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Comparative Life Cycle Cost Analysis of Flexible and Rigid Pavement Systems under Varying Traffic Conditions: A Review

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ABSTRACT

The selection of pavement systems plays a crucial role in transportation infrastructure, impacting economic efficiency, structural performance, and sustainability. Life Cycle Cost Analysis (LCCA) has emerged as a pivotal tool for optimizing pavement selection, considering not only initial costs but also long-term economic and environmental factors. This study compares flexible and rigid pavements, highlighting their performance under varying traffic and environmental conditions. Key considerations include maintenance costs, material behavior, and climate adaptability. The integration of sustainable materials further enhances pavement performance, providing a comprehensive framework for informed decision-making in pavement design and management.

Keywords: *Pavement Systems, Life Cycle Cost Analysis, Sustainability, Traffic Conditions, Environmental Impact.*

I. INTRODUCTION

The selection and design of pavement systems represent a critical component of transportation infrastructure development, directly influencing economic efficiency, structural performance, environmental sustainability, and long-term serviceability. Flexible and rigid pavements are the two primary pavement systems widely used in highway engineering, each possessing distinct material compositions, structural behaviors, and maintenance requirements. Flexible pavements, typically composed of asphaltic layers over granular bases, distribute loads through layered structural action, whereas rigid pavements, constructed using Portland cement concrete, transfer loads through slab action to a broader area of the subgrade. The choice between these systems has traditionally been influenced by initial construction cost; however, increasing emphasis on sustainability and long-term performance has shifted attention toward life cycle cost analysis (LCCA), which evaluates total costs incurred throughout a pavement's service life, including construction, maintenance, rehabilitation, user delay costs, and salvage value. In this context, LCCA has emerged as a comprehensive decision-support tool that enables transportation agencies to optimize investment strategies by considering both short-term expenditures and long-term economic implications. According to Guo et al. (2019), traditional deterministic approaches to pavement cost estimation often fail to account for uncertainties in deterioration rates and maintenance timing, leading to potential over- or under-estimation of life cycle costs. Therefore, probabilistic and simulation-based models have been increasingly recommended for improving the accuracy and reliability of pavement economic evaluations. Furthermore, Adanikin et al. (2021) emphasized that while rigid pavements typically involve higher initial construction costs, their long-term cost efficiency may surpass that of flexible pavements when maintenance and rehabilitation expenses are fully accounted for over a 40-year analysis period. This highlights the importance of adopting a holistic life cycle perspective in pavement engineering rather than relying solely on initial investment comparisons.

In addition to economic considerations, pavement performance is significantly influenced by traffic loading conditions, environmental factors, and material behavior over time. Flexible pavements are particularly susceptible to distress mechanisms such as rutting, fatigue cracking, and thermal deformation, which are exacerbated under high traffic volumes and elevated temperatures. Vámos and Szendefy (2026) demonstrated that rutting in flexible pavements is strongly affected by temperature-dependent variations in asphalt binder stiffness, leading to increased permanent deformation in unbound layers such as the base, subbase, and subgrade. This behavior directly impacts maintenance frequency and associated life cycle costs, thereby influencing long-term economic viability. Conversely, rigid pavements exhibit superior load distribution characteristics and lower susceptibility to deformation; however, they are prone to cracking and joint deterioration, which require specialized maintenance strategies. Rusida et al. (2025) observed that although flexible pavements may offer lower initial construction costs and shorter construction durations, rigid pavements tend to be more cost-efficient over extended service periods due to reduced maintenance requirements. Similarly, Deniz (2023) analyzed multiple pavement scenarios under varying traffic loads, soil conditions, and reliability levels, concluding that rigid pavements generally provide better life cycle cost performance under medium to heavy traffic conditions, while flexible pavements may only be competitive under low traffic and high subgrade strength scenarios. These findings underscore the importance of considering traffic intensity, climatic conditions, and material performance behavior when evaluating pavement alternatives. Moreover, climate change has introduced additional complexity into pavement design and cost analysis. Qiao et al. (2020) highlighted that future climatic variations significantly influence asphalt pavement performance and maintenance requirements, thereby altering life cycle cost outcomes. Their study demonstrated that upgraded asphalt binders could improve long-term performance and economic efficiency under projected climate conditions, reinforcing the need to incorporate climate adaptability into pavement design frameworks.

Beyond economic and structural considerations, sustainability has become a central focus in modern pavement engineering, driven by increasing environmental concerns and resource depletion. Life cycle assessment (LCA), when integrated with LCCA, provides a comprehensive framework for evaluating both economic and environmental impacts of pavement systems. Hossain et al. (2022) reported that pavement construction and maintenance activities contribute significantly to environmental degradation due to energy consumption, material extraction, and greenhouse gas emissions. Their comparative study indicated that while rigid pavements may exhibit higher impacts in terms of global warming potential during material production, flexible pavements often result in greater long-term environmental burdens due to frequent maintenance and rehabilitation activities. Suwarto et al. (2024) further emphasized that existing LCA and LCCA methodologies suffer from limitations such as inconsistent functional units, incomplete life cycle boundaries, and inadequate consideration of uncertainty. They recommended the development of integrated frameworks that combine economic and environmental assessments while incorporating probabilistic analysis and performance prediction models. Additionally, innovations in sustainable materials have shown potential to enhance pavement performance and reduce life cycle costs. Al-Nawasir et al. (2026) demonstrated that incorporating ceramic waste powder in semi-flexible pavement systems significantly improved mechanical properties while reducing environmental impacts, highlighting the potential of industrial by-products in sustainable pavement design. Similarly, Mahdi et al. (2023) found that the use of geosynthetics in flexible pavements can reduce maintenance costs by approximately 36.67% and significantly lower carbon emissions, thereby improving both economic and environmental performance. These advancements indicate a growing shift toward sustainable pavement engineering practices that prioritize resource efficiency, durability, and reduced environmental footprint. Collectively, the literature suggests that the optimal selection between flexible and rigid pavement systems cannot be based solely on construction cost but must incorporate a comprehensive evaluation of life cycle performance, environmental impact, traffic loading conditions, and future uncertainty factors. Therefore, this study on the life cycle cost analysis of flexible and rigid pavement systems under varying traffic conditions aims to provide a structured comparative framework that supports more informed and sustainable infrastructure decision-making.

II. RESEARCH BACKGROUND

Al-Nawasir et al. (2026) examined the sustainable utilization of construction waste in road engineering by investigating the incorporation of ceramic waste powder (CWP) as a partial replacement for cement in cementitious grout used for semi-flexible pavement (SFP) surfaces. The study reportedly replaced cement with CWP at proportions ranging from 15% to 50% and evaluated the resulting SFP mixtures through compressive strength testing, Marshall stability, wheel tracking tests, life cycle assessment (LCA), and statistical analyses. The findings indicated that a 20% replacement level was considered optimal, as it significantly enhanced pavement performance by reducing rutting depth by 80% and increasing compressive strength and Marshall stability by 50% and 23%, respectively, after 28 days of curing. These improvements were attributed to the improved fluidity and bonding characteristics of CWP, which reportedly enhanced void filling within the porous asphalt matrix and contributed to a denser microstructure, as supported by SEM observations. Furthermore, the LCA results suggested that increasing CWP content reduced global warming potential and fossil fuel depletion, thereby improving sustainability. Statistical analyses, including quadratic regression, ANOVA, and Tukey HSD testing, further confirmed the significance of these performance gains, highlighting the dual mechanical and environmental advantages of CWP incorporation in SFP systems for sustainable road construction.

Vámos and Szendefy (2026) had examined rutting as a critical distress mechanism in flexible pavements caused by repetitive traffic loading and had emphasized that pavement deformation comprised both recoverable (elastic) and unrecoverable (plastic) components. Their study had highlighted that rutting became more severe in hot climatic conditions due to the reduction in asphalt binder viscosity and stiffness with rising temperature, which increased the susceptibility of Hot Mix Asphalt (HMA) to permanent deformation. It had further been noted that a substantial portion of rutting occurred in the unbound layers beneath the asphalt surface, including the base, subbase, and subgrade, thereby necessitating greater attention to these layers. The authors had integrated the High Cycle Accumulation (HCA) model into a laminar pavement model to estimate permanent deformations in unbound granular layers while accounting for temperature-dependent asphalt stiffness. Rutting depths over the design life had been computed considering seasonal stiffness variations, and the results had shown that softer asphalt behavior significantly intensified rut development in the underlying soil layers. The study had also found that seasonal sequence effects were most pronounced during the first year of service, although these initial differences diminished with increasing axle repetitions over time.

Rusida et al. (2025) investigated the role of road infrastructure in supporting economic and social development, particularly in developing regions such as Mojokerto Regency, and highlighted that road development not only enhanced community mobility but also facilitated the efficient flow of goods and services. Their study aimed to compare the cost and construction time of rigid and flexible pavements on the Temuireng-Jetis road section in Mojokerto District using a comparative analysis approach, which examined construction specifications, budget plans, and project timelines. The results were reported to indicate that rigid pavement, with an estimated cost of IDR 3,202,246,813, was more cost-efficient than flexible pavement, which amounted to IDR 4,667,881,104. It was also observed that rigid pavement construction required 119 days with 25 workers per day, whereas flexible pavement had a shorter construction timeline but incurred higher long-term maintenance costs. The study was noted to emphasize the importance of selecting pavement types based on both initial costs and long-term efficiency and suggested that future research should explore environmental impacts and incorporate modern computational tools to optimize pavement design and decision-making.

Suwarto et al. (2024) were reported to have reviewed different approaches used to evaluate the environmental and financial impacts of road pavements over their life cycle. Their study was said to provide a methodological assessment of published research on asphalt pavement Life Cycle Assessment (LCA) and Life Cycle Cost Analysis (LCCA) and offered recommendations for future investigations. The findings were indicated to show that LCA studies faced limitations concerning functional units, selection of life cycle phases, maintenance schedule decisions, and uncertainty. In contrast, LCCA was described as being largely confined to evaluating maintenance strategies, with a primary focus on agency costs and often overlooking present or future uncertainties. Consequently, the authors were reported to have recommended the integration of both LCA and LCCA, the definition of a standard set of functional units, inclusion of the complete life cycle (including new materials), consideration of pavement performance predictions for realistic maintenance schedules, accounting for both short- and long-term costs and environmental impacts, and emphasis on probabilistic uncertainty analysis.

Deniz (2023) investigated the roles of maintenance and rehabilitation activities in preserving the serviceability of transportation networks, emphasizing their significant impact on total pavement costs, which include both agency costs (initial construction, maintenance, and rehabilitation) and user costs. The study applied Life Cycle Cost Analysis (LCCA) to optimize the cost-effectiveness of pavement investments, evaluating 108 cases of flexible and rigid pavements under varying design traffic levels (W180), soil conditions (MR), reliability levels (R), and analysis periods (t) based on the Türkiye General Directorate of Highway and AASHTO (1993) methods. The results suggested that although flexible pavements initially incurred lower costs, rigid pavements were ultimately more cost-effective according to LCCA, with comparable costs observed only under low-traffic and high-strength soil conditions. Furthermore, increases in W180, R, or t, or decreases in MR were associated with higher initial and overall costs for both pavement types, regardless of the design method. Sensitivity analysis on discount rates indicated that higher rates reduced the cost difference between pavement types. To address study limitations regarding the number of cases, the researcher developed a program allowing users to define design strategies and variables for cost optimization.

Mahdi et al. (2023) investigated the economic viability and cost-effectiveness of constructing or repairing flexible pavements reinforced with geosynthetics in Thailand. They conducted the analysis on a road construction project under the Muang District, Uttaradit province authority, adopting life cycle cost analysis (LCCA) that considered agency, user, and environmental costs for the selected road segment. The study evaluated National Primary Roads with and without geosynthetic materials through theoretical analysis and LCCA based on Thailand Highway Department costs. Two types of geosynthetics, Polyfelt PGM-G 100/100 geotextile fabric (430 g/m²) and Miragrid GX100/100 geogrid (335 g/m²), were considered. The results indicated that incorporating geosynthetics could extend the road maintenance cycle up to the material's service life, reducing maintenance costs by approximately 36.67% compared to conventional pavements. Nonwoven geotextiles exhibited lower embodied carbon values (2.35 CO2e/ton) than geogrids (2.36–2.97 CO2e/ton), and combining Polyfelt PGM-G 100/100 with on-site pavement production led to reduced total CO2 emissions (70,888 kg CO2 eq). The study concluded that geosynthetic use could promote more sustainable and economical road pavement construction in Southeast Asia.

Hossain et al. (2022) investigated the environmental impacts of pavement systems, noting that these systems consumed substantial resources and contributed significantly to environmental degradation. They emphasized that understanding these impacts could enable reductions in resource use and inform sustainable pavement design decisions. Observing a lack of comprehensive comparative sustainability assessments in highly urbanized contexts, the study aimed to evaluate the environmental performance of commonly used pavement systems in Hong Kong through a lifecycle assessment (LCA) approach. The authors designed flexible and rigid pavements for the same road section in accordance with local codes and practices, and collected practical construction and maintenance data via structured interviews with professionals and experts for LCA analysis. The results reportedly showed that rigid pavements had 21% and 54% higher global warming potential and mineral extraction impacts, respectively, compared to flexible pavements, whereas flexible pavements exhibited 64%, 65%, and 69% higher human health impact, ecosystem quality damage, and resource damage at the end-point level. Material production and transportation were found to dominate total impacts, contributing 57% for flexible and 97% for rigid pavements to global warming potential. Overall, the study indicated that flexible pavements had 49% higher total environmental impact than rigid pavements, and the authors suggested that incorporating recycled and eco-friendly materials could improve the sustainability of both pavement types, offering practical guidance for resource-conscious urban pavement design.

Adanikin et al. (2021) examined the use of Life Cycle Cost Analysis (LCCA) as a decision-support tool for the economic evaluation of agency and user costs in pavement type selection, maintenance, and rehabilitation strategies. They conducted the LCCA using the Present Worth of Cost method, applying the Technical Recommendations for Highways (TRH 12) for calculating agency costs, which included initial rehabilitation, maintenance, future, and salvage costs. The analysis period was taken as 40 years to adequately reflect long-term cost differences across reasonable design strategies. Their findings indicated that while the initial cost of rigid pavement was the highest, followed by rigid pavement with 15% cement by-product addition (CBA), and flexible pavement had the lowest initial cost, the present worth costs over the life cycle showed flexible pavement as the most expensive, followed by rigid pavement, with rigid pavement containing 15% CBA demonstrating the lowest life cycle cost. Consequently, they recommended considering rigid pavement with 15% CBA due to its lowest life cycle cost and relatively moderate initial cost.

Qiao et al. (2020) investigated the adaptation of pavement design and management practices in response to future climate change, noting that while several studies had explored methods to adjust pavements for anticipated climatic conditions, the associated economic impacts remained largely unquantified. They conducted a comprehensive life-cycle cost analysis (LCCA) to evaluate the potential economic effects of using an upgraded asphalt binder (PG 76-22) instead of the original binder (PG 70-22) for flexible pavement construction and maintenance. The study considered three Virginia Department of Transportation (VDOT) districts with distinct climates and analyzed typical interstate, primary, and secondary pavement sections as case studies. The LCCA incorporated costs from production, maintenance, and usage phases, explicitly accounting for future climate projections, pavement life-cycle performance, maintenance effects, and work zone user delays. The findings indicated that pavements constructed with the upgraded binder were projected to perform better over time and offered economic advantages compared to pavements with the original binder under the anticipated climate conditions for 2020–2039.

Haslett et al. (2020) examined the limitations of conventional pavement Life Cycle Assessment (LCA) practices, which typically relied on historical climate data to evaluate pavement performance and guide budgeting and maintenance and rehabilitation (M&R) strategies. They argued that such assumptions might be inappropriate under climate change, as flexible pavement performance is sensitive to climate stressors. The study investigated the effects of integrating future climate projections and realistic traffic data (RTD) into pavement M&R evaluations. A 26-km section of Interstate-495 was analyzed to assess costs and environmental impacts across various M&R scenarios and pavement structures. The authors reported that predicted performance using historical versus projected climate data combined with RTD influenced life cycle cost and global warming potential estimates, showing that incorporating future climate data and RTD could increase agency LCA impacts by up to 20%, with the magnitude of increase depending on the pavement structure and selected M&R alternative.

Guo et al. (2019) examined life-cycle cost analysis (LCCA) as a method for evaluating the long-term cost-effectiveness of various pavement designs and treatment strategies. They noted that due to inherent uncertainties, numerous probabilistic LCCA models had been developed, which generally relied on either prescribed treatment schedules or mechanistic-empirical analysis to determine schedules, potentially causing overestimation of life-cycle costs (LCC). The study proposed a novel probabilistic simulation-optimization LCCA model that determined treatment schedules by minimizing total LCC, encompassing both agency and user costs, which contrasted with existing probabilistic approaches. The model also incorporated uncertainties related to treatment costs and pavement deterioration processes. Through two case studies, they demonstrated the practical implications: the first highlighted how accounting for treatment schedule uncertainties led to a narrower LCC distribution, while the second showed that the simulation-optimization model could result in different pavement design selections compared to conventional prescribed-schedule models.

III. KEY FINDINGS FROM STUDY

Author (Year)	Objective	Methodology	Key Findings	Relevance to Study
Al-Nawasir et al. (2026)	Evaluate ceramic waste powder in semi-flexible pavements	Experimental testing + LCA + statistical analysis	20% CWP improved strength and reduced rutting by 80%; lowered environmental impact	Shows material innovation improves both performance and life cycle sustainability
Vámos & Szendefy (2026)	Analyze rutting behavior in flexible pavements	High Cycle Accumulation (HCA) model	Temperature significantly increases rutting; unbound layers major contributor	Explains performance degradation affecting maintenance cost in LCCA
Rusida et al. (2025)	Compare rigid and flexible pavement cost and time	Comparative cost–time analysis	Rigid pavement had higher initial cost efficiency over long term	Supports long-term economic advantage of rigid pavements
Suwarto et al. (2024)	Review LCA and LCCA methodologies	Systematic literature review	Lack of standardization and uncertainty in current models	Identifies gaps in integrated pavement evaluation frameworks
Deniz (2023)	Evaluate LCCA under traffic, soil, and reliability conditions	Simulation using AASHTO-based design	Rigid pavements more cost-effective under heavy traffic conditions	Strong evidence supporting rigid pavements in high-load scenarios

Mahdi et al. (2023)	Assess geosynthetics in flexible pavements	Case study + LCCA + carbon analysis	36.67% reduction in maintenance cost and emissions	Shows flexible pavement enhancement through sustainable materials
Hossain et al. (2022)	Evaluate environmental impacts of pavement systems	Life Cycle Assessment (LCA)	Flexible pavements show higher total environmental burden overall	Highlights environmental trade-offs between pavement types
Adanikin et al. (2021)	Compare life cycle costs of pavement types	Present worth method (LCCA)	Rigid pavement with additives had lowest life cycle cost	Supports modified rigid pavement as most economical option
Qiao et al. (2020)	Study climate change impact on pavement LCCA	LCCA with climate projection scenarios	Upgraded binder improves long-term performance and reduces costs	Shows climate adaptability affects pavement life cycle cost
Haslett et al. (2020)	Assess climate + traffic impact on pavements	LCA with real traffic data simulation	Climate change increases agency costs up to 20%	Highlights uncertainty in traditional LCCA assumptions
Guo et al. (2019)	Develop probabilistic LCCA model	Simulation–optimization approach	Treatment uncertainty significantly affects life cycle cost results	Emphasizes need for probabilistic cost modeling in pavements

IV. CONCLUSION

The present study on Life Cycle Cost Analysis (LCCA) of flexible and rigid pavement systems under varying traffic conditions highlights that pavement selection cannot be effectively based only on initial construction cost, but must incorporate long-term economic performance, structural durability, maintenance requirements, and environmental impacts. The reviewed literature consistently demonstrates that flexible pavements generally offer lower initial construction costs and faster execution; however, their long-term performance is significantly influenced by traffic loading intensity, temperature variations, and material deterioration mechanisms such as rutting and fatigue cracking. Vámos and Szendefy (2026) confirmed that temperature-induced stiffness reduction in asphalt layers accelerates rutting, particularly under heavy traffic conditions, thereby increasing maintenance frequency and life cycle cost. In contrast, rigid pavements, despite higher initial investment, exhibit superior load distribution characteristics and reduced susceptibility to deformation, resulting in lower maintenance and rehabilitation needs over extended service periods. Studies such as Deniz (2023) and Adanikin et al. (2021) consistently indicate that rigid pavements become more economically viable than flexible pavements under medium to high traffic conditions when evaluated over a full life cycle period. Furthermore, Rusida et al. (2025) also emphasized that rigid pavements demonstrate better cost efficiency over time despite higher upfront costs, reinforcing the importance of adopting a life cycle-based decision-making approach rather than focusing solely on initial expenditures. From an environmental perspective, the integration of Life Cycle Assessment (LCA) with LCCA provides a more comprehensive evaluation framework for sustainable infrastructure development. Hossain et al. (2022) revealed that both pavement systems contribute significantly to environmental impacts, although flexible pavements tend to generate higher cumulative environmental burdens due to frequent maintenance activities. However, rigid pavements show higher impacts during material production stages, particularly cement manufacturing. The inclusion of sustainable materials such as ceramic waste powder (Al-Nawasir et al., 2026) and geosynthetics (Mahdi et al., 2023) demonstrates strong potential to reduce both environmental impact and life cycle cost, indicating a shift toward greener pavement technologies. Overall, the study concludes that rigid pavements are generally more cost-effective and durable under high traffic conditions, while flexible pavements may remain suitable for low-volume roads or regions where initial budget constraints are critical. The optimal pavement selection therefore depends on a balanced consideration of traffic intensity, climatic conditions, material innovation, and long-term economic-environmental trade-offs.

V. FUTURE SCOPE

Future research in the field of Life Cycle Cost Analysis of pavement systems should focus on developing more advanced, integrated, and realistic evaluation frameworks that account for rapidly changing environmental, technological, and traffic conditions. One of the major future directions is the integration of artificial intelligence (AI), machine learning (ML), and data-driven predictive modeling techniques to improve the accuracy of pavement deterioration forecasting and cost estimation. These tools can enhance decision-making by reducing uncertainty in maintenance scheduling and improving life cycle cost prediction reliability. Another important area of research is the development of unified LCCA–LCA hybrid models that simultaneously evaluate economic costs and environmental impacts under a single standardized framework. As highlighted by Suwarto et al. (2024), current methodologies suffer from inconsistencies in functional units, system boundaries, and uncertainty treatment; therefore, future studies should aim to establish standardized global guidelines for pavement life cycle assessment. Additionally, future research should incorporate climate change scenarios and extreme weather impacts into pavement performance and cost evaluation models. Studies such as Qiao et al. (2020) and Haslett et al. (2020) have already demonstrated that climate variability significantly affects pavement life expectancy and maintenance requirements, indicating the need for climate-resilient pavement design strategies. Further exploration is also required in the development and large-scale implementation of sustainable construction materials such as recycled asphalt pavement (RAP), industrial waste by-products, nano-modified binders, and bio-based additives. These materials have the potential to significantly reduce both environmental footprint and long-term maintenance costs. Finally, future studies should emphasize real-world field validation of simulation-based LCCA models under actual traffic and environmental conditions. The inclusion of uncertainty modeling, probabilistic approaches, and long-term monitoring data will further enhance the reliability and practical applicability of pavement life cycle cost analysis, ultimately leading to more sustainable, cost-efficient, and resilient transportation infrastructure systems.

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