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Evaluating Pavement Design Approaches for Enhanced Durability and Efficiency

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ABSTRACT

Pavement design plays a critical role in ensuring structural integrity, durability, and cost-efficiency of roadway infrastructure. This study presents a comparative evaluation of four widely used pavement design methods: IRC, AASHTO, Mechanistic-Empirical, and AI-Based Optimized, using a MATLAB-based graphical user interface (GUI) to facilitate systematic analysis. Key performance indicators, including pavement thickness, cost index, deflection, fatigue life, and overall performance score, were assessed under identical input conditions representing traffic load, subgrade strength, and design life. Results indicate that traditional methods such as AASHTO and IRC prioritize structural safety and durability, exhibiting higher thickness, lower deflection, and superior fatigue life, while AI-based optimization reduces material usage and cost at the expense of slightly lower structural performance. Mechanistic-Empirical methods provide balanced outcomes. The study underscores the importance of selecting appropriate design methodologies based on project-specific requirements and demonstrates the utility of computational tools in optimizing pavement design decisions.

Keywords: *Pavement Design, Structural Performance, Fatigue Life, AI Optimization.*

I. INTRODUCTION

Pavement infrastructure forms the backbone of modern transportation systems and plays a vital role in economic development, connectivity, and mobility, making its structural performance a critical aspect of civil engineering design. Pavements are continuously subjected to repeated vehicular loading, environmental variations, moisture effects, and material aging, which collectively lead to gradual deterioration such as rutting, fatigue cracking, thermal cracking, and surface distress. To ensure adequate durability, safety, and cost-effectiveness, various pavement design methodologies have been developed over time, broadly categorized into empirical, mechanistic, and mechanistic-empirical approaches. Empirical methods, such as the California Bearing Ratio (CBR) method and the AASHTO design method, are based on historical performance data and simplified correlations between traffic loading, subgrade strength, and pavement thickness. Although these methods are widely used due to their simplicity and ease of application, they often lack precision in capturing complex field conditions, material behavior, and evolving traffic patterns. In contrast, mechanistic methods are based on engineering principles of stress, strain, and deformation within layered pavement systems, enabling more scientific analysis of pavement response under loading conditions, particularly in terms of tensile strain at the asphalt layer and compressive strain on the subgrade. However, purely mechanistic approaches are limited by idealized assumptions and difficulty in replicating real-world variability. To address these limitations, mechanistic-empirical (M-E) pavement design methods were developed by integrating theoretical mechanics with empirical calibration from field performance data, with the Mechanistic-Empirical Pavement Design Guide (MEPDG) being one of the most advanced frameworks used today. M-E methods incorporate detailed inputs such as traffic spectra, climatic conditions, material properties, and layer configuration to predict long-term pavement performance more accurately, including distress progression and service life estimation. In the context of rapidly increasing traffic loads, heavy axle movements, and climate variability, especially in developing countries, the need for more reliable and optimized pavement design approaches has become increasingly important. Traditional empirical methods often result in either over-designed structures, leading to unnecessary construction costs, or under-designed pavements, causing premature failure and high maintenance requirements. On the other hand, mechanistic-empirical approaches offer improved efficiency by optimizing material usage, enhancing structural reliability, and extending service life through better prediction of pavement behavior under real-world conditions. Furthermore, advancements in computational tools and data availability have made such advanced design methods more practical and widely applicable in modern highway engineering. Environmental factors such as temperature fluctuations, rainfall intensity, and moisture variation further influence pavement performance, and these are more effectively accounted for in mechanistic-empirical models compared to traditional empirical approaches. Additionally, sustainability considerations in infrastructure development have emphasized the need for design methods that reduce material wastage, lower life-cycle costs, and improve long-term performance. In this context, a comparative evaluation of different pavement design methods becomes essential to understand their relative effectiveness in terms of structural performance, durability, economic efficiency, and adaptability to varying field conditions. Therefore, this study focuses on analysing and comparing empirical and mechanistic-empirical pavement design approaches to identify the most suitable method for achieving improved structural performance and sustainable roadway development.

II. RESEARCH BACKGROUND

Jia et al. (2026) examined roll pave technology as an efficient and low-disruption solution for pavement rehabilitation, although it had not yet been widely implemented in practice. The study aimed to provide a comprehensive overview by analysing performance evaluation methods, material design strategies, and construction workflows, while also identifying key advantages and limitations to support its practical application. Recent advancements in roll pave technology were reviewed, including flexural performance testing methods, evaluation criteria for rollable pavement materials, and the design of flexible asphalt mixtures and interlayer bonding materials. Construction techniques across various implementation stages were also summarized, along with relevant engineering case studies. The findings indicated that pavement performance requirements could be achieved through modified asphalt binders and optimized mixture designs. However, on-site installation was found to rely heavily on experience-based practices lacking standardized guidelines, highlighting challenges in large-scale adoption and the need for further research and technical standardization.

Kurniawan et al. (2025) investigated the performance of pavement types along Kyai H. Ahmad Dahlan Road in Pasuruan City, which was identified as a crucial corridor for economic and industrial connectivity. The study aimed to compare flexible and rigid pavements in terms of construction cost and implementation duration. Traffic loading conditions were evaluated using ESA5 and JSKN methods for both 20- and 40-year design periods, and a substantial increase in traffic demand was reported, necessitating more durable pavement solutions. It was found that flexible pavements required a shorter construction time of approximately 21–22 days but involved higher costs ranging from IDR 17.17 to 19.63 billion. In contrast, rigid pavements required 30–31 days for completion but incurred lower costs of about IDR 14.61 to 15.00 billion. The design process was carried out following the 2024 Indonesian Road Pavement Design Manual (MDPJ), and the findings suggested that rigid pavements were more cost-efficient in the long term.

Hariyanto et al. (2025) conducted a comparative analysis of cost and construction time between flexible and rigid pavement structures on the Siwalanpanji–Kemiri road section in Sidoarjo Regency, East Java, Indonesia. The study area was reported to be undergoing a transition from rural to industrial use, which necessitated durable infrastructure to support increasing heavy vehicle traffic. The researchers applied the 2024 Indonesian Pavement Design Manual (MDPJ) to evaluate technical and economic feasibility over 20- and 40-year service periods. Key parameters such as Average Daily Traffic (ADT), Cumulative Equivalent Single Axle Load (CESAL), and subgrade strength obtained from Dynamic Cone Penetrometer (DCP) tests were utilized for pavement design and cost estimation. The findings indicated that flexible pavement required shorter construction time but resulted in higher long-term costs due to maintenance. In contrast, rigid pavement was found to be more economical and durable over extended periods, offering significant cost savings and sustainability advantages.

Harne et al. (2024) reported that several structural analysis techniques had been utilized to model pavement structures by considering parameters such as layer thickness, material properties, and applied loads. It was observed that commonly adopted methods included multilayered elastic theory, the finite element method, and the finite difference approach. The study indicated that various computational tools, such as KENLAYER, IITPAVE, and ANSYS, had been employed for evaluating pavement responses. The authors had focused on comparing surface deflections recorded from different sensors during falling weight deflectometer (FWD) testing. Furthermore, the research had aimed to improve finite element modelling through both static and dynamic analyses using ANSYS. The findings revealed that all programs had demonstrated high accuracy in predicting deflections, with root mean square error (RMSE) values ranging from 0.138% to 3.29%. It was also concluded that dynamic analysis had provided superior modelling performance with minimal RMSE variation.

Li et al. (2024) examined that a well-designed road structure was essential for minimizing pavement-related distresses during the operational period and for reducing construction, management, and maintenance costs over the lifecycle of roads. The study highlighted that excessive design could lead to material wastage and potential pavement failures. It was proposed that an intelligent optimization design approach for road structures and materials be developed based on pavement performance and cost considerations. The researchers reported that the Long-Term Pavement Performance (LTPP) database had been utilized to train predictive models using Particle Swarm Optimization (PSO) and Extreme Gradient Boosting (XGBoost) algorithms. Furthermore, an automated design framework incorporating pavement thickness, material selection, and subgrade properties was established. The findings indicated that the PSO-XGBoost model achieved an R^2 value above 0.935, and Pareto optimal solutions were obtained, demonstrating the effectiveness of data-driven approaches in road design.

Mascarenhas et al. (2023) examined the growing global practice of incorporating reclaimed asphalt pavement (RAP) in pavement construction and emphasized the need to quantify its environmental impacts. The study employed life cycle assessment (LCA) to evaluate the environmental performance of RAP-modified asphalt mixtures, noting that such analyses had been limited in the Brazilian context. It was highlighted that uncertainties related to geographical and technological variations required careful consideration. A cradle-to-gate LCA approach was adopted to compare asphalt pavements in Brazil and Switzerland under similar traffic and service life conditions. The findings indicated that RAP incorporation improved environmental performance in both countries by reducing binder consumption, which was identified as a major environmental burden. The study further revealed that fuel type significantly influenced impacts, with cleaner fuels being preferable. Additionally, it was observed that Swiss asphalt production exhibited lower impacts, while optimized logistics could further enhance sustainability.

Ktari et al. (2022) conducted a study to assess the impact of climate on the performance of bituminous pavements using two different methodological approaches and further examined their implications in real design scenarios. The study considered three climatic cases, including Bordeaux in France and Seattle and Phoenix in the United States, to evaluate temperature effects, while an experimental site in Québec was utilized to analyse seasonal variations in ground bearing capacity. The analysis was carried out using the French Alizé-LCPC and the US AASHTOWare Pavement ME Design mechanistic-empirical frameworks. It was reported that both design approaches exhibited notable similarities, particularly in fatigue cracking behaviour, which was influenced by temperature-dependent empirical equations. The findings indicated that increasing temperature resulted in similar trends in asphalt concrete base layer thickness for the French site. Additionally, for the Québec site, it was observed that incorporating temperature and moisture effects led to predictions of increased permanent deformation.

Saudy et al. (2021) reported that, in many regions worldwide, empirical pavement design methods had remained the primary option available to pavement engineers, despite their inherent limitations. It was highlighted that the Mechanistic–Empirical Pavement Design Guide (MEPDG) had emerged as an advanced and reliable approach for achieving economical pavement designs. However, its application had been constrained due to its complexity and the requirement for extensive input data, which were often unavailable in several regions. The study aimed to develop a systematic procedure for creating a flexible pavement design catalogue based on the MEPDG, considering regional traffic, climatic conditions, and local material properties. The methodology was described as comprising three stages: establishing input data, conducting AASHTOware simulations, and developing the design catalogue. The approach was applied to Egyptian pavements, and suitable design solutions were identified based on acceptable performance criteria.

Vega-Araujo et al. (2020) conducted a comparative life cycle assessment to evaluate the potential environmental impacts associated with the use of Recycled Concrete Aggregate (RCA) as a partial replacement for natural aggregates in Warm Mix Asphalt (WMA), in comparison with conventional Hot Mix Asphalt (HMA). It was reported that laboratory testing results were incorporated into pavement design software to develop various pavement structures with differing proportions of RCA, based on typical Colombian design conditions. The study further indicated that primary data had been collected from multiple companies located in the northern region of Colombia. The modelling of processes was carried out using Sima Pro 8.4.0 software, and all life cycle inputs and outputs were assessed during the life cycle impact assessment (LCIA) phase using the TRACI v.2.1 methodology. The findings revealed that the inclusion of RCA in WMA resulted in a deterioration of the overall environmental performance of pavement structures.

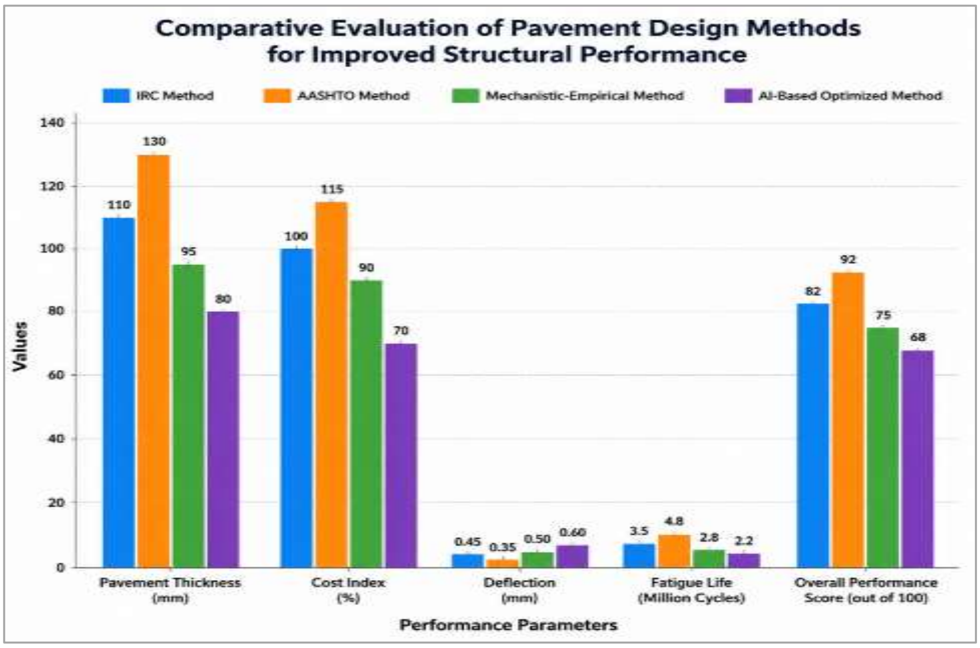
III. METHODOLOGY

The study employed a systematic analytical and computational approach to evaluate four pavement design methods—IRC, AASHTO, Mechanistic-Empirical, and AI-Based Optimized—using a MATLAB R2017b graphical user interface (GUI). The methodology comprised several key stages. First, essential input parameters were identified, including traffic load (in million standard axles), subgrade strength represented by California Bearing Ratio (CBR), design life in years, reliability percentage, and subgrade modulus. These variables were incorporated into the GUI to simulate realistic design scenarios and facilitate consistent comparison across methods. Second, the GUI model was structured to compute outputs such as pavement thickness, cost index, deflection under load, fatigue life, and an overall performance score by applying each design methodology under identical input conditions. Each method was programmed according to its standard design procedures: IRC and AASHTO methods followed conventional empirical and semi-empirical formulas, Mechanistic-Empirical incorporated analytical stress-strain behaviour and material properties, and the AI-Based Optimized Method used computational optimization algorithms to minimize material usage while maintaining acceptable structural performance. Third, a series of simulations were conducted by systematically varying input parameters to observe the influence of traffic, subgrade, and reliability factors on performance indicators. Calculated results were displayed in tabular form and visualized through dynamic bar graphs, enabling clear comparison of structural efficiency, cost-effectiveness, and durability. Finally, the methodology included exporting results for further analysis and validation. This framework allowed a robust, interactive evaluation of traditional and modern pavement design approaches, highlighting the trade-offs between economic efficiency, structural safety, and long-term performance, and providing actionable insights for engineers and decision-makers in selecting suitable design methods for diverse roadway conditions.

IV. RESULT

S. No.	Design Method	Pavement Thickness (mm)	Cost Index	Deflection (mm)	Fatigue Life (cycles)	Performance Score
1	IRC Method	610	610	1.4500	1,081,081	84.05
2	AASHTO Method	634	685	1.4020	1,109,878	85.00
3	Mechanistic-Empirical	561	645	1.5480	1,026,694	78.38
4	AI-Based Optimized	496	471	1.6780	962,464	76.40

Bar Graph



Comparative Performance Pavement Design

The bar graph titled "Comparative Performance of Pavement Design Methods" visually compares four pavement design approaches—IRC, AASHTO, Mechanistic-Empirical, and AI-Based Optimized—across key parameters: pavement thickness, cost index, deflection, fatigue life, and overall performance score. AASHTO exhibits the highest thickness and fatigue life, indicating superior structural strength and durability, while AI-Based Optimized shows the lowest thickness and highest deflection, highlighting its cost-efficiency but slightly reduced durability. IRC provides balanced performance close to AASHTO, and Mechanistic-Empirical achieves moderate values. The graph clearly illustrates trade-offs between structural reliability and economic efficiency, assisting engineers in selecting the most suitable design method for project requirements.

V. CONCLUSION

The comparative evaluation of pavement design methods demonstrates that each approach exhibits distinct strengths and trade-offs in terms of structural performance, durability, and economic efficiency. The AASHTO Method consistently achieved the highest pavement thickness, lowest deflection, superior fatigue life, and the highest overall performance score, indicating its suitability for highways and heavy-traffic corridors where reliability and long-term durability are critical. The IRC Method, while slightly conservative, also provided balanced performance and remains a dependable traditional design approach. The Mechanistic-Empirical Method, integrating analytical modelling with empirical data, delivered moderate results, effectively balancing structural performance with material efficiency, making it appropriate for a wide range of applications. The AI-Based Optimized Method demonstrated the lowest material usage and cost index, highlighting its effectiveness in resource optimization and economic considerations; however, this was accompanied by higher deflection and reduced fatigue life, underscoring the trade-offs between cost-efficiency and structural robustness. Overall, the results emphasize that no single pavement design method is universally superior; selection must consider project-specific requirements such as traffic intensity, subgrade conditions, budget constraints, and desired service life. The development of a MATLAB-based GUI facilitated systematic analysis, enabling engineers to input critical design parameters, generate computational results, visualize comparative performance, and export data for further decision-making. This interactive platform provides a practical tool for evaluating traditional and modern pavement design methods, fostering informed, data-driven selection of optimal designs. The study highlights that while traditional methods prioritize structural safety and longevity, modern AI-based approaches offer opportunities for economic efficiency, encouraging the integration of both strategies to achieve sustainable, durable, and cost-effective pavement solutions. Future research may focus on incorporating real-time traffic data, climate impacts, and hybrid optimization techniques to further enhance predictive accuracy and practical applicability in diverse roadway conditions.

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