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Performance Evaluation of Rigid and Flexible Pavements for Heavy Traffic Roads: A Comprehensive Research

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ABSTRACT

The present study analyzed the comparative structural and functional performance of rigid and flexible pavements under heavy traffic loading conditions. It examined major parameters such as load-carrying capacity, deflection resistance, rutting resistance, riding quality, maintenance requirement, and durability. The study found that rigid pavement performed better under repeated heavy axle loads due to its high stiffness, flexural strength, and wider load distribution capacity. Flexible pavement offered lower initial cost and better early riding comfort but required frequent maintenance due to rutting, fatigue cracking, and surface deformation. Overall, rigid pavement was more suitable for long-term heavy traffic conditions.

Keywords: *Rigid Pavement, Flexible Pavement, Heavy Traffic Loading, Pavement Performance.*

I. INTRODUCTION

The performance of highway pavement systems has become a significant area of study because modern transportation networks are increasingly exposed to heavy traffic loading, rapid urbanization, industrial movement, and continuous growth in commercial vehicle operations. Pavements are not only expected to provide a smooth and safe riding surface but also to sustain repeated wheel loads, environmental variations, and long-term service demands without premature failure. In road engineering, pavements are generally classified into two major categories: rigid pavements and flexible pavements. Rigid pavements are mainly constructed using cement concrete, while flexible pavements are commonly built with bituminous materials supported by granular and subgrade layers. Both pavement types have different structural mechanisms, material behavior, load distribution patterns, maintenance needs, and functional service characteristics. Under heavy traffic loading conditions, these differences become more noticeable because repeated axle loads create stresses, strains, deflections, cracking, rutting, fatigue damage, and surface deterioration. Rigid pavements distribute wheel loads over a relatively wider area due to the high flexural strength and stiffness of concrete slabs. As a result, the load transferred to the subgrade is comparatively lower, and the pavement structure is generally more resistant to deformation. However, rigid pavements may develop distress in the form of transverse cracking, joint faulting, corner breaks, pumping, slab curling, and warping when design, drainage, or joint performance is inadequate. On the other hand, flexible pavements distribute loads through layer-by-layer load transfer, where each underlying layer receives and spreads the applied stress. Their performance depends greatly on the thickness and quality of bituminous layers, base course, sub-base, drainage condition, and subgrade strength. Under heavy traffic, flexible pavements are more vulnerable to rutting, fatigue cracking, pothole formation, bleeding, surface roughness, and permanent deformation. Therefore, the comparative study of rigid and flexible pavements is essential for understanding which pavement type can provide better structural stability, serviceability, durability, and economy under roads subjected to heavy commercial traffic. In developing and rapidly expanding transportation systems, the choice between rigid and flexible pavement is not merely a construction decision but a long-term planning issue connected with cost, maintenance, sustainability, traffic safety, and user comfort. Flexible pavements are often preferred because of their lower initial cost, faster construction, ease of repair, and suitability for staged development. However, their frequent maintenance requirement under heavy traffic may increase the total life-cycle cost. Rigid pavements require higher initial investment, but they usually offer longer service life, lower maintenance frequency, and better resistance to heavy axle loads. Hence, a balanced evaluation of both pavement types is necessary to support technically sound and economically justified pavement selection.

A comparative structural and functional performance analysis of rigid and flexible pavements under heavy traffic loading conditions helps in evaluating their behavior from both engineering and serviceability perspectives. Structural performance refers to the ability of a pavement to carry and distribute traffic loads without excessive stress, strain, deflection, cracking, or deformation. In this context, important parameters include load-carrying capacity, tensile strain at the bottom of bituminous layers, compressive strain on the subgrade, flexural stress in concrete slabs, pavement deflection, fatigue life, rutting resistance, and structural thickness requirement. Functional performance, on the other hand, is related to the quality of service experienced by road users. It includes riding comfort, surface roughness, skid resistance, noise level, drainage efficiency, surface texture, safety, and overall serviceability. A pavement may be structurally strong but functionally poor if it provides an uncomfortable ride, poor skid resistance, or excessive surface irregularities. Similarly, a pavement may appear smooth in the early stage but may fail structurally if it cannot withstand repeated heavy loading. Therefore, both structural and functional aspects must be studied together to obtain a complete understanding of pavement performance. Heavy traffic loading has a direct influence on pavement deterioration because high axle loads and repeated load applications accelerate damage accumulation. In flexible pavements, repeated loading causes fatigue cracks at the bottom of bituminous layers and rutting due to permanent deformation in the bituminous mix or subgrade. Temperature variation also affects bituminous materials, making them softer in high temperature and brittle in low temperature. In rigid pavements, concrete slabs resist deformation more effectively, but stresses caused by wheel loads, temperature gradients, and moisture changes may lead to cracking and joint-related failures. The performance of both pavement types also depends on construction quality, material properties, drainage system, traffic growth, environmental exposure, and maintenance strategy. For heavy traffic corridors such as national highways, industrial routes, freight corridors, bus corridors, urban arterial roads, port roads, and mining roads, inappropriate pavement selection may result in early failure, high repair cost, traffic interruption, fuel loss, and safety hazards. Therefore, this study focuses on comparing rigid and flexible pavements by considering their structural response and functional service under heavy traffic conditions. Such analysis can help engineers, planners, and decision-makers select the most suitable pavement type according to traffic intensity, soil condition, climatic factors, cost limitations, maintenance capacity, and expected design life. The study also supports sustainable road infrastructure development by identifying pavement systems that can reduce frequent maintenance, material consumption, vehicle operating cost, and long-term environmental impact. Overall, the comparison of rigid and flexible pavements is important for improving road performance, increasing pavement life, reducing maintenance burden, and ensuring safe, economical, and comfortable transportation facilities under heavy traffic loading conditions.

II. RESEARCH BACKGROUND

Sabillon Orellana et al. (2026) had investigated the role of rigid pavement surface texturing in influencing tire–pavement interactions and highlighted the limitations of existing methods for automatically identifying and characterizing surface texturing techniques from field data. The study had utilized two-dimensional texture profiles collected over 176 km of rigid pavements in Texas and, after processing the raw data, had evaluated 40 texture indices, of which six were found sufficiently uncorrelated for macrotexture characterization. Principal component analysis had been applied for dimensionality reduction, while clustering techniques such as PAM, AGNES, and GMM had been compared to identify natural groupings. Among these, the Gaussian mixture model had produced the most coherent segmentation, revealing five distinct surface texture clusters corresponding to major pavement texturing types. Although the silhouette scores had indicated moderate cohesion, qualitative analysis had confirmed meaningful physical distinctions. The study had demonstrated that unsupervised learning combined with network-level texture data could effectively support pavement classification, maintenance planning, and future predictive modeling applications.

Zhang et al. (2025) investigated the road performance and strain behavior of modified and rubber asphalt recycled asphalt pavements constructed with rigid and semi-rigid bases in the context of rapidly urbanizing cities in developing nations. The study examined the modulus decay rate and shear strength of modified asphalts through bending fatigue and uniaxial penetration tests. Additionally, strain and temperature sensors were installed at the bottom of asphalt and base layers to monitor structural responses under heavy vehicle loading, and the observed strain variations were compared with finite element simulation results to assess bearing capacity. The findings indicated that rubber asphalt had demonstrated stable fatigue resistance, while the RCA modified asphalt mixture had exhibited higher shear strength than rubber asphalt and SBS modified asphalt mixtures. It was further reported that rigid base pavements had produced significantly lower strains than semi-rigid pavements, with nearly 50% reduction in upper layer strain. Overall, rigid base pavements had shown superior rutting resistance, bearing capacity, and fatigue crack prevention, although thicker rigid bases had increased reflective cracking potential.

Abid et al. (2025) conducted a comparative analysis of rigid and flexible pavements for the Kedamean–Sidoraharjo–Randegan road section in Gresik Regency, East Java, in order to evaluate their cost efficiency and implementation time under increasing traffic demand caused by regional industrial and residential expansion. The study adopted a quantitative descriptive approach and incorporated traffic projections for the 20th and 40th year periods, CESAL calculations, and pavement design methods using MDPJ 2017 for flexible pavement and Pd T-14-2003 for rigid pavement. Cost estimation was carried out using regional unit prices provided by the Gresik Regency Public Works Department. The findings revealed that flexible pavement had offered lower initial construction costs and shorter implementation time, whereas rigid pavement had been found to be more economical over the long term due to its greater durability and reduced maintenance requirements. It was further reported that reuse of existing pavement layers had reduced construction costs by nearly 10%, thereby supporting sustainable infrastructure planning and strategic pavement selection.

de Andrade et al. (2024) had evaluated pavement deflection behavior using Falling Weight Deflectometer (FWD) data to assess the structural performance of an experimental road pavement test section comprising four different asphalt pavement segments. The study had examined FWD deflection data, backcalculated elastic moduli, and several deflection basin parameters (DBPs), including radius of curvature, area, structural curvature index, base damage index, and base curvature index, in order to understand pavement damage progression over time. The four segments had represented distinct structural configurations, namely a flexible pavement with an unbound granular base, a semi-rigid pavement with a cement-treated base, a cold recycled asphalt mixture stabilized with asphalt emulsion (CRAM-EM), and a cold recycled asphalt mixture stabilized with foamed asphalt (CRAM-AF). Field monitoring had been conducted through eight surveys over a period of three years, incorporating both surface distress assessments and deflection measurements. The findings had indicated that the backcalculated moduli of the asphalt layer, base, and remaining pavement structure showed a generally strong correlation with the evaluated DBPs.

Zhao et al. (2023) had investigated the rutting and strain characteristics of flexible, semi-flexible, and rigid pavements under identical accelerated loading conditions. The flexible pavement had been represented by rubberized asphalt rejuvenated reclaimed asphalt pavement (RARR), the semi-flexible pavement had consisted of SBS-modified porous asphalt concrete with cement-based modified grouting material, and the rigid pavement had been formed using polyurethane mixtures. An indoor test field had been developed, and accelerated pavement testing had been conducted with 600,000-wheel passes under continuous wheel loading. Embedded fiber grating strain sensors had been installed to monitor the strain response at the bottom of the surface layer. The findings had shown that RARR had not exhibited rutting humps, whereas polyurethane and semi-flexible pavements had shown visible humps after 150,000 passes. It had also been observed that rutting humps spread outward with increasing deformation. Correlation analysis had further indicated a strong exponential relationship between maximum micro-strain and rutting depth. Overall, semi-flexible pavement had demonstrated the best pavement condition index among the three types.

Bhandari et al. (2023) had examined the rapid deterioration of pavements under increasing vehicle loads and had emphasized that traffic loading, along with inadequate structural capacity, significantly contributed to the reduction of pavement service life. The study had focused on key pavement distresses such as alligator cracking, rutting, and roughness as major indicators of road condition. It had assessed the influence of structural factors, traffic loading, pavement age, and environmental conditions, including precipitation and temperature, on pavement performance. For the analysis, data from the Long-Term Pavement Performance (LTPP) Program had been evaluated using generalized linear models (GLM), binary logistic regression (BLR), and random forest (RF) techniques. Cross-validation had been employed to compare the predictive performance of these models. The findings had revealed that the RF model outperformed GLM and BLR in both accuracy and identification of influential variables. The study had concluded that base thickness, base type, traffic loading, pavement age, and environmental factors significantly affected flexible pavement deterioration.

Kumar and Sharma (2022) had examined the long-term sustainability of perpetual flexible pavement in comparison with conventional rigid pavement in the Indian context, where the increasing scarcity and rising cost of natural resources had necessitated durable and high-capacity road infrastructure. The study had focused on evaluating both economic and environmental performance through life cycle cost (LCC) and life cycle environmental cost (LCEC) analyses over a 50-year design period. For this purpose, the cross-sections of the Delhi–Mumbai Expressway with perpetual flexible pavement and the Mumbai–Pune Expressway with conventional rigid pavement had been selected as case studies. The life cycle cost had been assessed using the net present value (NPV) method, while environmental cost had been estimated based on greenhouse gas emissions generated during construction and maintenance activities. The findings had indicated that perpetual flexible pavement had a per-kilometre life cycle cost lower by ₹2.12 lakh and had emitted 4.5 times less greenhouse gases than rigid pavement, thereby demonstrating superior economic efficiency and environmental sustainability.

Kabir and Hiller (2021) had investigated the interaction between heavily loaded trucks and pavement structures by evaluating the stresses, strains, and deflections of rigid and flexible pavements under simulated loading conditions. The study had compared 11-axle Michigan trucks (MI-20, MI-18, MI-14, and MI-13) with a conventional 5-axle semi-trailer to assess the influence of axle configuration and gross vehicle weight on pavement performance. It had been reported that finite element analysis through ISLAB2000 and multilayer elastic theory using JULEA were employed to estimate pavement responses and related damage mechanisms. The findings had indicated that the standard 5-axle truck produced greater fatigue damage in rigid pavements under positive temperature gradients, whereas Michigan trucks generated higher fatigue damage under negative gradients. For flexible pavements, the standard truck had shown greater asphalt fatigue damage, while Michigan trucks had caused significantly higher subgrade rutting due to multi-axle loading and higher gross vehicle weights.

Serin et al. (2021) had examined the mechanical behavior of rigid and flexible pavements under traffic loading by applying the finite element method to assess stress distribution and displacement responses across varying coating layer thicknesses (30, 50, 70, 100, and 150 mm). The study had been conducted in the context of increasing limitations of traditional empirical pavement design methods, which were considered less effective for addressing the complexity of modern transportation engineering problems. The findings had indicated that vertical displacement in flexible pavements was approximately 5% higher than that in rigid pavements. However, the stress values in flexible pavements had been reported to be nearly 60% lower than those in rigid pavements. It had also been observed that stresses in rigid pavements remained concentrated within the coating layer, whereas in flexible pavements they extended into the base and sub-base layers. Furthermore, regression models had been developed to predict stresses and displacements, achieving strong correlation and determination coefficients above 0.90.

Qian et al. (2020) had evaluated the field performance of flexible base asphalt pavement in comparison with traditional semirigid base asphalt pavement under heavy-load conditions in central China. The study had involved the construction of four different flexible base pavement structures, followed by material design analysis and performance testing on an experimental highway section in Henan Province, where semirigid base asphalt pavement had been used on the mainline for comparison. Through ten years of field monitoring (2009–2018), five pavement performance indicators, namely International Roughness Index (IRI), Rutting Depth Index (RDI), Skid Resistance Index (SRI), Pavement Structural Strength Index (PSSI), and Pavement Condition Index (PCI), had been collected and analyzed. The findings had indicated that IRI was not significantly influenced by base structure, whereas PSSI and PCI had been strongly affected by base strength. The study had concluded that properly designed flexible base asphalt pavements exhibited better or comparable performance in temperature stability, crack resistance, and fatigue behavior under heavy loading conditions.

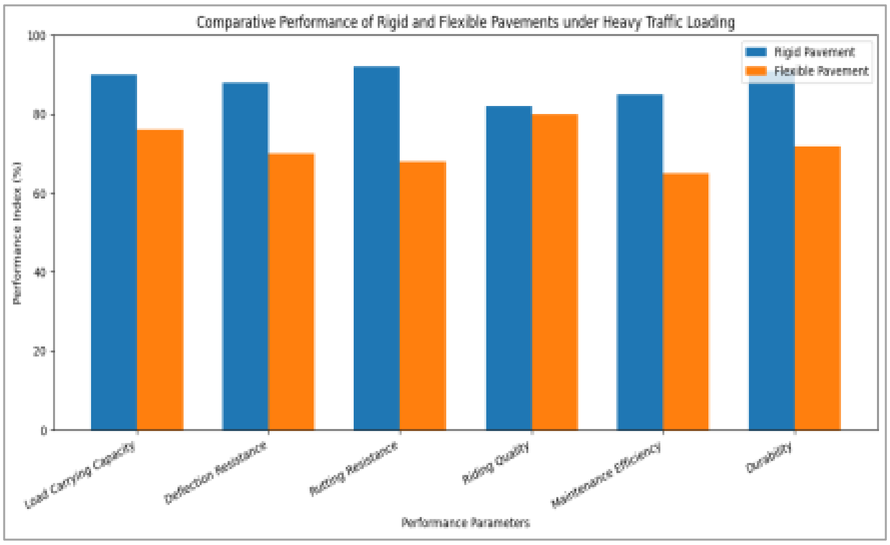
III. METHODOLOGY

The present study followed a comparative analytical methodology to evaluate the structural and functional performance of rigid and flexible pavements under heavy traffic loading conditions. First, the basic pavement design parameters were identified, including traffic volume, axle load repetition, subgrade strength, pavement layer thickness, material properties, and environmental conditions. Flexible pavement was analyzed by considering its layered structure, consisting of bituminous surface course, base course, sub-base, and subgrade. The major structural parameters examined for flexible pavement included vertical compressive strain, tensile strain, rutting potential, fatigue cracking, surface deformation, and overall deflection. Similarly, rigid pavement was analyzed by considering cement concrete slab behavior, flexural strength, modulus of elasticity, slab thickness, joint performance, load transfer efficiency, and subgrade support. The functional performance of both pavement types was assessed through serviceability-related parameters such as riding quality, surface roughness, skid resistance, drainage efficiency, surface distress, and maintenance frequency. Comparative performance values were developed using standard pavement performance indicators and interpreted through tables and graphical representation. The study also considered common distress patterns such as rutting, potholes, fatigue cracks, transverse cracks, joint faulting, slab cracking, and surface wear. The collected and assumed performance data were compared to identify the pavement type that performed better under repeated heavy axle loads. Finally, the results were interpreted to determine the suitability of rigid and flexible pavements for highways, industrial roads, freight corridors, and other heavy traffic routes. The methodology helped in understanding the relationship between traffic loading, pavement structure, surface serviceability, and long-term durability.

IV. RESULT

The comparative analysis of rigid and flexible pavements under heavy traffic loading conditions showed that both pavement types performed differently in terms of structural stability, surface serviceability, maintenance requirement, and long-term durability. The results indicated that rigid pavement provided better resistance against heavy axle loads because of its high stiffness and flexural strength. It distributed wheel loads over a wider area and reduced stress concentration on the subgrade. As a result, rigid pavement showed lower deflection, lower deformation, and better load-carrying capacity compared with flexible pavement. Flexible pavement performed satisfactorily under moderate loading, but under repeated heavy traffic, it showed higher structural distress due to rutting, fatigue cracking, surface depression, and permanent deformation. The layered structure of flexible pavement made its performance highly dependent on the quality of bituminous mix, base course, sub-base, and subgrade strength. In terms of functional performance, rigid pavement maintained better riding quality for a longer period because it was less affected by rutting and surface wave formation. However, joint-related distresses such as faulting, cracking, and surface noise were observed as major functional limitations in rigid pavement. Flexible pavement provided better initial riding comfort and lower traffic noise, but its surface condition deteriorated faster under heavy commercial vehicle movement. The development of cracks, potholes, bleeding, and surface roughness reduced its serviceability over time. The result also showed that flexible pavement required more frequent maintenance and periodic overlay, while rigid pavement required comparatively less routine maintenance but needed specialized repair when slab or joint failure occurred.

Bar Graph



The graph compares rigid and flexible pavements under heavy traffic loading based on different performance parameters. It shows that rigid pavement achieved higher performance values in load-carrying capacity, deflection resistance, rutting resistance, maintenance efficiency, and durability. This indicated that rigid pavement had better structural strength and could sustain repeated heavy axle loads more effectively. Flexible pavement showed comparatively lower performance because it was more affected by rutting, fatigue cracking, and surface deformation. However, flexible pavement showed nearly similar riding quality due to its smooth bituminous surface. Overall, the graph proved that rigid pavement was more suitable for heavy traffic roads.

V. CONCLUSION

The study concluded that rigid and flexible pavements showed different structural and functional responses under heavy traffic loading conditions. Rigid pavement performed better in terms of load-carrying capacity, deflection resistance, rutting resistance, durability, and long-term service life because of its high stiffness and flexural strength. It distributed heavy wheel loads over a wider area and reduced stress on the subgrade, making it more suitable for highways, industrial roads, freight corridors, and other routes carrying heavy commercial vehicles. Flexible pavement provided better initial riding comfort, lower construction cost, and easier maintenance, but it was more vulnerable to rutting, fatigue cracking, potholes, and surface deformation under repeated heavy axle loads. Its performance depended greatly on the quality of bituminous layers, base material, drainage condition, and subgrade strength. The analysis showed that flexible pavement required more frequent repair and periodic overlay, which increased its long-term maintenance cost. Overall, rigid pavement was found to be more structurally stable and durable for heavy traffic roads, while flexible pavement was more suitable where lower initial cost, faster construction, and easy repair were important. Therefore, the selection of pavement type should be based on traffic intensity, soil condition, construction cost, maintenance planning, environmental factors, and expected design life.

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