

# Comparative Evaluation of Pavement Design Methods for Improved Structural Performance and Sustainable Transportation Infrastructure

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## ABSTRACT

This study examines the comparative evaluation of pavement design methods for improving structural performance in modern transportation infrastructure. It highlights the limitations of traditional empirical methods and the advantages of mechanistic–empirical approaches in predicting pavement distress, load response, and long-term durability. The study considers key factors such as traffic loading, subgrade strength, climatic conditions, material properties, sustainability, and life cycle cost. Advanced tools such as FWD, TSDD, LCA, and performance-based evaluation support more reliable pavement assessment. The study emphasizes the need for optimized design strategies to enhance durability, cost efficiency, and sustainable pavement performance.

**Keywords:** *Pavement Design, Structural Performance, Mechanistic–Empirical Method, Sustainability.*

## I. INTRODUCTION

The rapid expansion of transportation infrastructure has necessitated the development of efficient and durable pavement systems capable of supporting increasing traffic loads, environmental stresses, and long-term performance demands. Pavement design plays a critical role in ensuring structural integrity, serviceability, and economic feasibility over the lifespan of road networks. Traditionally, pavement design methods have evolved from empirical approaches, which were largely based on historical performance observations, to more advanced mechanistic and mechanistic–empirical (M–E) approaches that incorporate material behavior, loading conditions, and environmental factors. Empirical methods, such as Road Note 29 (RN29) and other conventional guidelines, have been widely used due to their simplicity and ease of application; however, they often lack the ability to accurately predict performance under varying conditions. In contrast, mechanistic–empirical methods, such as those implemented in AASHTOWare Pavement-ME, provide a more comprehensive framework by combining theoretical models with field calibration data to predict distress mechanisms such as rutting, fatigue cracking, and thermal deformation (Justo-Silva et al., 2022). With increasing concerns regarding sustainability, cost-effectiveness, and resilience, there has been a growing need to comparatively evaluate different pavement design methods to identify the most suitable approach for improved structural performance under diverse operational conditions (Nascimento et al., 2020).

Recent advancements in pavement engineering have emphasized the importance of incorporating performance-based parameters, material innovations, and advanced evaluation techniques into the design process. Studies have demonstrated that the structural performance of pavements is significantly influenced by factors such as subgrade strength, traffic loading, climatic conditions, and material properties. For instance, the use of geogrid reinforcement in flexible pavements has been shown to enhance load distribution and reduce deformation, although its effectiveness varies depending on subgrade conditions, as indicated by California Bearing Ratio (CBR) values (Praveen & Baadiga, 2026). Similarly, the comparison between rigid and flexible pavements has revealed that while rigid pavements may involve higher initial construction time, they often provide superior long-term cost efficiency and durability (Oetomo & Marleno, 2026). In addition to material

and structural considerations, modern pavement design also relies on advanced data collection and analysis techniques. Technologies such as Traffic Speed Deflection Devices (TSDD) and Falling Weight Deflectometers (FWD) have enabled continuous and accurate assessment of pavement conditions, thereby improving maintenance planning and performance evaluation (Jiang et al., 2025). Furthermore, specialized pavement applications, such as airport pavements, require consideration of higher load magnitudes and dynamic effects, leading to the adoption of more sophisticated design methodologies, particularly those recommended by regulatory bodies like the Federal Aviation Administration (Sun et al., 2024).

In recent years, the scope of pavement design has expanded beyond structural performance to include sustainability, environmental impact, and adaptability to future transportation trends. The integration of Life Cycle Assessment (LCA) and Data Envelopment Analysis (DEA) into pavement selection processes has enabled engineers to evaluate alternatives not only based on technical performance but also on environmental and economic efficiency (Nascimento et al., 2020). Additionally, emerging challenges such as climate change and the introduction of autonomous vehicles (AVs) have necessitated a re-evaluation of existing design methods. Research has indicated that these factors can significantly accelerate pavement deterioration, leading to increased rutting and fatigue cracking if not adequately addressed in the design stage (Rana et al., 2023). Moreover, innovative pavement types, such as Roller-Compacted Concrete (RCC) and stone pavement structures, have gained attention for their unique performance characteristics, although their design methodologies often remain conservative and require further refinement (Sengun et al., 2024; Fiorentini et al., 2023). Despite significant progress in pavement engineering, there remains a need for a comprehensive comparative evaluation of existing design methods to identify their strengths, limitations, and applicability under varying conditions. Such an evaluation is essential for developing optimized pavement design strategies that ensure improved structural performance, cost efficiency, and long-term sustainability in modern transportation infrastructure.

## II. RESEARCH BACKGROUND

**Oetomo and Marleno (2026)** examined the Sambeng–Kedewan area in Bojonegoro Regency, which was characterized as an agrarian region experiencing growth in both agricultural and energy sectors but facing significant road infrastructure challenges. It was reported that inadequate road access had adversely affected the distribution of agricultural products and overall logistical efficiency, particularly in the Kasiman and Kedewan sub-districts. The study aimed to evaluate the most technically and economically feasible type of pavement. It was stated that the analysis had been conducted using the 2017 Manual for Pavement Design (MDPJ) for flexible pavements and the PDT-14 (2003) guidelines for rigid pavements. Various data, including soil characteristics, average daily traffic, and design life spans of 20 and 40 years, were considered. The findings indicated that rigid pavement was more cost-efficient in the long term, although it required slightly longer construction time compared to flexible pavement.

**Praveen and Baadiga (2026)** investigated the growing need for mechanistic and performance-based inputs in pavement design by conducting field-scale cyclic plate load tests to evaluate the influence of subgrade strength, expressed through the California Bearing Ratio (CBR), on the structural behavior of geogrid-reinforced flexible pavements. It was reported that CBR values of 6%, 8%, 10%, and 15% were considered along with three types of geogrids, namely PP30, PET60, and PET80. The reinforcement benefits were assessed using Traffic Benefit Ratio (TBR), Modulus Improvement Factor (MIF), and Layer Coefficient Ratio (LCR). The study found that reinforcement effectiveness decreased with increasing CBR, with the highest TBR observed at 6% and the lowest at 15%. Among the materials, PET80 was found to perform superiorly. Furthermore, optimized pavement performance indicated potential material savings without compromising structural integrity.

**Jiang et al. (2025)** reported that the rapid development of the transportation industry had significantly increased the demand for efficient highway maintenance, while conventional pavement structural evaluation based on fixed-point deflection detection was found to be inefficient. The study highlighted that traffic speed deflection devices (TSDD) had enabled continuous collection of pavement deflection data at normal driving speeds, offering advantages such as minimal traffic disruption and realistic loading conditions. It was observed that TSDD aligned well with emerging trends in intelligent transportation systems. Furthermore, comparisons between TSDD and falling weight deflectometer (FWD) indicated similar data trends, confirming its reliability. However, the detection process was noted to be complex, requiring adjustments for factors such as speed, roughness, and temperature. The study emphasized the need for advanced data processing systems and suggested integrating TSDD into pavement management systems for improved decision-making and performance evaluation.

**Sengun et al. (2024)** reported that industrial applications had historically represented the primary market sector for Roller-Compacted Concrete (RCC) pavements due to their high load-bearing capacity, cost-effectiveness, and minimal maintenance requirements. It was observed that RCC had often been perceived to behave similarly to conventional concrete, and therefore, limited efforts had been directed toward improving its structural design. The authors indicated that, despite advancements in analytical methods and experimental techniques, existing RCC pavement design approaches had remained largely conservative. The study further examined heavy-duty pavement design methodologies with respect to load evaluation, analytical procedures, and transfer functions. A comparative analysis had been carried out between established design manuals for both static loading conditions, such as container stacking, and dynamic loading scenarios, including reach stacker traffic, for plain concrete and RCC pavements. The review was intended to support the development of a more rational, mechanically based RCC pavement design framework.

**Sun et al. (2024)** examined those flexible and rigid pavements had commonly been constructed for airport applications to sustain aircraft loads throughout the design life. It was reported that, during the planning stage, factors such as pavement structure, material characteristics, aircraft loading, environmental conditions, and damage models had been carefully evaluated. The study highlighted that airport pavement design differed significantly from road pavements due to higher load magnitudes, elevated tire pressures, and dynamic loading conditions. It was observed that there had been a shift from empirical methods to mechanistic–empirical approaches, which had been widely adopted in computational design programs. The methodologies proposed by the Federal Aviation Administration (FAA) were reviewed and compared to identify advancements in structural design practices. Furthermore, recent FAA specifications had been analyzed. The study also indicated that Falling Weight Deflectometer and Heavy Weight Deflectometer tests had been utilized for structural evaluation, supporting effective maintenance and rehabilitation strategies.

**Fiorentini et al. (2023)** examined stone pavement structures (SPS), commonly referred to as stone-paved roads, where stones were utilized as the primary surfacing material. It was reported that, historically, irregular-shaped stones with downward protrusions had been widely adopted due to production constraints, whereas recent developments had enabled the use of regular cuboid stones. The study highlighted that pavement designers were required to decide between historical and regular stones during construction and rehabilitation, although both followed similar design principles. It was observed that limited research had been conducted comparing their performance. Therefore, a comprehensive investigation was undertaken involving laboratory characterization and in situ analysis using Falling Weight Deflectometer (FWD). Furthermore, a Finite Element Method (FEM)-based comparative analysis was performed to evaluate mechanical behavior, failure mechanisms, joint efficiency, and subgrade influence. The study also discussed functional, maintenance, and cultural aspects of both SPS types.

**Rana et al. (2023)** examined the influence of autonomous vehicles (AVs) and anticipated climate change on asphalt concrete (AC) pavement performance, particularly under conditions of narrower traffic lane usage. The study was conducted for a road section in Ontario, Canada, and the performance of AC pavement was evaluated using the AASHTOWare Mechanistic-Empirical pavement design approach. It was reported that AVs were incorporated into the design framework by modifying traffic parameters such as load equivalency factors and lane distribution. The analysis was carried out to assess both the individual and combined impacts of AVs and climate change on pavement distress. It was observed that comparisons between human-driven vehicles under historical climate and AVs under projected climate conditions revealed significant deterioration effects. The findings indicated that both AVs alone and in combination with climate change accelerated rutting and fatigue cracking. It was suggested that regulating AV distribution could minimize pavement distress.

**Justo-Silva et al. (2022)** described the characteristics of a new pavement design methodology developed by the American Association of State Highway and Transportation Officials (AASHTO), known as AASHTOWare Pavement-ME®. The study was reported to have evaluated its application to flexible pavement structures outlined in the Portuguese Manual of Pavement Structures for the national road network. The findings indicated that the tool was highly useful for road engineers, not only in the design of new pavement systems but also in assessing their long-term performance and facilitating effective maintenance and rehabilitation planning. It was further observed that, based on the specific conditions of the case study, rutting had emerged as the most critical form of pavement distress. The reported rutting values were found to be close to the threshold limit of 20.0 mm, as specified in the Portuguese Quality Control Plans, thereby highlighting the need for careful monitoring and design consideration.

**Umar et al. (2021)** reported that various methods for flexible pavement design had been developed over the years, ranging from empirical and mechanistic approaches to the more recent mechanistic–empirical methods. In their study, seven different pavement design methods were examined, and each method was applied to determine the thickness of flexible pavement structures. It was further noted that the Fuzzy PROMETHEE decision-making technique had been employed to identify the most suitable design method. The selection criteria were stated to include pavement thickness, environmental considerations, pavement performance, recommended design life, and minimum strength requirements for subbase and base materials. The findings indicated that Road Note 29 (RN29) had been ranked as the most preferred method, followed by HD26/01. However, it was also observed that HD26/01 had been recommended for new road design, as pavements designed using RN29 had reportedly experienced complete failure after 20 years of service.

**Nascimento et al. (2020)** reported that decision-making for infrastructure investment had consistently posed challenges due to the numerous variables involved in project selection. In the context of flexible road pavements, it was observed that traditional approaches primarily relied on technical and economic criteria, such as material characteristics and construction techniques. However, the study emphasized that, with increasing concerns regarding resource optimization, sustainability parameters were also considered essential in the decision-making process. The authors noted that advancements in engineering had facilitated the development of mechanistic-empirical design methods for more accurate estimation of pavement life. It was proposed that integrating Life Cycle Assessment (LCA) with Data Envelopment Analysis (DEA) served as an effective decision-support tool. The findings indicated that a bitumen-stabilized base with 15% recycled tire rubber was identified as the most efficient option in terms of cost and environmental performance in the Brazilian case study.

## III. KEY FINDINGS FROM STUDY

S. No.	Author(s) & Year	Study Area / Focus	Methodology / Design Approach	Key Findings	Limitations / Research Gap
1	Oetomo & Marleno (2026)	Sambeng–Kedewan Road, Indonesia	Comparative analysis using MDPJ (2017) for flexible and PDT-14 (2003) for rigid pavements	Rigid pavement was more cost-effective over long-term; flexible pavement had shorter construction time	Did not consider environmental and maintenance variability
2	Praveen & Baadiga (2026)	Flexible pavements with geogrid reinforcement	Field cyclic plate load tests; evaluation using CBR, TBR, MIF, and LCR	Reinforcement effectiveness decreased with increasing CBR; PET80 performed best; material savings achieved	Limited long-term durability analysis under real traffic conditions
3	Jiang et al. (2025)	Pavement condition evaluation systems	Comparison of TSDD and FWD technologies	TSDD provided continuous, real-time data with minimal traffic disruption; results comparable to FWD	Complex data processing and need for calibration under varying conditions
4	Sengun et al. (2024)	RCC vs conventional concrete pavements	Comparative analysis of design manuals for static and dynamic loads	RCC offered high load capacity and durability; design approaches remained conservative	Lack of advanced mechanistic design frameworks for RCC
5	Sun et al. (2024)	Airport pavement design	Review of FAA mechanistic–empirical design methods and nondestructive testing (FWD, HWD)	M–E methods improved prediction accuracy; airport pavements required higher structural considerations	Limited integration of real-time monitoring and adaptive design
6	Fiorentini et al. (2023)	Stone pavement structures (historical vs regular)	Laboratory tests, FWD analysis, and FEM modeling	Regular stones improved mechanical performance; similar design principles followed	Lack of large-scale field validation studies
7	Rana et al. (2023)	Impact of AVs and climate change on pavements	AASHTOWare ME-based simulation	AVs and climate change increased rutting and fatigue cracking significantly	Absence of adaptive design strategies for future mobility trends

8	Justo-Silva et al. (2022)	Flexible pavement design (Portugal)	Application of AASHTOWare Pavement-ME	Identified rutting as critical distress near threshold limits	Requires regional calibration and validation
9	Umar et al. (2021)	Comparative evaluation of pavement design methods	Multi-criteria decision analysis using Fuzzy PROMETHEE	RN29 ranked best overall; HD26/01 better for long-term durability	Conflicting results between ranking and actual performance
10	Nascimento et al. (2020)	Sustainable pavement selection	Integration of LCA and DEA methods	Bitumen with recycled rubber found most sustainable and cost-efficient	Structural performance aspects not deeply analyzed

#### IV. CONCLUSION

The comparative evaluation of pavement design methods highlights the significant evolution from traditional empirical approaches to advanced mechanistic–empirical frameworks aimed at improving structural performance, durability, and cost efficiency. The reviewed studies collectively demonstrate that no single pavement design method is universally optimal; rather, the suitability of a method depends on multiple factors including traffic loading, subgrade conditions, environmental influences, material properties, and design life requirements. Empirical methods, although simple and widely adopted, were found to have limitations in accurately predicting long-term pavement performance under varying conditions. In contrast, mechanistic–empirical approaches, such as AASHTOWare Pavement-ME, have shown improved reliability by integrating material behavior and real-world performance data, particularly in predicting distresses like rutting and fatigue cracking. Furthermore, advancements in evaluation technologies, including Traffic Speed Deflection Devices and Falling Weight Deflectometers, have enhanced the accuracy of pavement condition assessment, enabling better maintenance and rehabilitation planning. The studies also revealed that rigid pavements generally offer better long-term cost efficiency, while flexible pavements provide advantages in terms of construction speed and adaptability. Additionally, the incorporation of innovative materials such as geogrids and recycled components has demonstrated potential for improving pavement performance and sustainability. Emerging challenges, including climate change and the increasing adoption of autonomous vehicles, were found to significantly influence pavement deterioration, thereby necessitating adaptive and resilient design strategies. Moreover, the integration of sustainability assessment tools like Life Cycle Assessment and Data Envelopment Analysis has broadened the scope of pavement design by considering environmental and economic impacts alongside structural performance. Despite these advancements, gaps remain in terms of regional calibration, long-term field validation, and the development of unified design frameworks that can effectively address future transportation demands. Therefore, a holistic and integrated approach combining mechanistic analysis, performance evaluation, and sustainability considerations is essential for optimizing pavement design methods and ensuring improved structural performance in modern transportation infrastructure.

## V. FUTURE SCOPE

The future scope of pavement design methods lies in the development of more integrated, adaptive, and data-driven frameworks that can effectively address the growing complexities of modern transportation systems. There is a strong need to enhance mechanistic–empirical design approaches by incorporating real-time field data, advanced material characterization, and region-specific calibration to improve prediction accuracy and reliability. The integration of emerging technologies such as artificial intelligence, machine learning, and big data analytics offers significant potential for optimizing pavement design, performance prediction, and maintenance planning through intelligent decision-support systems. Additionally, future research should focus on the long-term performance evaluation of innovative materials, including geosynthetics, recycled aggregates, and sustainable binders, to ensure both structural efficiency and environmental sustainability. The increasing impact of climate change necessitates the development of resilient pavement design models that account for temperature variations, moisture effects, and extreme weather events. Furthermore, the rise of autonomous and electric vehicles requires modifications in pavement design parameters, such as load distribution patterns and traffic characteristics, to minimize accelerated deterioration. There is also a need to standardize advanced evaluation techniques, including Traffic Speed Deflection Devices and other non-destructive testing methods, for widespread practical implementation. Expanding the application of Life Cycle Assessment and multi-criteria decision-making tools will further support the selection of optimal pavement alternatives by balancing structural, economic, and environmental considerations. Moreover, future studies should emphasize the development of unified design guidelines that integrate flexible, rigid, and composite pavement systems under a single framework for improved comparability and efficiency. Field validation through large-scale pilot projects and continuous monitoring systems will be essential to bridge the gap between theoretical models and real-world performance. Overall, the advancement of pavement design methodologies will depend on interdisciplinary research, technological innovation, and sustainable engineering practices to ensure durable, cost-effective, and resilient transportation infrastructure.

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