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A COMPREHENSIVE REVIEW OF FLEXIBLE PAVEMENT DESIGN METHODS: COMPARATIVE ANALYSIS OF EMPIRICAL, MECHANISTIC–EMPIRICAL, AND PERFORMANCE-BASED APPROACHES

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Abstract

Pavement design using flexible pavements has moved from empirical design to mechanistic-empirical design as well as performance-based design over time. This literature review looks at these designs in light of the design principles, material characteristics, traffic conditions, climatic influences, structural behaviour, and feasibility of use. While empirical designs can still be used in projects where data is not available, they lack adaptability. Mechanistic-empirical designs are enhanced through structural and material studies with better predictions of pavement performance, though their accuracy is regionally dependent. Performance-based designs use the consideration of reliability, durability, maintenance and lifecycle for sustainable pavement designs. Some of the emerging uses are AI, climate change resilient materials and advanced models. Some of the areas where more research is required are regional validation, uncertainty in performance prediction and lack of use of long-term data.

Keywords: Flexible Pavement, Empirical Design, Mechanistic–Empirical Design, Performance-Based Design, Pavement Performance, Life-Cycle Assessment.

1. INTRODUCTION

A flexible pavement is a multi-layered pavement structure, where an asphalt-bound surface layer spreads the effect of repeated wheel loads via granular layers down to the subgrade. The performance of a pavement structure depends on interaction between the size and frequency of traffic, tyre pressure, material stiffness, temperature, moisture, construction variability and aging [1].

Traditional empirical design relies on the use of relationships developed based on the field observations and road tests to determine the required thickness of pavement layers. The appeal of such approaches is in a standardised data input and simple design charts or formulae. However, an empirical relationship developed for specific traffic load spectrum, subgrade type, climate and material combination would be unreliable when applied to significantly different conditions [2]. This was one of the factors contributing to the development of mechanistic design based on structural response calculations coupled with empirically based relationships for pavement distresses.

The concept of mechanistic-empirical (M-E) design consists in calculating the critical stress, strain and deflections of the structure, together with fatigue cracking, rutting and other forms of pavement deterioration. Thus, M-E design becomes more sensitive to the changes in material properties, axle configuration, seasonal variations and layering. However, the mechanistic element of this approach does not remove the empirical aspect of pavement distress models; calibration and validation are still the key aspects of successful design.

Performance-based design shifts the focus from whether a particular structure complies with some thickness or strain criteria to whether it fulfils certain service performance criteria throughout its designed lifetime, within an acceptable level of risk and cost [3]. Such criteria include rut depth, cracking severity, roughness, serviceability, reliability, maintainability and resistance to extreme weather conditions. Thus, the shift in design philosophy brings structural design into alignment with asset management, resilience and life-cycle optimisation.

Current research in climate change, flooding, mixture durability, artificial intelligence and uncertainty-based life-cycle management suggests that the next generation of pavement design should combine structural mechanics, material properties and operation decisions. This paper reviews different philosophies of pavement design without presenting them as alternative technologies and looks at the conditions, where the hybrid approach can be justified.

1.1 Review Objectives

- To describe the theoretical background, input factors, and constraints of empirical, mechanistic-empirical, and performance-based flexible pavements.
- To make a critical analysis of how these models deal with traffic, material, weather, deterioration, reliability, and life cycle aspects.

- To review recent advances in regionalization, rehabilitation, resilience, novel materials, and digital predictions of flexible pavements.
- To highlight barriers to implementation and future research directions.

2. METHODOLOGY

The current study involved a narrative literature review of the empirical, mechanistic–empirical, and performance-based approaches to flexible pavement design. Literature reviews and scientific articles related to the study topic and published between 2015 and 2026 were selected to provide a comprehensive understanding of the approaches of pavement design. Special emphasis was laid on significant parameters, such as pavement structural composition, traffic loads, material properties, environmental effects, pavement structural performance, and design reliability.

The collected literature was critically reviewed and classified into main topics, namely conventional empirical designs, mechanistic–empirical analysis, performance-based design, pavement degradation, and life cycle assessment. The focus of this literature review is the benefits, drawbacks, computational needs, and applicability of the aforementioned approaches. The latest research advancements in the field of sustainable pavement materials, climate-resistant pavement design, artificial intelligence, and performance prediction were also assessed. Comparison of these approaches enabled to determine the areas of research gap and technical challenge in the development of flexible pavements' sustainability and cost-effectiveness.

3. EMPIRICAL FLEXIBLE PAVEMENT DESIGN AND STRUCTURAL FOUNDATIONS

Flexible pavement design using an empirical approach depends upon pavement behavior, traffic loads, materials, and environmental factors [5]. The empirical methods set up correlations between design variables and pavement distress to come up with appropriate thicknesses of layers. It is important to know the structure of pavement, loading behavior, material properties, and modes of pavement failure for conventional empirical methods.

3.1 Pavement Structure, Load Transfer, and Failure Mechanisms

The components of flexible pavements include the asphalt layers, granular base, subbase, and subgrade. The pavement structure distributes the load and provides resistance to deformation. The performance of the pavement is influenced by the thickness of the layers, the material stiffness, temperature, moisture, and loading. Some of the modes of failures include fatigue cracking, rutting, and moisture induced deterioration.

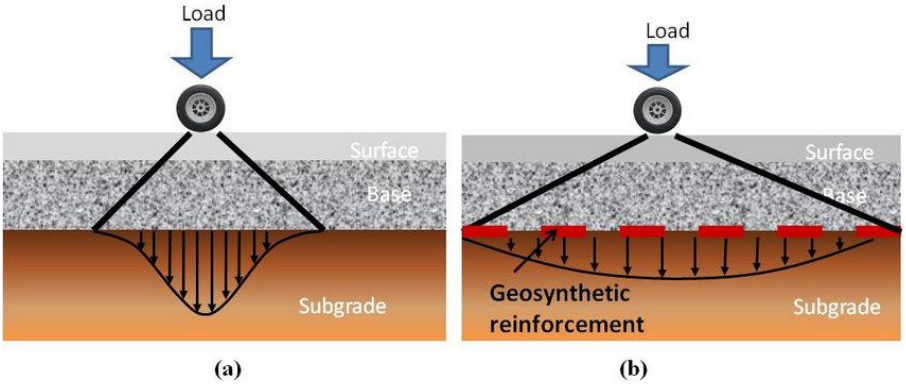

Figure 1: Typical Multilayer Flexible Pavement Structure and Critical Load-Response Locations [6]

Pavement design needs to take into account many mechanisms that may cause distress since fatigue cracking is not enough to eliminate other problems like rutting and environment. Consequently, structural analysis needs to focus on material and loading aspects.

3.2 Traffic Characterisation and Design Period

Traffic loading can be specified in terms of cumulative standard equivalent axle loadings or axle load spectra. Key considerations include the classification of vehicles, axle arrangement, tyre inflation, traffic progression and the pavement’s design life. Overloaded traffic needs to be considered for heavily loaded pavements.

3.3 Material Characterisation and Environmental Inputs

The properties of materials have a major impact on the performance of pavements. Such factors as resilient modulus, dynamic modulus, Poisson's ratio, asphalt mixture properties, and subgrade stiffness have been identified as being important [7]. Changes in temperature and moisture will affect the stiffness and stability of materials.

3.4 Principle and Conventional Procedures

Empirical pavement design provides correlations between performance of pavements observed and variables like traffic loading, subgrade properties, drainage and material properties. Traditionally, pavement thickness is determined using standard equations and observed relationships of performance using procedures developed by AASHTO historically.

3.5 Strengths and Practical Applications

These techniques provide simple computations, reduced data needs, and economical application. They are especially well-suited for low traffic volume pavements, initial pavement design, and areas where technical expertise is lacking [8]. Practical performance is best achieved when the conditions are comparable to those used for developing these empirical models.

3.6 Limitations and Transferability

Empirical methods rely very much on past performances, which cannot fully account for today's traffic loadings, materials, and climatic changes. The inability of empirical models to forecast each distress process makes them less applicable in various regions. Therefore, localization is required in order to enhance the applicability of empirical models [9].

4. MECHANISTIC–EMPIRICAL FLEXIBLE PAVEMENT DESIGN

The Mechanistic-Empirical Flexible Pavement Design method merges scientific principles with laboratory-derived performance models to enhance the efficiency of pavement design. This differs from the traditional empirical approaches in that this technique considers the responses of the structure, behavior of materials used, traffic loading, and other environmental factors that influence pavement distress. This method helps determine optimum pavement thickness, performance of pavements, and appropriate rehabilitation techniques [10].

4.1 Mechanics-Based Structural Response

The M-E design procedure analyzes the responses of pavements to vehicular loadings by employing the mechanical properties and structural properties of the materials used. Some of the factors taken into account are the horizontal tensile strain in the bottom of the asphalt layers and the vertical compressive strain in the subgrade layer.



Figure 2: Integrated Mechanistic–Empirical and Performance-Based Pavement Design Workflow [11]

The design process entails selection of pavement thicknesses, evaluation of structural behavior, estimation of distress, and modification of design to meet performance needs. It requires accurate material information for its precision.

4.2 Fatigue, Rutting, and Distress Prediction

The M-E approach forecasts pavement deterioration through the relationship between structural responses and loading by traffic. The fatigue model uses the tensile strain of asphalt to predict the occurrence of cracking, while the rutting model uses compressive strain to predict permanent deformations. There are other models which predict thermal cracking, aging, and surface roughness. Calibration of the models in specific regions is very important [12].

4.3 Regional Calibration and Simplified Design

Regional calibration increases the suitability of M–E techniques because regional climatic, traffic, and material conditions are taken into consideration. The studies in mild to hot climates, Egypt, and Oklahoma show the significance of performance models that are locally calibrated and the need for proper input database.

The simplified M–E technique is especially suitable for low volume pavements. Strain-based thickness optimization is an ideal method for balancing all three factors.

4.4 Rehabilitation and Material Innovations

M-E analysis helps in the rehabilitation of pavements by examining the present structural condition, service life left, and optimal overlay thicknesses. Moreover, the M–E analysis helps in the examination of new materials such as polymer modified asphalt and geogrids. Combination of material behavior and structural modeling increases effectiveness in pavement rehabilitation [13].

5. PERFORMANCE-BASED DESIGN AND COMPARATIVE ANALYSIS

Performance-oriented pavement design considers the factors like durability, performance, reliability, and economic evaluation of the pavement structure. In contrast to the traditional pavement design methods, the concept of performance-oriented pavement design stresses the attainment of particular objectives under variable traffic, material, and environmental conditions.

5.1 Performance Objectives and Acceptance Criteria

Performance design sets quantifiable standards such as allowable rut depth, cracking, surface texture, serviceability, and reliability. The standards determine the design thickness of the pavement, optimize materials, and plan for maintenance. The approach focuses on meeting particular performance standards during the design period.

5.2 Reliability and Uncertainty

The reliability-based design approach takes into consideration variability in traffic loads, material characteristics, pavement thickness, weather conditions, and construction quality. Probabilistic approaches, such as Monte Carlo simulations, determine the probability of exceeding tolerable levels of distress. The reliability-based approach enhances design through the incorporation of uncertainty, but its efficiency is contingent on accurate data inputs.

5.3 Performance-Based Mix and Structural Design

A Performance-based mix design technique assesses the properties of asphalt mixes using laboratory tests and mechanical modeling. Some of the important features of the asphalt mixtures are the capacity to withstand rutting, fatigue cracking, and environmental damage.

5.4 Whole-Life Performance and Asset Management

Whole-life pavement design takes into account factors such as construction cost, maintenance, rehabilitation, service life, and the environment. Life-cycle assessment facilitates the choice of sustainable options. The combination of performance prediction and maintenance planning helps achieve better resource allocation.

Table 1: Conceptual Comparison of Flexible Pavement Design Approaches [14]

Evaluation Dimension	Empirical	Mechanistic–Empirical	Performance-Based
Primary basis	Historical performance relationships	Structural response and distress models	Service outcomes and reliability

Main inputs	Traffic, subgrade, material class	Axle loads, material properties, climate	Structural inputs, performance targets, uncertainty
Principal output	Pavement thickness	Predicted cracking and rutting	Probability of meeting performance targets
Calibration	Historical field data	Regional distress models	Reliability and performance validation
Computational demand	Low	Moderate to high	Moderate to high
Main advantage	Simplicity and affordability	Improved structural analysis	Long-term performance optimisation
Main limitation	Limited adaptability	Input and calibration sensitivity	Extensive data requirements

Table 1 brings out the difference between the three approaches. Empirical approaches focus on simple thickness calculations, mechanistic-empirical models estimate structural decay, while performance-based approaches consider reliability and performance considerations. These approaches can be used together depending on the project conditions.

5.5 Comparative Evidence from Published Studies

Comparative studies have assessed the variations between traditional AASHTO approach and mechanistic-empirical method in terms of prediction of life of pavements [15]. Some researchers have assessed regional calibration, laboratory testing of materials, and reliability-based design. It is found from available literature that mechanistic-empirical and performance-based methods offer better capabilities for assessment; however, their effectiveness depends on the particular site and performance data.

Table 2: Selected Studies and Their Contribution to Pavement Design Comparison [16]

Study	Principal Emphasis	Relevance to Comparative Design
Maadani (2015) [17]	AASHTO M–E design evaluation	Model calibration and validation
El-Ashwah et al. (2021) [18]	Simplified M–E design	Regional climatic adaptation
Saudy et al. (2023) [19]	Egyptian M–E implementation	Local calibration requirements
Ahmed et al. (2023) [20]	AASHTO and M–E comparison	Pavement service-life prediction
Norouzi et al. (2022) [21]	Reliability-based design	Probabilistic performance assessment
Leon et al. (2023) [22]	Performance-based asphalt design	Regional performance optimisation
Xin et al. (2026) [23]	Life-cycle performance	Maintenance and uncertainty management

Table 2 presents the key findings of a few studies that contribute to flexible pavement design through regional calibration, structural performance prediction, reliability analysis, and life-cycle evaluation.

6. CHALLENGES, RESEARCH GAPS AND FUTURE PERSPECTIVES

6.1 Climate Change and Environmental Loading

Changes in climate have a major impact on the behavior of flexible pavements due to changes in temperature, rainfall, and weather extremes. High temperatures contribute to increased rut formation, while variations in moisture reduce pavement strength. An environmentally robust design requires an accurate understanding of future climates [24].

6.2 Moisture Variability and Flood Events

Water intrusion and flooding have a weakening effect on the pavement structure, causing premature pavement failure. The mechanistic-empirical models consider changes in the properties of pavements due to moisture conditions [25]. Drainage improvements, moisture-resistant materials, and assessment of pavements after flooding are critical for improved pavement durability.

6.3 Asphalt Mixture Durability and Ageing

The process of ageing affects the stiffness, flexibility and toughness of the asphalt binder. The effects of the environment and vehicle loadings on the asphalt cause its ageing process. It is possible to enhance durability and predictability of asphalt using new tests, models and mixes [26].

6.4 New Materials and Alternative Pavement Systems

Innovations like polymer modified asphalt, recycled plastic, and semi-flexible pavements provide potential for enhancing sustainability and performance of pavements. But their success relies on their mechanical and environmental properties, as well as real world validation. Additional research is needed to define design parameters of alternative materials.

6.5 Computational Tools, Optimisation, and Digital Methods

The use of artificial intelligence and machine learning algorithms is growing for the prediction of distress on pavements, material evaluation, and maintenance scheduling. These technologies help in data analysis and optimal design. The limitations of AI include quality of data, interpretability of models, and applicability to different regions, which need further research.

6.6 Lack of Transferable Regional Calibration

The current designs and methods of designing pavements are not always validated properly to account for different climates, different traffic loads, and different material properties. Calibration is necessary to enhance predictability and reliability of such designs.

6.7 Fragmentation Between Material Tests and Field Performance

Laboratory tests assess the performance of the asphalt mixes under controlled conditions; however, the outcomes might not be representative of the real-life performance of the pavement. There is need for further research to combine the performance characteristics assessed in the lab with those in the field.

6.8 Inadequate Representation of Climate Extremes

Traditional techniques for pavement design might not consider extreme temperatures, heavy rain, and flooding. Climate modeling and scenarios need to be developed in order to assess the impact of these changes on structure performance and maintenance needs.

6.9 Limited Reliability and Life-Cycle Integration

Several pavement design methods use deterministic forecasting, which overlooks the elements of uncertainty and future maintenance costs. Combining probabilistic reliability analysis with life cycle cost analysis may help make economic and sustainable decisions regarding pavement design.

6.10 Data Governance and Explainable AI

A pavement management system in the digital age needs reliable database information, standardized data collection methodologies, and transparent analytical models. Predictive analysis based on AI systems needs to be independently validated and benchmarked against the existing mechanistic-empirical approaches [27].

Table 3: Priority Research Gaps and Recommended Directions [28]

Research Priority	Recommended Approach	Expected Practical Benefit
Regional calibration	Long-term monitoring and field validation	Improved prediction accuracy
Climate resilience	Temperature, moisture, and flood modelling	Reduced environmental deterioration
Material performance	Integration of laboratory and field testing	Improved material selection
Reliability and cost	Probabilistic life-cycle optimisation	Cost-effective design decisions
Digital validation	Explainable AI and M–E model integration	Reliable performance forecasting

Table 3 highlights the key areas where research is needed for improving the design of flexible pavements. The following areas of regional calibration, climate resiliency, material performance, reliability assessment, and digital tools have been identified as significant research avenues.

6.11 Critical Discussion

Comparative analysis reveals that the effectiveness of flexible pavement design relies on material properties, traffic loading, environment, and model calibration. While the mechanistic–empirical method provides precise structure calculations, its accuracy is conditional on reliable input data and deterioration modeling validation. Performance approach is better at predicting the service life but requires a lot of performance data and uncertainty assessment [29].

Regional peculiarities play a major role in choosing the appropriate design method. Empirical design approaches stay applicable for designing low volume roads, while mechanistic–empirical design is more precise when dealing with highly loaded pavements [30]. Performance approach is especially useful when the long-term reliability of pavements, optimization of maintenance, and cost estimation are needed.

For future pavement design, it is necessary to combine laboratory tests, field monitoring, structural modeling, and artificial intelligence. Climate-resistant materials and reliability-based assessment may be added to these approaches.

7. CONCLUSION

The review explored different methodologies for designing flexible pavements including empirical, mechanistic-empirical, and performance-based designs. Empirical design techniques give simple and economic solutions but lack flexibility in diverse situations. Mechanistic-empirical designs give more accurate structural analysis and prediction of distresses; however, the effectiveness of these models relies on accurate input values and regional calibration of the model. Performance-based design technique gives reliability and durability considerations for sustainable pavement design. The choice of methodology will depend on the traffic condition, resource availability, and performance considerations among others. Future research needs to focus on designing climate resilient pavements, regional calibration, testing of materials, and application of artificial intelligence.

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