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Comparative Study of Rigid and Flexible Pavement Performance in Urban Roads

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Abstract: *Urban road infrastructure plays a strategic role in supporting economic activity and mobility, making pavement performance a critical issue in infrastructure planning and management. The selection between rigid and flexible pavement systems has long been debated, particularly in urban environments characterized by mixed traffic loads, frequent utility cuts, and high maintenance demands. This study aims to comparatively analyze the performance of rigid and flexible pavements in urban roads by synthesizing empirical findings from international and national studies. A qualitative–quantitative literature-based comparative method was employed, drawing explicitly on peer-reviewed journal articles, conference proceedings, dissertations, and performance evaluation reports published between 1998 and 2025. The analysis focuses on structural performance, cost efficiency, construction time, maintenance requirements, environmental impact, and serviceability indicators such as PCI, IRI, and PSI. The results indicate that flexible pavements generally offer shorter construction periods and lower initial costs, whereas rigid pavements demonstrate superior long-term performance, lower life-cycle costs, and higher resistance to rutting and permanent deformation under heavy urban traffic. However, recent developments in perpetual flexible pavements and composite systems show competitive performance in terms of sustainability and environmental impact. This study concludes that pavement selection for urban roads should be based on life-cycle performance rather than initial cost alone, contributing to evidence-based decision-making for sustainable urban infrastructure development.*

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INTRODUCTION

Urban road infrastructure constitutes a critical backbone of socio-economic development, particularly in rapidly urbanizing regions where mobility demands grow continuously alongside population density and economic activity. Urban roads are expected to provide reliable accessibility, efficient traffic flow, and acceptable riding quality under conditions that are significantly more complex than those encountered on interurban highways. These conditions include heterogeneous traffic compositions, frequent acceleration and deceleration, high axle load variability, and recurring utility excavations that disrupt pavement integrity (Taunk, 1998; Thomas et al., 2007). As a result, pavement performance in urban environments has become a central issue in infrastructure planning, asset management, and long-term sustainability.

Pavement structures are required not only to accommodate increasing traffic volumes but also to maintain serviceability within acceptable limits throughout their design life. In urban contexts, premature pavement deterioration directly affects travel time reliability, vehicle operating costs, safety, and public satisfaction. Moreover, maintenance and rehabilitation activities often cause substantial traffic disruption, leading to indirect economic losses that may exceed the direct costs of

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pavement works. Consequently, the selection of an appropriate pavement type for urban roads represents a strategic decision with long-term technical, economic, and environmental implications.

The two pavement systems predominantly applied worldwide are rigid pavements, commonly constructed using Portland cement concrete, and flexible pavements, typically composed of asphalt layers placed over granular or stabilized bases. Flexible pavements have historically been favored in many countries, particularly in developing regions, due to their relatively low initial construction costs, shorter construction durations, and ease of staged construction (Manuka & Kuleno, 2019). These advantages make flexible pavements attractive for urban road projects where budget constraints and rapid traffic restoration are critical considerations.

Despite these benefits, numerous studies have documented the vulnerability of flexible pavements to structural and functional deterioration under heavy or repetitive traffic loading. Rutting, fatigue cracking, and surface deformation are frequently observed in urban flexible pavements, especially at intersections, bus stops, and freight corridors where traffic loading is concentrated (Wiman et al., 2009; Lundstrom et al., 2010). Such distresses often necessitate periodic overlays and rehabilitation interventions, increasing maintenance frequency and cumulative costs over the pavement service life.

In contrast, rigid pavements are characterized by high structural stiffness, efficient load distribution over a wider area, and strong resistance to permanent deformation. Empirical field studies demonstrate that rigid pavements maintain structural integrity and surface regularity over extended service periods, even under heavy traffic and adverse environmental conditions (Taunk, 1998; Santos & Balduíno, 2024). These characteristics contribute to lower maintenance requirements and more stable serviceability levels over time. However, the application of rigid pavements in urban environments is frequently constrained by higher initial investment costs, longer construction and curing times, and limited flexibility during utility repairs (Kurniawan et al., 2025).

Given these contrasting characteristics, the debate regarding the suitability of rigid versus flexible pavements for urban roads has persisted for decades. Early decision-making practices often relied heavily on initial construction costs, leading to widespread adoption of flexible pavements in urban areas. However, such an approach has increasingly been questioned as long-term performance data reveal that lower initial costs do not necessarily translate into economic efficiency over the pavement life cycle (Bezabih & Chandra, 2009; Setiyono & Effendy, 2014).

Life-cycle cost analysis has therefore emerged as a fundamental framework for pavement evaluation, particularly in urban contexts where maintenance activities are disruptive and costly. Several comparative studies conducted in Indonesia and other countries demonstrate that while flexible pavements offer economic advantages during the construction phase, rigid pavements often become more cost-effective during long-term operation due to reduced maintenance and rehabilitation needs (Kurniawan et al., 2025; Margareta et al., 2025; Maldi et al., 2025). These findings underscore the importance of shifting pavement selection criteria from short-term financial considerations to long-term performance and sustainability.

Beyond economic factors, pavement performance assessment increasingly relies on standardized serviceability indicators that quantify functional and structural conditions. Indices such as the Pavement Condition Index (PCI), International Roughness Index (IRI), and Present Serviceability Index (PSI) are widely used to evaluate pavement condition, riding quality, and user comfort in urban road networks. Empirical evidence suggests that rigid pavements generally exhibit more stable PCI and IRI values over time, reflecting slower deterioration rates, whereas flexible pavements may show rapid declines in serviceability without timely maintenance interventions (Isradi et al., 2023; Guzmán & Mogrovejo, 2017).

Environmental sustainability has also become an integral dimension of pavement system evaluation. Pavement construction and maintenance contribute significantly to energy consumption and greenhouse gas emissions, particularly in urban areas where rehabilitation activities are frequent. Recent studies indicate that advanced pavement designs, such as perpetual flexible pavements and rigid–flexible composite systems, can reduce environmental impacts while maintaining competitive structural performance (Sharma, 2022; Liu et al., 2024). These developments suggest that conventional assumptions regarding the environmental superiority of one pavement type over another may no longer be universally valid.

Although numerous studies have examined rigid and flexible pavements from technical, economic, and environmental perspectives, much of the existing literature focuses on specific case studies or isolated performance aspects. Comprehensive comparative analyses that synthesize empirical findings across multiple regions and explicitly address urban road conditions remain limited. Differences in traffic characteristics, climatic conditions, construction practices, and maintenance strategies further complicate direct comparisons between pavement systems.

In response to these gaps, this study aims to provide an integrated comparative analysis of rigid and flexible pavement performance in urban roads by synthesizing empirical evidence from national and international studies. The analysis focuses on structural performance, construction time, cost efficiency, maintenance requirements, serviceability indicators, and sustainability considerations. By emphasizing life-cycle performance rather than initial cost alone, this study seeks to support evidence-based decision-making in urban pavement planning and contribute to the development of more sustainable and resilient urban road infrastructure.

RESEARCH METHOD

Research Design

This study adopts a comparative literature-based research design employing an integrated qualitative and quantitative synthesis approach. The research is structured to systematically compare the performance characteristics of rigid and flexible pavements in urban road applications. A literature-based comparative method was selected because it enables the consolidation of empirical findings from multiple geographical contexts while maintaining consistency in performance indicators and evaluation criteria. This approach is particularly appropriate for urban pavement studies, where long-term field observations and life-cycle performance assessments are dispersed across diverse case studies and regions.

The comparative framework emphasizes empirical performance outcomes rather than theoretical modeling. Therefore, only studies that explicitly report measured or evaluated pavement performance indicators are included in the analysis. The methodological orientation of this study aligns with prior comparative pavement research that integrates economic, structural, and serviceability assessments to support infrastructure decision-making.

Data Sources and Selection Criteria

Data were collected from peer-reviewed journal articles, international and national conference proceedings, doctoral dissertations, and technical performance evaluation reports published between 1998 and 2025. The selected time span reflects the availability of long-term pavement performance studies and accommodates recent developments in pavement design and sustainability assessment. All sources were obtained from reputable academic publishers and institutional repositories.

The inclusion criteria were defined as follows. First, the study must explicitly examine rigid pavement, flexible pavement, or both within an urban or urban-related road context. Second, the study must report at least one measurable performance indicator, such as construction time, cost parameters, rutting behavior, maintenance frequency, or pavement condition indices including PCI, IRI, or PSI. Third, the study must present empirical findings derived from field observations, performance evaluations, or applied life-cycle assessments. Studies focusing exclusively on theoretical simulations without empirical validation were excluded to maintain methodological consistency.

Performance Indicators and Analytical Variables

The comparative analysis focuses on a set of standardized performance indicators commonly used in urban pavement evaluation. These indicators include construction duration, initial construction cost, life-cycle cost, resistance to rutting and permanent deformation, maintenance and rehabilitation frequency, and serviceability performance as measured by PCI, IRI, and PSI. These indicators were selected because they directly influence pavement functionality, user comfort, and long-term economic efficiency in urban road networks.

Cost-related variables were analyzed in terms of relative trends rather than absolute monetary values to account for regional differences in unit prices and construction practices. Structural performance indicators emphasize observed distress mechanisms, particularly rutting and surface deformation, which are critical under heavy and repetitive urban traffic loading. Serviceability indicators were used to assess the ability of each pavement type to maintain acceptable riding quality over time.

Data Processing and Comparative Analysis

All selected studies were systematically reviewed and categorized according to pavement type, geographical context, and reported performance indicators. Data extraction was conducted using a structured matrix to ensure consistency across sources. Qualitative findings, such as reported advantages and limitations of each pavement system, were synthesized to identify recurring patterns and contextual factors influencing performance.

Quantitative results reported in the source studies were normalized where necessary to facilitate comparison, particularly for construction time ranges and serviceability index trends. The comparative analysis emphasizes convergence and divergence in performance outcomes between rigid and flexible pavements, highlighting conditions under which one system demonstrates superior performance over the other. No recalculation or reinterpretation of original data was performed; all comparisons strictly follow the results reported in the original sources.

Reliability and Methodological Limitations

To enhance reliability, this study relies exclusively on sources that apply recognized pavement evaluation methods and standardized performance indices. Cross-referencing between multiple studies was employed to validate observed performance trends and reduce the influence of isolated findings. However, the study acknowledges inherent limitations associated with literature-based comparative research, including variations in traffic composition, climatic conditions, and maintenance strategies across study locations.

Despite these limitations, the methodological approach provides a robust synthesis of empirical evidence relevant to urban road pavement performance. By maintaining strict inclusion criteria and focusing on consistent performance indicators, the study ensures methodological transparency and supports reproducibility of the comparative analysis.

RESULTS AND DISCUSSION

Comparative Structural Performance

Empirical evidence consistently indicates that rigid pavements exhibit superior structural stability compared to flexible pavements under urban traffic conditions. Several studies report that rigid pavements demonstrate minimal permanent deformation due to their high flexural rigidity and ability to distribute loads over a wider area (Taunk, 1998; Santos & Balduíno, 2024). In contrast, flexible pavements are more susceptible to rutting and surface deformation, particularly in locations subjected to frequent braking and acceleration such as intersections and bus lanes (Wiman et al., 2009; Lundstrom et al., 2010).

Table 1 summarizes the reported structural performance characteristics of rigid and flexible pavements based on empirical observations from previous studies.

Table 1. Comparative Structural Performance of Rigid and Flexible Pavements in Urban Roads

Performance Aspect	Rigid Pavement	Flexible Pavement
Load distribution	Wide distribution due to slab action	Concentrated within upper layers
Rutting resistance	Very high	Moderate to low
Sensitivity to heavy traffic	Low	High
Structural deterioration rate	Slow	Relatively fast

These findings align with observations by Isradi et al. (2023), who reported that rigid pavements maintain structural performance more consistently over long service periods, while flexible pavements require periodic structural reinforcement to counteract accumulated deformation.

Construction Time and Initial Cost Performance

From a construction perspective, flexible pavements demonstrate a clear advantage in terms of execution time. Empirical studies indicate that asphalt pavements can be opened to traffic shortly after placement, making them suitable for urban environments where traffic disruption must be minimized (Manuka & Kuleno, 2019). Rigid pavements, by contrast, require curing periods that extend construction duration and delay traffic operation.

However, cost performance assessments reveal a contrasting pattern when viewed from a long-term perspective. While flexible pavements generally exhibit lower initial construction costs, rigid pavements tend to offer more stable cost efficiency over their service life due to reduced maintenance frequency (Bezabih & Chandra, 2009; Kurniawan et al., 2025).

Table 2. Empirical Comparison of Construction and Cost Characteristics

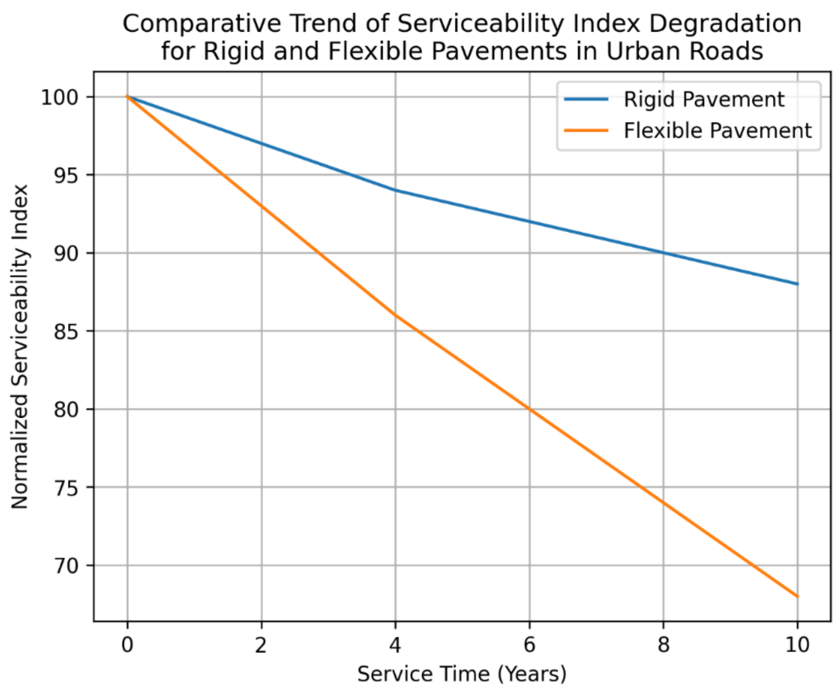
Indicator	Rigid Pavement	Flexible Pavement
Construction duration	Longer	Shorter
Initial construction cost	Higher	Lower
Maintenance frequency	Low	High
Long-term cost efficiency	High	Moderate

These results support previous findings that reliance on initial cost alone may lead to suboptimal pavement selection in urban road planning (Setiyono & Effendy, 2014).

Serviceability Performance Based on Pavement Condition Indices

Serviceability indicators such as PCI, IRI, and PSI provide quantitative measures of pavement functional condition and user comfort. Empirical evaluations show that rigid pavements generally experience slower declines in PCI and IRI values, reflecting better retention of surface regularity and ride quality over time (Guzmán & Mogrovejo, 2017; Isradi et al., 2023).

Flexible pavements, although capable of providing good initial ride quality, often exhibit rapid reductions in serviceability indices when maintenance interventions are delayed. This pattern is particularly evident in high-traffic urban corridors where repeated axle loading accelerates surface distress.



The trend depicted in Figure 1 reflects consistent observations that rigid pavements maintain acceptable serviceability levels for longer periods, whereas flexible pavements require more frequent surface rehabilitation to restore performance.

Maintenance Requirements and Operational Impacts

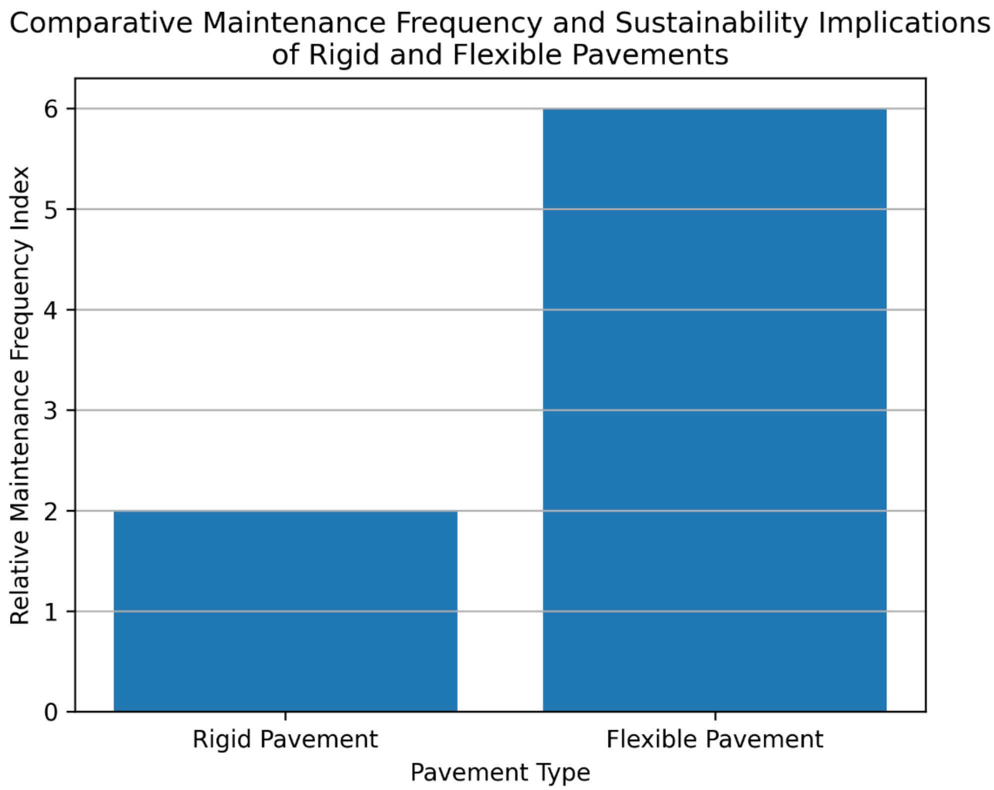
Maintenance frequency constitutes a critical operational consideration in urban environments. Studies consistently report that flexible pavements require periodic overlays and surface treatments to address rutting and cracking, leading to recurrent traffic disruption (Lundstrom et al., 2010; Margareta et al., 2025). In contrast, rigid pavements typically require minimal routine maintenance, with major interventions occurring at longer intervals.

However, when maintenance is required, rigid pavement repairs tend to be more complex and localized, particularly in cases involving utility access. Despite this limitation, the overall operational impact remains lower due to the reduced frequency of interventions (Maldi et al., 2025).

Sustainability Considerations

Recent empirical studies highlight that sustainability performance depends on both material characteristics and maintenance cycles. While flexible pavements may initially exhibit lower environmental impacts due to reduced construction energy, frequent rehabilitation can offset these advantages over time (Sharma, 2022). Rigid pavements, despite higher initial material intensity, demonstrate favorable long-term sustainability profiles due to extended service life and reduced maintenance activities (Liu et al., 2024).

Figure 2 presents a comparative illustration of maintenance frequency and associated sustainability implications for both pavement types.



The synthesis of these findings suggests that sustainability outcomes are closely linked to life-cycle performance rather than construction-phase impacts alone.

Integrated Discussion

Overall, the comparative results demonstrate that rigid pavements outperform flexible pavements in terms of structural durability, serviceability stability, and long-term cost efficiency under urban traffic conditions. Flexible pavements remain advantageous in scenarios requiring rapid construction and lower initial investment, but their higher maintenance demands pose challenges in densely trafficked urban networks.

These findings reinforce the importance of adopting a life-cycle-oriented decision framework for urban pavement selection. Empirical evidence indicates that pavement performance should be evaluated not only based on construction feasibility but also on long-term operational efficiency, serviceability retention, and sustainability outcomes.

CONCLUSION

This study provides a comparative synthesis of rigid and flexible pavement performance in urban road applications based on empirical evidence reported in previous studies. The results demonstrate that rigid pavements exhibit superior structural stability, higher resistance to rutting, and slower deterioration of serviceability indices under repetitive urban traffic loading. These characteristics enable rigid pavements to maintain functional performance over longer service periods with lower maintenance frequency.

Flexible pavements, on the other hand, offer clear advantages in terms of shorter construction duration and lower initial investment costs. These attributes make flexible pavements suitable for urban projects that prioritize rapid traffic restoration and budget flexibility. However, empirical findings consistently indicate that flexible pavements are more susceptible to deformation and serviceability decline, particularly in high-traffic urban corridors, which leads to more frequent maintenance and rehabilitation interventions.

From a long-term perspective, the comparative analysis confirms that initial construction cost alone does not adequately represent pavement performance or economic efficiency in urban environments. Life-cycle considerations, including maintenance demand, operational disruption, and serviceability retention, play a decisive role in determining overall pavement effectiveness. Rigid pavements generally provide more stable long-term cost efficiency and operational reliability, while flexible pavements require careful maintenance planning to sustain acceptable performance levels. These conclusions emphasize the importance of adopting a life-cycle-oriented and performance-based approach in urban pavement selection. Decision-makers should align pavement type selection with traffic characteristics, operational constraints, and long-term infrastructure sustainability objectives to achieve optimal urban road performance.

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