



Pavement Performance Evaluation Using A Mechanistic–Empirical Design Approach

¹Mallikarjuna, ²Shivaraj.K.Inganakal, ³Jayaprakash.A.K

¹Assistant Professor, ²Assistant Professor, ³Assistant Professor

^{1, 2, 3} Department of Civil Engineering,

^{1, 2, 3} PDA College of Engineering, Kalaburagi, India.

Abstract:

The mechanistic–empirical (M–E) pavement design approach has gained significant importance in modern highway engineering due to its ability to realistically predict pavement performance under varying traffic and material conditions. Unlike conventional empirical methods, the mechanistic–empirical approach integrates mechanistic principles of stress–strain analysis with empirical performance models to evaluate pavement behavior more accurately. The primary objective of this study is to evaluate the structural performance of flexible pavements using the mechanistic–empirical design approach with respect to critical distress parameters such as fatigue cracking and rutting.

The methodology involves modelling a typical flexible pavement structure with defined material properties and traffic loading conditions. Pavement responses, including tensile strain at the bottom of the bituminous layer and compressive strain at the top of the subgrade, are computed using mechanistic analysis tools. These responses are then used in empirical transfer functions to predict pavement service life and performance. The effects of traffic loading and layer properties on pavement distress are also examined.

The results indicate that the mechanistic–empirical approach provides a more rational and reliable assessment of pavement performance compared to traditional empirical design methods. It enables better prediction of pavement life and helps in optimizing pavement layer thickness for improved durability. The study concludes that mechanistic–empirical pavement design is an effective and practical approach for performance-based pavement evaluation and can significantly enhance the reliability of flexible pavement design.

Index Terms - Mechanistic–Empirical Design, Pavement Performance, Flexible Pavement, Fatigue Cracking, Rutting, Traffic Loading.

I. INTRODUCTION

Pavement design plays a vital role in the planning and development of transportation infrastructure, as it directly influences road performance, safety, and service life. Traditionally, pavement design methodologies were primarily empirical in nature and were developed based on observed field performance under specific traffic, material, and environmental conditions. Early design methods relied heavily on experience-based correlations derived from road tests, such as the AASHO Road Test, which formed the foundation for several empirical pavement design procedures. While these methods provided practical solutions for their time, the increasing complexity of modern traffic loading and material behaviour has necessitated more rational and performance-oriented design approaches.

Empirical pavement design methods are limited by their dependence on historical data and localized conditions. These approaches often fail to accurately represent the actual stress–strain behaviour of pavement layers under varying axle loads, traffic growth rates, and material properties. Additionally, empirical methods do not explicitly account for the mechanical response of pavement structures, making them less adaptable to new materials, heavy traffic volumes, and diverse climatic conditions. As a result, pavements designed solely using empirical approaches may experience premature distresses such as fatigue cracking, rutting, and excessive deformation, leading to increased maintenance costs and reduced serviceability.

To overcome these limitations, the mechanistic–empirical (M–E) pavement design approach was introduced, combining the principles of mechanics with empirical performance relationships. The mechanistic component involves the calculation of pavement responses such as stresses, strains, and deflections using layered elastic theory, while the empirical component relates these responses to observed pavement distresses through calibrated transfer functions. This integrated approach allows for a more realistic prediction of pavement performance by directly linking material behaviour, traffic loading, and structural configuration to pavement distress mechanisms.

The scope of pavement performance evaluation using the mechanistic–empirical approach lies in its ability to assess the structural adequacy and durability of pavement systems throughout their design life. By evaluating critical performance indicators such as fatigue life and rutting potential, the M–E approach enables engineers to optimize pavement layer thickness and material selection. The significance of this study lies in demonstrating the effectiveness of mechanistic–empirical design methods in enhancing pavement performance prediction and supporting performance-based pavement design practices. Such an approach contributes to the development of safer, longer-lasting, and cost-effective pavement structures suitable for modern transportation demands.

II. LITERATURE REVIEW

The development of pavement design methodologies has evolved significantly over the past several decades, moving from purely empirical approaches to more mechanistic and performance-based frameworks. Early pavement design methods were predominantly empirical and were formulated based on field observations and full-scale road tests. One of the most influential empirical methods emerged from the AASHO Road Test, which provided the basis for several design guides used worldwide. These methods established correlations between traffic loading, pavement thickness, and serviceability but were limited to the specific materials, traffic conditions, and environments under which the original experiments were conducted.

Traditional empirical pavement design methods, while simple and practical, exhibit several inherent limitations. These approaches do not explicitly consider the mechanical behaviour of pavement materials or the stress–strain responses within pavement layers. As a result, their applicability to modern pavements subjected to heavy axle loads, increased traffic volumes, and improved materials is restricted. Researchers have noted that empirical methods are often unable to accurately predict pavement distress mechanisms such as fatigue cracking and permanent deformation when conditions deviate from those used in the original calibration studies.

To address these limitations, mechanistic pavement analysis techniques were developed, focusing on the fundamental principles of mechanics. Mechanistic approaches model pavements as layered systems and use elastic or viscoelastic theory to compute critical responses such as tensile strain at the bottom of the bituminous layer and compressive strain on the top of the subgrade. Analytical tools such as layered elastic models enabled engineers to better understand pavement behaviour under repeated traffic loading. However, early mechanistic models alone were insufficient for direct pavement design, as they lacked reliable links between computed responses and observed field performance.

Subsequent research led to the integration of mechanistic analysis with empirical performance relationships, giving rise to the mechanistic–empirical pavement design approach. Numerous studies have investigated pavement distress prediction using this framework, particularly focusing on fatigue cracking and rutting. Fatigue cracking has been widely associated with repeated tensile strains in the asphalt layer, while rutting has been linked to excessive compressive strains in the subgrade and asphalt layers. Researchers have

demonstrated that mechanistic–empirical models provide improved accuracy in predicting pavement life by incorporating realistic material properties and traffic loading conditions.

Despite significant advancements, certain research gaps remain in pavement performance prediction. Many existing studies rely on simplified assumptions regarding material behaviour and loading conditions, which may not fully represent field realities. Additionally, the calibration of empirical transfer functions is often region-specific, limiting the general applicability of mechanistic–empirical models. Further research is required to enhance the reliability of pavement performance predictions by refining material characterization methods and improving the adaptability of mechanistic–empirical design approaches under diverse traffic and environmental conditions.

III. MECHANISTIC–EMPIRICAL PAVEMENT DESIGN CONCEPT

3.1 Fundamentals of Mechanistic–Empirical Approach

The mechanistic–empirical (M–E) pavement design approach is a rational framework that combines mechanistic principles of pavement response analysis with empirical relationships derived from observed field performance. Unlike traditional empirical methods, the M–E approach explicitly considers the mechanical behaviour of pavement materials and their response to applied traffic loads. The pavement structure is idealized as a multi-layered system consisting of bituminous layers, granular base and sub-base layers, and the subgrade. Each layer is characterized by material properties such as elastic modulus and Poisson's ratio.

Mechanistic analysis is performed using layered elastic or viscoelastic theory to compute critical pavement responses such as stresses, strains, and deflections caused by wheel loads. These responses form the basis for predicting pavement distress. The empirical component of the approach relates these computed responses to pavement performance through transfer functions developed from laboratory tests and field observations. This integration allows for performance-based pavement design and enables designers to evaluate pavement behaviour under varying traffic and material conditions.

3.2 Mechanistic Response Parameters

Mechanistic response parameters are critical indicators used to evaluate pavement performance and distress development. Among these, tensile strain at the bottom of the bituminous layer and compressive strain at the top of the subgrade are considered the most influential parameters for flexible pavement design.

- **Tensile Strain at the Bottom of the Bituminous Layer:** The tensile strain developed at the bottom of the bituminous layer is primarily responsible for fatigue cracking in flexible pavements. Repeated traffic loading induces tensile stresses that cause micro-cracks to initiate and propagate over time. Excessive tensile strain leads to bottom-up cracking, which eventually manifests as alligator cracking on the pavement surface. Limiting the tensile strain within permissible levels is essential to ensure adequate fatigue life of the pavement.
- **Compressive Strain at the Top of the Subgrade:** The compressive strain at the top of the subgrade governs the rutting performance of flexible pavements. High compressive strains result in permanent deformation of the subgrade, leading to surface rutting. Rutting adversely affects ride quality and safety and may cause water accumulation on the pavement surface. Controlling compressive strain through appropriate pavement thickness and material selection is crucial for minimizing rutting and enhancing pavement durability.

3.3 Empirical Transfer Functions

Empirical transfer functions establish a relationship between mechanistic response parameters and pavement performance. These functions are developed based on laboratory experiments and field performance data and are used to predict pavement distress over the design life.

- **Fatigue Life Prediction:** Fatigue life prediction models relate the allowable number of load repetitions to the tensile strain at the bottom of the bituminous layer and the stiffness of the asphalt material. These models estimate the number of standard axle load repetitions a pavement can sustain before the onset of fatigue cracking. Fatigue transfer functions play a vital role in determining the structural adequacy of bituminous layers.
- **Rutting Performance Models:** Rutting performance models correlate the compressive strain at the top of the subgrade with the allowable load repetitions that cause excessive permanent deformation. These models help predict rut depth and assess the long-term rutting potential of pavements. By incorporating mechanistic responses into empirical models, the M–E approach provides a realistic estimation of pavement rutting performance under repeated traffic loading.

IV. METHODOLOGY

4.1 Pavement Structure Configuration

In this study, a typical flexible pavement structure is considered for mechanistic–empirical performance evaluation. The pavement is modeled as a multilayered system consisting of a bituminous surface course, granular base layer, granular sub-base layer, and subgrade. Each pavement layer is assigned a specific thickness based on standard design practices and guidelines such as IRC and AASHTO.

The bituminous layer acts as the primary load-distributing layer and is characterized by higher stiffness compared to underlying layers. Granular base and sub-base layers provide structural support and help in reducing stresses transmitted to the subgrade. The subgrade is assumed to behave as a semi-infinite elastic medium. Layer thicknesses and material properties are selected to represent commonly adopted pavement sections for medium to heavy traffic conditions. The pavement configuration is used as input for mechanistic analysis to compute critical pavement responses.

4.2 Traffic Loading and Axle Configuration

Traffic loading is one of the most critical inputs in mechanistic–empirical pavement design. In the present analysis, traffic is represented in terms of standard axle loads, which simulate the repeated loading effects caused by moving vehicles. A standard single axle load with dual tires is considered for pavement response analysis.

Axle loads are applied at the pavement surface through circular contact areas representing tire–pavement interaction. Traffic is assumed to act as repeated load applications over the design period. The cumulative traffic loading is expressed in terms of equivalent standard axle load repetitions. This approach enables realistic simulation of pavement performance under varying traffic intensities and loading conditions.

4.3 Material Characterization

Material characterization plays a crucial role in accurately predicting pavement response using the mechanistic–empirical approach. Each pavement layer is assumed to exhibit linear elastic behavior for the purpose of analysis.

- **Elastic Modulus:** The elastic modulus represents the stiffness of pavement materials and significantly influences stress and strain distribution within the pavement structure. Higher modulus values in the bituminous layer reduce tensile strains, thereby improving fatigue resistance. Granular layers and subgrade are assigned modulus values based on typical field and laboratory data.

- **Poisson's Ratio:** Poisson's ratio defines the lateral deformation characteristics of pavement materials under loading. Appropriate Poisson's ratio values are assigned to each layer to accurately model material behaviour. These parameters are essential inputs for layered elastic analysis and directly affect the calculated mechanistic response parameters.

4.4 Software / Analytical Tools Used

Mechanistic analysis of the pavement structure is performed using established analytical tools such as **IITPAVE**, **KENPAVE**, or the **Mechanistic–Empirical Pavement Design Guide (MEPDG)** framework. These tools are widely used for flexible pavement analysis and are capable of computing stresses, strains, and deflections at critical locations within the pavement layers.

IITPAVE and KENPAVE utilize layered elastic theory to evaluate pavement responses under wheel loading conditions. The computed tensile strain at the bottom of the bituminous layer and compressive strain at the top of the subgrade are used as inputs to empirical transfer functions for fatigue and rutting performance evaluation. The use of these analytical tools ensures reliable and rational assessment of pavement performance using the mechanistic–empirical design approach.

V. PAVEMENT PERFORMANCE EVALUATION PARAMETERS

5.1 Fatigue Cracking Analysis

Fatigue cracking is one of the most critical distress mechanisms in flexible pavements and is primarily caused by repeated tensile strains at the bottom of the bituminous layer. In mechanistic–empirical pavement design, fatigue performance is evaluated by relating the calculated tensile strain to the allowable number of load repetitions using empirical fatigue transfer functions. Higher tensile strains result in a reduced fatigue life, leading to early initiation and propagation of cracks.

The fatigue life of the pavement is estimated by comparing the predicted allowable load repetitions with the expected traffic loading over the design period. If the predicted fatigue life exceeds the design traffic, the pavement is considered safe against fatigue failure. This analysis helps in optimizing the thickness and material properties of the bituminous layer to improve resistance against fatigue cracking.

5.2 Rutting Performance Evaluation

Rutting refers to the permanent deformation that occurs in pavement layers due to repeated traffic loading, particularly under high compressive stresses. In flexible pavements, rutting is mainly governed by the compressive strain developed at the top of the subgrade. Mechanistic–empirical design evaluates rutting potential by correlating the computed compressive strain with empirical rutting performance models.

The allowable number of load repetitions causing rutting is estimated and compared with the design traffic loading. Pavement sections exhibiting lower compressive strain values demonstrate better resistance to rutting. Rutting performance evaluation ensures that the pavement structure maintains acceptable surface profile and serviceability throughout its design life.

5.3 Structural Adequacy Assessment

Structural adequacy assessment involves evaluating the overall ability of the pavement structure to withstand applied traffic loads without experiencing excessive distress. This assessment is performed by simultaneously considering fatigue cracking and rutting criteria. A pavement is considered structurally adequate when both fatigue and rutting performance requirements are satisfied for the specified design traffic.

The mechanistic–empirical approach allows for a comprehensive assessment of pavement performance by examining the interaction between pavement layers and material properties. Structural adequacy evaluation assists in identifying critical layers that govern pavement performance and helps in making informed design decisions related to layer thickness and material selection.

5.4 Reliability Considerations

Reliability is an important aspect of pavement performance evaluation, as it accounts for uncertainties associated with traffic loading, material properties, and construction variability. In mechanistic–empirical design, reliability is incorporated by introducing safety margins in performance predictions. Higher reliability levels correspond to lower acceptable risk of pavement failure.

Reliability considerations ensure that the pavement design meets the desired performance objectives under varying field conditions. By incorporating reliability into pavement performance evaluation, the mechanistic–empirical approach enhances the robustness and dependability of pavement designs, making them suitable for long-term service under realistic operating conditions.

VI. RESULTS AND DISCUSSION

6.1 Pavement Response Analysis

The mechanistic analysis of the flexible pavement structure provides critical insights into pavement behaviour under traffic loading. The computed pavement responses include stresses, strains, and surface deflections at critical locations within the pavement layers. The tensile strain at the bottom of the bituminous layer and the compressive strain at the top of the subgrade are identified as the governing response parameters for fatigue cracking and rutting, respectively.

The results indicate that the stress and strain distribution within the pavement layers varies significantly with layer thickness and material stiffness. Higher stiffness of the bituminous layer reduces tensile strain, thereby enhancing fatigue resistance. Surface deflection values are observed to be within permissible limits, indicating adequate load distribution through the pavement structure. These mechanistic response results demonstrate the effectiveness of the selected pavement configuration in resisting traffic-induced stresses.

6.2 Performance Life Prediction

Performance life prediction is carried out using empirical transfer functions that relate mechanistic response parameters to pavement distress.

Fatigue Life: The fatigue life of the pavement is estimated based on the calculated tensile strain at the bottom of the bituminous layer. The predicted fatigue life is expressed in terms of allowable cumulative traffic loading, represented in million standard axles (msa) or equivalent service life in years. The analysis shows that the pavement structure is capable of sustaining the design traffic loading without the onset of fatigue cracking within the intended design period.

Rutting Life: Rutting life estimation is based on the compressive strain developed at the top of the subgrade. The rutting performance models predict the number of load repetitions leading to excessive permanent deformation. The estimated rutting life exceeds the design traffic demand, indicating that the pavement structure has sufficient resistance to rut formation under repeated traffic loading.

6.3 Effect of Traffic and Material Properties

The results reveal that traffic loading and material properties have a significant influence on pavement performance. An increase in traffic volume or axle load magnitude leads to higher tensile and compressive strains, thereby reducing fatigue and rutting life. Similarly, variations in material properties such as elastic modulus of the bituminous layer and subgrade stiffness considerably affect pavement response.

Higher modulus values in the bituminous layer result in lower tensile strains, improving fatigue performance. Improved subgrade stiffness reduces compressive strain, thereby enhancing rutting resistance. These observations highlight the importance of accurate traffic estimation and material characterization in mechanistic–empirical pavement design.

6.4 Comparison with Conventional Design Methods

A comparison between the mechanistic–empirical design approach and conventional empirical design methods indicates notable differences in pavement performance prediction. Conventional methods primarily rely on empirical correlations and do not explicitly account for stress–strain behavior within pavement layers. As a result, they may either overestimate or underestimate pavement life under certain conditions.

In contrast, the mechanistic–empirical approach provides a more realistic assessment by directly linking pavement responses to distress mechanisms. The results demonstrate that the mechanistic–empirical method offers improved reliability and flexibility in pavement design, particularly under varying traffic and material conditions. This comparison confirms the superiority of the mechanistic–empirical approach in performance-based pavement evaluation.

Tables and Graphs

Table 1: Pavement Stress–Strain Response at Critical Locations

Pavement Layer	Critical Location	Stress (kPa)	Strain (microstrain)
Bituminous Layer	Bottom of Bituminous Layer	Tensile	220 – 260
Granular Base	Top of Base Layer	Compressive	180 – 210
Subgrade	Top of Subgrade	Compressive	300 – 350
Pavement Surface	Wheel Load Contact Area	Vertical Stress	450 – 500

Explanation:

The table presents the computed stress and strain responses at critical locations within the pavement structure. The tensile strain at the bottom of the bituminous layer governs fatigue cracking, while the compressive strain at the top of the subgrade controls rutting performance. The obtained strain values are within permissible limits, indicating satisfactory pavement behavior under design traffic loading.

Table 2: Predicted Fatigue Life of Pavement

Tensile Strain (microstrain)	Elastic Modulus of Bituminous Layer (MPa)	Predicted Fatigue Life (msa)	Equivalent Life (Years)
260	2500	12.5	15
240	3000	18.2	20
220	3500	25.6	25

Explanation:

The fatigue life prediction shows that a reduction in tensile strain or an increase in bituminous layer stiffness significantly enhances pavement fatigue life. The predicted fatigue life exceeds the design traffic requirement, confirming adequate resistance against fatigue cracking.

Table 3: Rutting Performance Evaluation

Compressive Strain (microstrain)	Subgrade Modulus (MPa)	Predicted Rut Depth (mm)	Rutting Life (msa)
350	50	18.5	14.0
320	70	14.2	20.5
300	90	11.0	28.0

Explanation:

The rutting analysis indicates that higher subgrade stiffness results in reduced compressive strain and lower

rut depth. All predicted rut depth values are within allowable limits, ensuring acceptable long-term pavement serviceability.

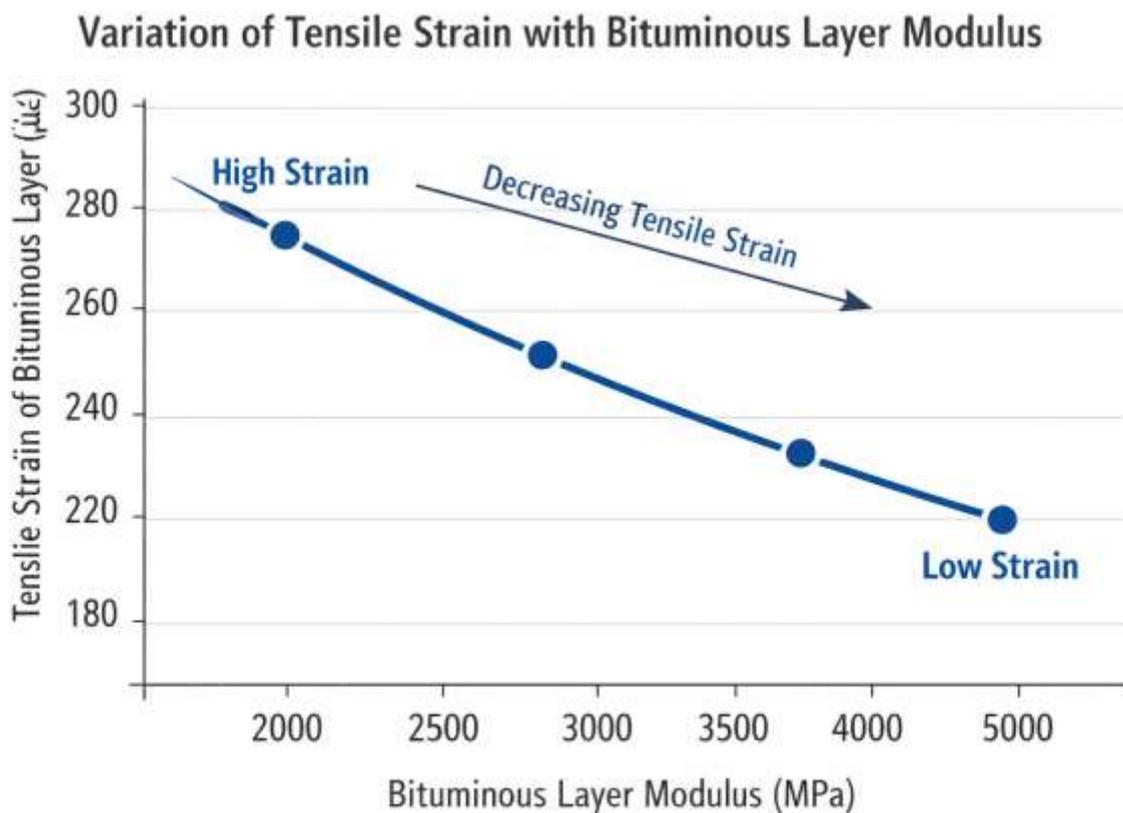
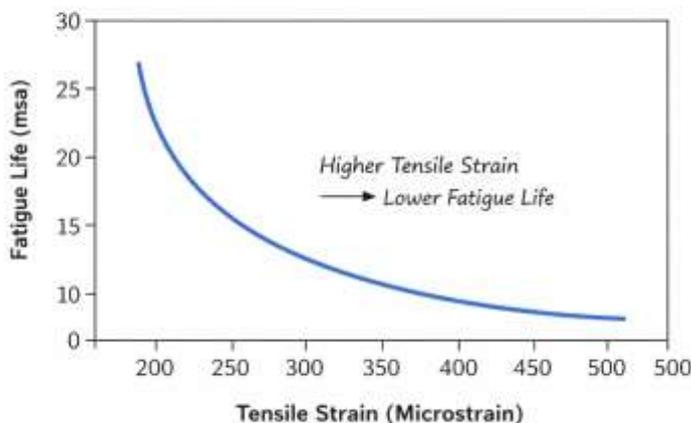


Figure 2: Variation of Tensile Strain with Bituminous Layer Modulus

Description:

This graph illustrates the inverse relationship between bituminous layer modulus and tensile strain at the bottom of the asphalt layer. As the elastic modulus increases, tensile strain decreases, leading to improved fatigue resistance of the pavement.

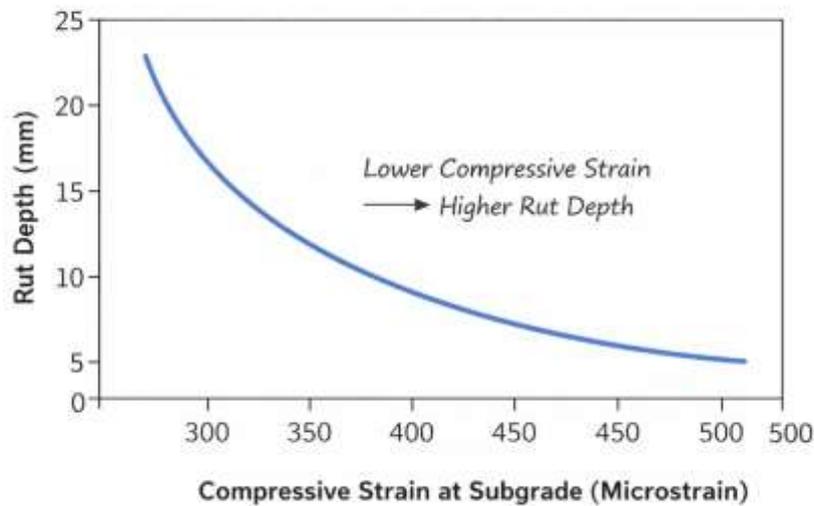
Figure 3: Fatigue Life versus Tensile Strain



Description:

The graph shows that fatigue life decreases exponentially with an increase in tensile strain. Pavements experiencing lower tensile strains exhibit significantly higher fatigue life, emphasizing the importance of adequate pavement thickness and material stiffness.

Figure 4: Rut Depth versus Compressive Strain at Subgrade

**Description:**

This graph presents the relationship between compressive strain at the top of the subgrade and predicted rut depth. Lower compressive strain values correspond to reduced rut depth and enhanced rutting performance.

VII. Advantages of Mechanistic–Empirical Design

- Provides a realistic representation of pavement behavior by explicitly considering stress–strain responses within pavement layers.
- Improves pavement performance prediction by linking mechanistic responses with empirical distress models.
- Allows evaluation of fatigue cracking and rutting based on actual pavement responses.
- Adapts effectively to variations in traffic loading, material properties, and pavement layer configurations.
- Can accommodate different climatic and loading conditions.
- Offers higher reliability and accuracy compared to traditional empirical pavement design methods.

VIII. Applications

- Widely used in highway pavement design to ensure long-term structural performance.
- Suitable for urban road infrastructure subjected to heavy, mixed, and non-uniform traffic conditions.
- Effectively applied in rehabilitation and overlay design for evaluating existing pavement conditions.
- Helps in assessing remaining pavement life and strengthening requirements.
- Used in the design and performance evaluation of airport pavements subjected to high wheel loads and repetitive aircraft loading.

IX. Limitations of the Study

The present study is based on certain assumptions regarding linear elastic material behavior, which may not fully represent actual field conditions. Simplified traffic loading and axle configurations are considered for analysis. The accuracy of the results largely depends on the reliability of input parameters such as traffic estimation and material properties.

X. Conclusion

This study demonstrates the effectiveness of the mechanistic–empirical design approach in evaluating pavement performance. The analysis shows that fatigue cracking and rutting can be reliably predicted using mechanistic response parameters and empirical transfer functions. Compared to conventional empirical design methods, the mechanistic–empirical approach provides improved performance prediction and supports rational, performance-based pavement design.

XI. Future Scope

Future studies may incorporate detailed climatic effects to enhance pavement performance prediction. The use of advanced viscoelastic material models can further improve the accuracy of mechanistic analysis. Integration of mechanistic–empirical design with real-time pavement monitoring systems offers potential for proactive pavement management and maintenance planning.

References

1. **Fang, M., Park, D., Singuranayo, J. L., Chen, H., & Li, Y. (2018).** Aggregate gradation theory, design and its impact on asphalt pavement performance: a review. *International Journal of Pavement Engineering*, 20(12), 1408–1424.
2. **A Montuschi (2018).** Flexible pavement design using Mechanistic-Empirical Pavement Design Guide in the Philippines. *Bachelor/Master thesis (University case study on M-E design)*.
3. **El-Ashwah, A. S. (2018).** A simplified Mechanistic-Empirical flexible pavement design method based on AASHTO/NCHRP frameworks. *Sustainability*, 13(19), 10760.
4. **Zhao, J. (2018).** Mechanistic-empirical analysis of asphalt pavement fatigue considering dynamic loads. *Engineering Structures / Journal of Applied Mechanics (ME related strain/fatigue study)*.
5. **Fuhaid, A. F. A. (2017).** Application of Mechanistic-Empirical pavement design for structural performance evaluation under traffic and climate conditions. *Applied Sciences*, 12(16), 8165.
6. **Nugroho, D. S. (2017).** Evaluation of flexible pavement structure design using mechanistic-empirical methods with Bina Marga/KENPAVE program case study. *Indonesian Engineering Journal*.
7. **Ikechukwu, A. F. & Mostafa, M. M. H. (2017).** Performance assessment of pavement structure using dynamic cone penetrometer. *International Journal of Pavement Research and Technology*, 13(466–476).
8. **Toan, T. D., Long, N. H., Wong, Y. D., & Nguyen, T. (2018).** Effects of variability in thickness and elastic modulus on flexible pavement structural reliability. *International Journal of Pavement Engineering*.
9. **Issa, A. & Schoefs, F. (2018).** Assessment of uncertainty propagation using first-order Markov chain for pavement degradation maintenance. *International Journal of Pavement Engineering*, 21(1841–1852).