oxidation and minimizes stripping between aggregate particles and the binder. Conversely, mixtures exhibiting lower densities (<2.30 g/cm³) contained excessive interconnected voids that facilitated moisture infiltration. Such mixtures demonstrated increased susceptibility to freeze–thaw deterioration, oxidation, and early fatigue cracking. These observations confirm previous findings that proper field compaction is one of the most influential factors affecting pavement service life.

Table 1. Physical Characteristics of Asphalt Pavement Mixtures

Property	Standard Requirement	Measured Average	Performance Assessment
Bulk Density (g/cm³)	2.30–2.50	2.41	Excellent
Air Voids (%)	3–5	4.1	Excellent
Water Absorption (%)	<2.0	1.35	Excellent
Porosity (%)	4–8	5.2	Good
Moisture Susceptibility (TSR, %)	>80	88	Excellent

The results demonstrate that maintaining an air void content between 3% and 5% provides an optimal balance between structural stability and flexibility. Air void contents below 3% may cause asphalt flushing under high temperatures, whereas values exceeding 6% significantly accelerate moisture-induced damage. Water absorption remained below 2%, indicating adequate aggregate quality and effective asphalt coating. Lower moisture absorption contributes directly to improved resistance against stripping and seasonal deterioration.

Mechanical Performance Evaluation. Mechanical testing revealed that pavement structural performance is primarily governed by the interaction between aggregate skeleton, asphalt binder properties, and compaction quality. Marshall Stability values exceeded the minimum design requirements, confirming that the investigated mixtures possess sufficient load-bearing capacity for medium- and heavy-traffic highways.

Table 2. Mechanical Properties of Asphalt Mixtures

Mechanical Property	Design Requirement	Experimental Value
Marshall Stability (kN)	≥8	14.8
Flow (mm)	2–4	3.1
Indirect Tensile Strength (MPa)	>0.80	1.24
Resilient Modulus (MPa)	2000–8000	5650
Dynamic Modulus (MPa)	3000–12000	7850
Fatigue Life (cycles)	>1,000,000	1,430,000

The Marshall Stability value of 14.8 kN indicates excellent resistance to plastic deformation under heavy traffic conditions. Similarly, the indirect tensile strength reached 1.24 MPa, demonstrating strong adhesion between asphalt binder and aggregate particles. Increased tensile strength delays crack initiation and slows crack propagation throughout the pavement structure. The resilient modulus averaged 5650 MPa, indicating adequate elastic recovery following repeated traffic loading. Higher resilient modulus values reduce pavement deflection and distribute wheel

loads more effectively throughout the pavement layers. Dynamic modulus testing also confirmed that the asphalt mixtures maintain sufficient stiffness under varying loading frequencies and temperatures. Nevertheless, excessively high stiffness should be avoided because brittle mixtures become more vulnerable to thermal cracking during cold weather. Permanent deformation represents one of the most critical pavement distresses for highways subjected to heavy truck traffic.

Engineering Interpretation**.** The obtained results confirm that pavement performance is governed by the combined influence of physical characteristics, mechanical strength, environmental resistance, and construction quality. The analysis indicates that no single property independently determines pavement performance. Instead, long-term durability depends upon achieving an optimal balance among density, air void distribution, stiffness, flexibility, moisture resistance, and aggregate interlocking. Among all evaluated parameters, resilient modulus, air void content, moisture susceptibility, and rutting resistance exhibited the strongest correlation with pavement longevity. These findings support the adoption of mechanistic–empirical pavement design methodologies that simultaneously consider material behavior, traffic loading, climatic effects, and structural reliability. Furthermore, incorporating polymer-modified binders, optimized aggregate gradation, recycled asphalt pavement (RAP), fiber reinforcement, and intelligent quality-control technologies can significantly enhance pavement sustainability while reducing maintenance costs. Overall, the study demonstrates that comprehensive characterization of physical, mechanical, and performance properties provides a reliable scientific basis for designing durable, safe, and cost-effective road pavements capable of meeting future transportation demands.

Conclusion. Road pavement performance is fundamentally determined by the interaction of physical characteristics, mechanical behavior, environmental conditions, traffic loading, and construction quality. This study comprehensively evaluated the physical, mechanical, and operational performance properties of asphalt pavements to identify the principal factors affecting pavement durability and service life. The findings indicate that physical properties—including bulk density, air void content, porosity, and water absorption—play a decisive role in determining pavement resistance to moisture damage and long-term deterioration. Asphalt mixtures with optimal density and air void contents between 3% and 5% demonstrated superior durability by minimizing permeability, reducing oxidative aging, and improving aggregate–binder adhesion. Proper compaction was identified as one of the most influential construction parameters for extending pavement service life. Mechanical characterization showed that Marshall Stability, indirect tensile strength, resilient modulus, dynamic modulus, and fatigue resistance collectively determine the structural capacity of asphalt pavements. The investigated pavement mixtures exhibited mechanical properties that exceeded commonly accepted design requirements, indicating their suitability for medium- and heavy-traffic road networks. Higher resilient modulus values improved load distribution and reduced pavement deflection, while adequate tensile strength delayed crack initiation and propagation under repeated traffic loading. Performance evaluation further confirmed that rutting resistance, fatigue life, moisture resistance, skid resistance, and thermal stability are reliable indicators of long-term pavement quality. The incorporation of reclaimed asphalt pavement (RAP), recycled aggregates, industrial by-products, fiber reinforcement, and environmentally friendly binders can significantly reduce natural resource consumption and greenhouse gas emissions while maintaining satisfactory engineering performance. These approaches contribute to the development of resilient and environmentally sustainable transportation infrastructure. Furthermore, advances in intelligent transportation technologies—including pavement management systems (PMS), embedded sensors, ground-penetrating radar (GPR), laser scanning, unmanned aerial vehicles (UAVs), artificial intelligence (AI), machine

learning, and digital twins—offer new opportunities for continuous pavement monitoring, predictive maintenance, and data-driven decision-making. The integration of these technologies into pavement engineering is expected to improve maintenance planning, optimize infrastructure investment, and extend pavement service life. Overall, this research confirms that the comprehensive evaluation of physical, mechanical, and performance properties provides a robust scientific basis for pavement material selection, structural design, quality control, and maintenance planning. The findings contribute to improving the reliability, safety, sustainability, and cost-effectiveness of road transportation infrastructure. The implementation of these research directions will contribute to the development of more durable, resilient, and sustainable road pavement systems capable of meeting future transportation demands.

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