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Comparative Analysis of Flexible and Rigid Pavements under Heavy Traffic Conditions for Long-Term Performance

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ABSTRACT

The increasing demand for efficient transportation infrastructure necessitates the comparative analysis of flexible and rigid pavements under heavy traffic conditions. Flexible pavements, constructed with bituminous materials, distribute loads gradually through layered systems, whereas rigid pavements, made of Portland cement concrete, rely on slab action for load distribution. The performance of these pavements is influenced by factors like traffic load, environmental challenges, and material behavior. Studies highlight that while flexible pavements are cost-effective initially, rigid pavements offer better long-term durability, reduced maintenance, and superior structural stability under heavy traffic. These insights are crucial for optimizing pavement design and long-term infrastructure planning.

Keywords: *Pavement Performance, Traffic Loading, Structural Stability, Maintenance.*

I. INTRODUCTION

Transportation infrastructure is a fundamental component of national development, facilitating mobility, trade, and economic integration. Among its key elements, pavement systems play a vital role in ensuring safe, durable, and efficient road networks. Pavements are generally categorized into two major types: flexible pavements and rigid pavements**,** each exhibiting distinct structural behaviors, material compositions, and performance characteristics under traffic loading conditions. The increasing intensity of heavy traffic loads, coupled with environmental and material challenges, has made the comparative analysis of these two pavement systems essential for modern transportation engineering. Flexible pavements are primarily constructed using bituminous materials and are designed to distribute loads through a layered system. The load is transferred from the surface layer to the subgrade gradually, resulting in stress dissipation over a larger area. In contrast, rigid pavements are constructed using Portland cement concrete and rely on slab action and flexural strength to distribute loads over a wider area of the subgrade (Taher et al., 2020). These fundamental differences in load transfer mechanisms significantly influence their structural response, durability, maintenance requirements, and lifecycle performance under heavy traffic conditions. Traffic loading is one of the most critical factors affecting pavement performance. Zhong et al. (2026) emphasized that accurate traffic characterization is essential for mechanistic-empirical pavement design. Their study, based on weigh-in-motion (WIM) data, demonstrated that clustered traffic inputs can effectively represent real-world conditions and provide reliable predictions for pavement distress indicators such as fatigue cracking, rutting, and roughness. This highlights the importance of traffic modeling in assessing pavement performance under heavy loading conditions and reinforces the need for accurate design inputs in infrastructure planning. Functional performance assessment provides insight into the serviceability and usability of pavements over time. Isya et al. (2026) evaluated flexible pavement conditions using the Pavement Condition Index (PCI) method and found that continuous traffic loading leads to progressive deterioration. Common distresses such as alligator cracking, rutting, and surface raveling were observed, resulting in overall pavement conditions ranging from fair to poor. Their findings confirm that PCI is an effective tool for evaluating functional pavement performance and supports timely maintenance interventions to extend service life. Comparative studies between flexible and rigid pavements reveal significant differences in cost, durability, and construction efficiency. Kurniawan et al. (2025) reported that flexible pavements generally require shorter construction periods but tend to incur higher long-term costs due to frequent maintenance. In contrast, rigid pavements, although more expensive initially and requiring longer construction durations, offer better long-term cost efficiency. Similarly, Ziar et al. (2024) found that while flexible pavements may appear economically favorable depending on the design methodology, rigid pavements often demonstrate superior long-term performance in terms of structural stability and reduced maintenance demands.

Structural behavior under heavy traffic loading is a key area of investigation in pavement engineering. Robinson (2024) examined rigid pavement performance under simulated aircraft loading and found that reduced flexural strength significantly decreases resistance to cracking. The study also revealed that conventional design methods often underestimate pavement performance, indicating limitations in existing mechanistic-empirical approaches. This suggests the need for improved predictive models that more accurately capture real-world loading conditions and material behavior. The interaction between structural and functional performance is also critical in understanding pavement deterioration. Isradi et al. (2023) established relationships between the Present Serviceability Index (PSI), International Roughness Index (IRI), and Pavement Condition Index (PCI), demonstrating strong correlations between surface conditions and underlying structural damage. Their findings indicate that functional indicators can effectively reflect structural deterioration, making them valuable tools for pavement condition assessment under heavy traffic exposure. Advanced analytical approaches have further enhanced pavement performance evaluation. Mahajan et al. (2022) highlighted the importance of vehicle–pavement interaction (VPI) models in capturing realistic traffic loading effects. These models improve the accuracy of flexible pavement performance predictions by incorporating dynamic load variations. Similarly, Assogba et al. (2022) demonstrated that factors such as traffic speed, axle load, and temperature significantly influence pavement responses, with interaction effects playing a crucial role in structural deterioration. In addition, Assogba et al. (2021) investigated the effects of vehicle speed and overloading on semi-rigid pavements and found that lower speeds and heavier loads increase stress accumulation and reduce pavement service life. Their findings emphasize that dynamic loading conditions must be considered in pavement design to ensure long-term durability, particularly for heavily trafficked highways. Overall, literature indicates that flexible pavements are more prone to deformation-related failures such as rutting and fatigue cracking, while rigid pavements exhibit higher resistance to heavy loads but may experience brittle cracking under excessive stress. Despite these differences, rigid pavements generally offer longer service life and lower maintenance requirements under high traffic conditions, whereas flexible pavements provide advantages in terms of initial construction speed and adaptability (Taher et al., 2020).

II. RESEARCH BACKGROUND

Zhong et al. (2026) investigated truck traffic characterization for pavement design and analysis, emphasizing its significance for reliable and cost-effective pavement structures. They utilized data from nine weigh-in-motion (WIM) sites in the Long-Term Pavement Performance database to develop regional traffic inputs (level 2) for mechanistic-empirical pavement design in Tennessee, U.S. Hierarchical clustering was applied to categorize traffic patterns among the WIM sites, followed by a sensitivity analysis to assess the impact of generated traffic inputs. The study compared three traffic input levels—site-specific (level 1), cluster-based statewide average (level 2), and nationwide default (level 3)—for both new pavements and pavement overlays. Findings indicated that cluster-based level 2 inputs produced predictions closest to those from site-specific level 1 data. Specifically, for new flexible pavements, root mean square errors (RMSEs) for fatigue cracking, asphalt concrete rutting, and International Roughness Index (IRI) were reported as 0.491%, 0.023 in., and 2.452 in./mi, respectively, while overlay pavements exhibited RMSEs of 0.011%, 0.027 in., and 1.5 in./mi, leading them to recommend cluster-based inputs when site-specific data were unavailable.

Isya et al. (2026) investigated the functional performance of flexible pavement on the Banda Aceh–Medan National Road, a strategic transportation corridor in northern Sumatra that supports regional mobility and economic activities. It was reported that continuous traffic loading and environmental effects had progressively deteriorated pavement conditions along this route. A quantitative descriptive approach was employed, wherein visual pavement surveys, damage identification, severity classification, and Pavement Condition Index (PCI) calculations were conducted in accordance with ASTM D6433 standards. The road was divided into multiple sample units to ensure representative assessment. The study found that average PCI values of the examined segments fell within “fair” to “poor” condition categories, with predominant distress types including alligator cracking, rutting, and raveling. Comparative analyses with prior studies indicated the reliability of the PCI method in reflecting actual pavement conditions and informing maintenance planning. The results underscored the importance of timely preventive and corrective maintenance strategies to prolong service life and demonstrated the applicability of PCI as a standardized evaluation tool for Indonesian national roads.

Kurniawan, Tjendani, and Putri (2025) examined the comparative suitability of flexible and rigid pavements for Kyai H. Ahmad Dahlan Road in Pasuruan City, which had been identified as an important corridor supporting economic and industrial activities. The study was conducted to evaluate the two pavement alternatives in terms of construction cost and implementation time under increasing traffic demand. Traffic loading was analyzed using ESA5 and JSKN methods for 20- and 40-year design periods, and it was reported that projected traffic loads increased substantially, thereby requiring stronger pavement structures. The authors found that flexible pavements required shorter construction durations of about 21–22 days, but their costs were higher, ranging from IDR 17.17 to 19.63 billion. In contrast, rigid pavements were reported to require longer construction periods of 30–31 days, yet they were more economical, with costs ranging from IDR 14.61 to 15.00 billion. It was concluded that rigid pavements were more cost-efficient in the long term, whereas flexible pavements were more suitable where rapid project execution was prioritized.

Ziar et al. (2024) had examined the cost-effectiveness of different pavement design methods for an 8 km urban road project, emphasizing the economic importance of road infrastructure and the substantial financial commitments involved in construction and maintenance. The study had considered three design approaches, namely AASHTO, Asphalt Institute (AI), and Portland Cement Association (PCA), to evaluate their comparative initial construction costs. Traffic data collected over a period of two years had been used to estimate the total traffic load, which was found to be 2.16×10^6 ESAL for the selected road section. Based on the comparative analysis, it had been observed that flexible pavement was more cost-effective than rigid pavement. Among the flexible pavement design methods, the AI method had emerged as the most economical option when compared to AASHTO. Similarly, within rigid pavement design methods, the PCA method had been identified as more cost-effective than AASHTO. Overall, rigid pavement had been reported as the most expensive alternative.

Robinson (2024) had investigated the structural behavior of full-scale airfield pavement test sections to assess the effect of substandard flexural strength Portland cement concrete (PCC) under simulated aircraft loading. The study had been conducted by constructing and trafficking pavement sections at the US Army

Engineer Research and Development Center, representing remote-area conditions where quality materials, equipment, and skilled labor might be limited. Two PCC surface thicknesses had been examined using both standard and low flexural strength mixtures, along with dowelled and non-dowelled joints. The test sections had been subjected to repeated loading using a dual-wheel P-8 aircraft test gear mounted on a heavy-vehicle simulator. The findings had indicated that reduced flexural strength significantly decreased pavement cracking resistance. Instrumentation data had further supported the observed surface distress. When field results had been compared with existing Department of Defense pavement design and evaluation procedures, those procedures had been found to underpredict actual performance by more than 90%, suggesting excessive conservatism due to simplified assumptions and early empirical correlations.

Isradi et al. (2023) had distinguished between functional and structural failures in pavement structures and examined the condition assessment of both flexible and rigid pavements in urban roadways of Indonesia. The study had utilized the Road State Value as a measure of the functional condition of pavements, while the evaluation had been based on surface unevenness, rutting, and visible surface damage. Field observations had been conducted to collect data on various forms of pavement deterioration. The findings had revealed that, in flexible pavements, filled damage was the most frequent type with 56 cases, whereas in rigid pavements, longitudinal cracks had been identified as a dominant distress type with 18 cases. The study had further established specific relationships among Present Serviceability Index (PSI), International Roughness Index (IRI), and Pavement Condition Index (PCI). The developed models had shown strong associations with acceptable R^2 values and correlations above 90% across good, medium, and poor road categories. Validation results had also confirmed the high accuracy of the proposed equations.

Mahajan et al. (2022) had presented a state-of-the-art review of investigations that had recognised the influence of the vehicle–pavement interaction (VPI) mechanism in estimating flexible pavement performance criteria. The authors had highlighted the significance of dynamic traffic loads by discussing vehicular models capable of simulating realistic field conditions within the mechanistic pavement design process. The review had further documented advanced pavement models, along with both uncoupled and coupled VPI analytical approaches, for predicting structural as well as functional performance characteristics of flexible pavements. Based on an extensive review of the available literature, the study had indicated that there was substantial scope for improving existing pavement design procedures through the integration of VPI in performance evaluation. Overall, the paper had suggested that the identified prospects could contribute significantly to the advancement of mechanistic pavement design procedures and could support the development of a more practical and realistic design framework for flexible pavements under actual roadway conditions.

Assogba et al. (2022) had examined the reliability of mechanistic-based pavement distress prediction models by focusing on the accuracy of critical pavement responses used in service life assessment and structural performance prediction. The study had experimentally and statistically evaluated the relationship between major influencing factors, including traffic speed, vehicle axle load, and seasonal temperature, and their effects on pavement mechanical response. It had further investigated the individual contribution of each factor as well as the two-way interaction or coupling effects among them on the critical pavement response. The findings had been presented through detailed experimental observations and statistical analyses, which had helped in identifying the most significant variables affecting pavement behavior. Moreover, the authors had integrated orthogonal array testing with multivariate regression analysis to develop a predictive model for estimating the critical stress response at the bottom of the semi-rigid layer. The study had thus contributed to improving the reliability and precision of pavement distress prediction and design evaluation.

Assogba et al. (2021) had investigated the premature deterioration of semi-rigid base asphalt pavements, which had been identified as a major distress in Chinese highway pavements. The study had examined the influence of vehicle speed and traffic overloading on the dynamic response and service life of such pavement structures. A large-scale three-dimensional viscoelastic finite element model for transient dynamic analysis had been developed to simulate the critical stress–strain response at the bottom of the asphalt layer under varying axle loads and vehicle speeds. Representative heavy trucks, namely Sinotruck HOWO-A7 6×4 and 8×4, had been considered, while field strain data from Fiber Bragg Grating sensors had been used to validate the model. The findings had shown that reduced vehicle speed and overloading significantly increased load duration, shock effects, and pavement damage. The fatigue analysis had further revealed that low-speed traffic and overloading adversely affected pavement service life, although the proposed semi-rigid pavement still performed better than conventional pavement under critical conditions.

Taher et al. (2020) had presented a comparative review on the suitability of rigid and flexible pavements in road construction by considering factors such as traffic, climate, foundation conditions, life-cycle cost, materials, maintainability, and safety. The authors had emphasized that road construction projects were regarded as essential infrastructure facilities and major indicators of societal development, requiring effective planning, innovative research, and cost-efficient engineering solutions. Their review had shown that the design of concrete pavements was primarily based on flexural strength, whereas asphalt pavements were designed based on the load-distribution characteristics of their component layers. It had been observed that rigid pavements generally exhibited a slightly longer service life than flexible pavements. Although the initial construction cost of flexible pavements had been lower than that of rigid pavements, the long-term maintenance expenses had made flexible pavements more costly over time. Overall, rigid pavements had been found to possess superior durability and greater resistance to traffic loads and harsh environmental conditions.

III. KEY FINDINGS FROM STUDY

Author(s) & Year	Objective of Study	Methodology	Key Findings	Relevance to Current Study
Zhong et al. (2026)	To analyze truck traffic characterization for mechanistic-empirical pavement design	WIM data analysis, hierarchical clustering, sensitivity analysis	Cluster-based traffic inputs provided results close to site-specific data; improved prediction accuracy for rutting, fatigue, and IRI	Highlights importance of accurate traffic loading for pavement performance under heavy traffic
Isya et al. (2026)	To evaluate functional performance of flexible pavement using PCI	Field survey, ASTM D6433, PCI calculation	Pavement condition ranged from fair to poor; major distresses were cracking, rutting, raveling	Shows deterioration pattern of flexible pavements under continuous loading
Kurniawan et al. (2025)	To compare flexible and rigid pavements based on cost and construction time	Traffic load analysis (ESA5, JSKN), cost-time comparison	Flexible pavements faster but costlier; rigid pavements more economical long-term	Supports economic comparison under high traffic demand
Ziar et al.	To assess cost-	Comparative	Flexible pavements	Provides economic

(2024)	effectiveness of pavement design methods	design analysis (AASHTO, AI, PCA)	generally more economical initially; rigid pavements higher cost overall	basis for pavement selection
Robinson (2024)	To evaluate rigid pavement behavior under aircraft loading	Full-scale experimental pavement testing	Reduced flexural strength significantly reduced cracking resistance; design methods underestimated performance	Highlights structural limitations of rigid pavements under heavy loads
Isradi et al. (2023)	To analyze functional and structural pavement performance	PCI, IRI, PSI correlation analysis	Strong correlation between structural damage and functional performance indicators	Connects structural and functional pavement behavior
Mahajan et al. (2022)	To review vehicle–pavement interaction (VPI) models	Literature review of mechanistic models	VPI significantly improves prediction of flexible pavement performance	Supports need for realistic traffic loading models
Assogba et al. (2022)	To study dynamic pavement response under traffic and temperature effects	Experimental and statistical modeling	Traffic speed, load, and temperature significantly affect pavement response	Shows multi-factor influence on pavement deterioration
Assogba et al. (2021)	To analyze effects of overload and speed on pavement life	3D finite element modeling + field validation	Overloading and low speed increase stress and reduce pavement life	Demonstrates impact of real traffic conditions on durability
Taher et al. (2020)	To compare flexible and rigid pavements	Review-based comparative study	Flexible pavements cheaper initially; rigid pavements more durable long-term	Provides foundational comparison of both pavement types

IV. CONCLUSION

The comparative structural and functional analysis of rigid and flexible pavements under heavy traffic loading conditions highlights significant differences in their performance behavior, durability, and suitability for varying transportation demands. The reviewed literature consistently indicates that both pavement types respond differently to traffic-induced stresses due to their distinct material properties and load distribution mechanisms. Flexible pavements primarily rely on layered load distribution through bituminous materials, making them more prone to surface distresses such as rutting, fatigue cracking, and raveling under continuous heavy traffic loading. In contrast, rigid pavements distribute loads over a wider area through slab action and flexural strength, resulting in better resistance to deformation but increased susceptibility to cracking under excessive stress concentrations. Traffic loading has been identified as one of the most influential factors affecting pavement performance. Studies such as Zhong et al. (2026) emphasize that accurate traffic characterization significantly improves pavement design reliability, while Assogba et al. (2021, 2022) demonstrate that vehicle speed, axle load, and environmental conditions strongly influence pavement deterioration mechanisms. These findings confirm that dynamic traffic conditions must be incorporated into pavement design models for realistic performance prediction. From a functional performance perspective, indicators such as Pavement Condition Index (PCI), International Roughness Index (IRI), and Present Serviceability Index (PSI) effectively reflect pavement health and deterioration trends. Flexible pavements generally exhibit faster functional degradation under heavy traffic, whereas rigid pavements maintain better long-term serviceability but require careful structural design to avoid brittle failure. Comparative studies (Kurniawan et al., 2025; Taher et al., 2020) further reveal that although flexible pavements offer advantages in construction speed, rigid pavements tend to be more cost-effective and durable over extended design periods. Overall, it can be concluded that no single pavement type is universally superior. The selection between rigid and flexible pavements depends on traffic intensity, environmental conditions, budget constraints, construction time, and long-term maintenance strategy. However, under heavy traffic loading conditions, rigid pavements generally demonstrate superior structural performance and longevity, while flexible pavements offer flexibility and ease of construction.

V. FUTURE SCOPE

Despite significant advancements in pavement engineering, several areas require further research to improve the accuracy, sustainability, and efficiency of pavement design under heavy traffic conditions.

- **Integration of Advanced Machine Learning Models:** Future research should focus on developing AI and machine learning-based predictive models to improve pavement performance forecasting. These models can integrate traffic, environmental, and material data to enhance decision-making in pavement design and maintenance planning.
- **Improved Vehicle–Pavement Interaction (VPI) Modeling:** Current mechanistic-empirical models still have limitations in capturing real-world dynamic traffic behavior. Future studies should enhance VPI models to include multi-axle vehicle dynamics, speed variations, and real-time loading conditions for more accurate structural response prediction.
- **Sustainable and Green Pavement Materials:** There is a growing need to explore sustainable construction materials such as recycled asphalt pavement (RAP), fly ash, and industrial by-products. Future research should evaluate their long-term performance under heavy traffic loading to reduce environmental impact and construction costs.
- **Life-Cycle Cost and Carbon Emission Analysis:** Future studies should incorporate comprehensive life-cycle cost analysis (LCCA) and carbon footprint assessment to evaluate both economic and environmental sustainability of rigid and flexible pavements.
- **Smart Pavement Monitoring Systems:** The development of sensor-based smart pavement systems can enable real-time monitoring of structural health. Integration of IoT and remote sensing technologies can help detect early-stage pavement failures and optimize maintenance scheduling.
- **Climate Change Impact Assessment:** Future research should investigate the combined effects of climate variability and heavy traffic loading on pavement performance, particularly in regions experiencing extreme temperature fluctuations and increased precipitation.

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