RHEOLOGICAL MODELLING OF FLEXIBLE PAVEMENT MATERIALS USING ADVANCED FINITE ELEMENT METHODS FOR THE DEVELOPMENT OF A MECHANISTIC-EMPIRICAL DESIGN APPROACH.

E.B.Joldasbaev,
S.Q. Raximov.
Tashkent state transport university,
Tashkent, Uzbekistan

Abstract: Flexible pavements are composed of layered materials, including an asphalt concrete surface, unbound granular base and subbase, and a subgrade. Each layer has distinct mechanical characteristics, making the structural response to traffic loading highly complex. Accurate modelling of these materials is essential for reliable pavement performance predictions. The Mechanistic-Empirical (ME) design method addresses this complexity by combining mechanical analysis with empirical performance models. Constitutive models are used to simulate stresses, strains, and displacements, which are then linked to pavement deterioration through transfer functions. This article critically reviews current pavement design methodologies, emphasizing differences across international standards. Modelling approaches are classified into analytical, experimental, and numerical categories, with a particular focus on finite element modelling of unbound granular materials (UGMs). The finite element method (FEM) is applied as a numerical tool for simulating pavement behavior. The main objective is to develop a refined modelling approach using FEM, supported by advanced rheological characterization of flexible pavement materials.

Keywords: *Ring and Ball Test, Softening Point of Bitumen, Rheological properties*

1. Introduction

The history of pavement construction traces back to the earliest civilizations, where societies such as the Persians and Romans developed innovative techniques to enhance roadway durability and functionality. In the modern era, pavement engineering has evolved significantly with the widespread use of materials like asphalt and cement, leading to the dominance of flexible pavement systems in transportation infrastructure. Among these, the layered flexible pavement structure remains one of the most common due to its adaptability, cost-effectiveness, and performance.[1]

This structure typically consists of an asphalt concrete (AC) surface layer supported by granular base and subbase layers, which distribute the traffic load to the underlying subgrade. Each layer is composed of materials with distinct mechanical behaviors: asphalt concrete exhibits viscoelastic properties influenced by temperature, aging, and loading rate, while the granular layers derive strength primarily through

interparticle friction. The subgrade, highly variable in geotechnical quality, may range from soft, cohesive soils to stiff, elastic rock formations.[2]

The complexity of flexible pavement lies in the interaction among these heterogeneous layers under repeated traffic loading. As a result, the overall pavement response cannot be captured by examining individual layers in isolation. A comprehensive understanding of the multilayered system's mechanical interaction is essential for reliable design.

Historically, pavement design began with empirical methods based on observed field performance. However, limitations in scalability and adaptability led to the development of more advanced techniques. The Mechanistic-Empirical (ME) design approach emerged to bridge the gap between observed performance and theoretical modeling. In this method, constitutive models are applied to simulate the pavement's mechanical response—stress, strain, and deformation—which are then linked to long-term performance predictions through empirical transfer functions.[3]

This article aims to explore the complexity of flexible pavement behavior through the lens of advanced modelling, with a particular focus on the application of constitutive models and the finite element method. By integrating rheological characterization and numerical simulation, this study contributes to the development of more accurate and efficient pavement design methodologies.

Finite element software such as ABAQUS and ANSYS offer advanced built-in constitutive models to simulate nonlinear elastic behavior. However, these models are primarily formulated based on strain-dependent behavior, which poses limitations when modeling unbound granular materials (UGMs)—a key component in flexible pavement structures. As highlighted in the background, UGMs respond predominantly to stress conditions rather than strain, making conventional models insufficient for capturing their true mechanical performance. To address this gap, there is a need for user-defined constitutive models that better reflect the stress-dependent nature of these materials.

The core aim of this study is to develop and implement a nonlinear elastic-plastic model that accurately represents the behavior of UGMs, incorporating stress dependency and shakedown characteristics in line with the Mohr-Coulomb failure criterion. The research also considers the dynamic interaction between asphalt and granular layers under traffic loading to ensure a more realistic representation of pavement behavior.

By integrating these advanced material models into finite element simulations, this work seeks to improve the predictive capability of pavement design tools. Ultimately, the goal is to support the evolution of mechanistic-empirical design

methods, enabling more accurate, efficient, and performance-oriented pavement solutions.

This article presents a systematic literature review on the modeling of unbound granular materials (UGMs) in flexible pavement structures. It critically examines both experimental and numerical approaches to provide a comprehensive scientific foundation for future research. Special attention is given to the nonlinear stress-dependent behavior of UGMs and the application of shakedown theory in pavement analysis. The review aims to identify current limitations in modeling techniques and highlight opportunities for developing more realistic and reliable constitutive models to improve mechanistic-empirical pavement design practices.

Early pavement design was mainly based on empirical methods, relying on experience and observation rather than scientific analysis. Before the 1920s, important factors like the effect of subgrade soil on pavement thickness were largely overlooked (Huang, 2004). This approach became insufficient as heavier vehicles appeared after World War II, causing many pavements designed by these empirical methods to fail.

A major advancement came in 1961 when the American Association of State Highway Officials (AASHTO) carried out a full-scale road test. This test provided crucial data that led to improved pavement design methods. The results helped shift pavement engineering from purely empirical rules to mechanistic-empirical approaches that better predict pavement performance.

Since then, growing traffic demands and technological progress in the U.S. have further refined these design procedures, making them more accurate and reliable for various conditions.

2.Methodology

Flexible pavement design primarily follows two approaches: the earlier-developed empirical method and the more recent mechanistic-empirical method.

Empirical pavement design methods trace back to 1929 with the establishment of soil classification concepts (Huang, 2004). This foundation was further refined into the group index method, now known as the AASHTO soil classification system. In this system, soils and granular subgrade materials are categorized from A-1 to A-7, with each classification guiding specific applications and considerations in road construction.

The influence of soil strength on pavement thickness was incorporated through the development of the California Bearing Ratio (CBR) test. The CBR measures the resistance of a subgrade soil to penetration relative to the resistance of crushed rock under the same conditions, providing a practical index for assessing subgrade support in pavement design.

2.1. Empirical design

Empirical pavement design methods based on the California Bearing Ratio (CBR) establish a relationship between the required pavement thickness, the CBR value, and predicted traffic loads measured as equivalent standard axles (ESA). According to AASHTO (Bodhinayake, 2008), the ESA is calculated by raising the ratio of the single axle load to 80 kN to the fourth power.

A comparable method is presented in Austroads (2004), where a design chart enables engineers to estimate pavement thickness using ESA and CBR values, as shown in Figure 2.2.

While empirical methods have been widely used, they have inherent limitations. These methods rely primarily on field observations and do not fully capture the mechanical behavior of pavement materials. This restricts their reliability when applied to new or varying conditions. Additionally, empirical approaches are limited in accounting for different loading scenarios, environmental influences, and material variations.

As a result, there is an increasing demand for more scientifically robust design methods that combine laboratory data with analytical models. Such approaches can provide more accurate and adaptable pavement designs across a wider range of conditions.

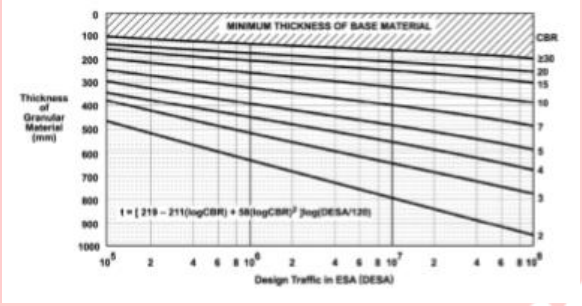


Figure 1. Thickness Design Chart (from Figure 8.4, AUSTROADS 2004)

2.2. Mechanistic Empirical Design

The mechanistic-empirical (ME) design method is a more recent approach that blends mechanical principles with empirical observations to improve pavement design. In this method, the pavement's response—expressed through stress, strain, and displacement—is first calculated by solving the layered pavement system using mechanical models. These key values are then plugged into empirical formulas that relate them to actual pavement performance, with the ultimate goal of creating longer-lasting and more reliable pavements.

The ME approach uses fundamental mechanical concepts like continuity, equilibrium, and the principle of virtual work applied to a layered pavement structure. The materials in each layer are modeled using different behaviors, including elasticity, plasticity, and viscoelasticity. The design process typically involves two main steps. First, the pavement structure is analyzed using either analytical or numerical methods such as finite element analysis, with materials modeled by elastic, nonlinear elastic, or

elastoplastic models like von Mises or Mohr-Coulomb criteria. Next, the critical stresses and strains obtained from these calculations are used in empirical relationships to predict performance issues such as rutting, cracking, and fatigue life. Commonly used indicators include tensile strain at the bottom of the asphalt layer and vertical compressive strain at the top of the subgrade.

Both empirical and ME methods aim to design pavements that can withstand a specific number of load cycles while maintaining serviceability. Serviceability is measured by limiting critical distress modes, primarily fatigue cracking and rutting. Fatigue cracking, often called alligator cracking due to its distinctive pattern, starts at the bottom of the asphalt layer because of high tensile strains and propagates upward under repeated traffic loading, eventually forming interconnected cracks resembling an alligator's skin. Figure 2.3 shows a typical example of this kind of damage.



Figure 2. Fatigue Cracking (Nicholson Road WA, Picture is provided by Colin Leek)

It's important to note that fatigue failure in testing is usually defined as the number of load cycles at which the sample ultimately fails. However, this number can vary depending on test conditions, such as the type of loading used (Al-Khateeb and Shenoy, 2004). Some studies have considered complete fracture of the sample as the failure point in stress-controlled tests (Pell and Cooper, 1975; Tayebali, Rowe, and Sousa, 1992). On the other hand, Rowe (1993) proposed a different failure criterion aimed at protecting the testing equipment. According to his approach, failure occurs when the specimen's stiffness drops by 90% at the location of the largest crack. This shifted the focus from total fracture to crack initiation as a more practical definition of fatigue failure. Despite various proposals, the exact definition of fatigue failure from tests remains debated. One interesting method by Ghuzlan and Carpenter (2000) defines failure based on changes in the energy dissipated between consecutive load cycles. More recently, Nega et al. (2013a) explored different ways to characterize fatigue performance in wheel assemblies.

Another common distress in flexible pavements is rutting, which appears as surface depressions in the wheel paths (see Figure 2.4). Sometimes, you can see slight uplift along the edges of these ruts. Rutting mainly happens due to permanent deformation within the pavement layers or the subgrade below. The subgrade is especially

vulnerable to repeated traffic loads, which can cause consolidation, shear failure, or other types of movement that result in permanent deformation. Asphalt layers can also contribute to rutting if they undergo plastic deformation, especially when they haven't been properly compacted or are exposed to high temperatures. Severe rutting can seriously reduce the pavement's serviceability and may lead to early failure of the whole pavement system (Huang, 2004).



Figure 3. Rut Failure (Nicholson Road WA, Picture is provided by Colin Leek)

As previously discussed, the mechanistic-empirical (ME) method involves calculating the stress and strain responses of pavement materials under vehicle loading. To understand this, consider a small cubic element within the pavement structure. When a tire applies pressure on the surface, stresses develop on all faces of this element. For the element to remain in equilibrium, the stresses acting on opposite faces must be equal in magnitude but opposite in direction. These stresses are categorized into two types: normal stresses, which act perpendicular to the surface, and shear stresses, which act parallel to the surface.

The stresses cause the material to deform, resulting in strains that correspond to the direction and type of applied stress. Similarly, strain is divided into normal strain, representing changes in length along the direction of stress, and shear strain, which relates to angular distortions.

In continuum mechanics, the relationship between stress and strain depends on the material's behavior. In the simplest case, assuming linear elasticity, this relationship can be described mathematically, linking stress directly to strain through material properties.

$$\sigma = E\varepsilon$$
$$\tau = G\gamma \quad (1)$$

Where E and G are Young and shear modulus, respectively.

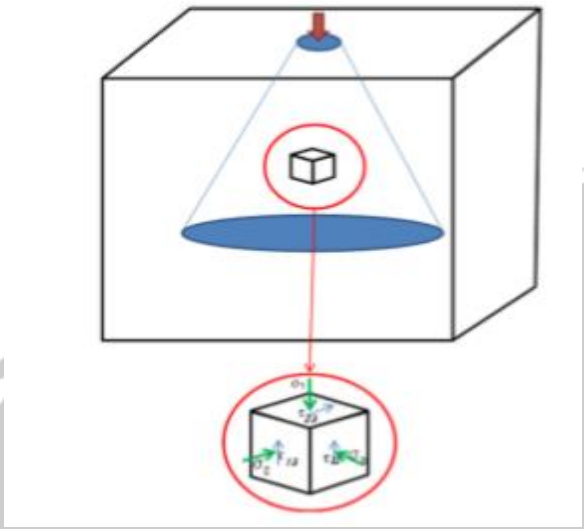


Figure 4. Induced Stress under Wheel Load

A simple way to analyze how flexible pavement responds to tire pressure is to model the pavement system as a homogeneous half-space. This means imagining a space bounded by a surface plane—where the tire load is applied—and extending infinitely in the horizontal directions and downward.

In this context, Boussinesq's theory can be used to calculate the stresses and strains beneath a concentrated load applied on the surface of an elastic half-space. By integrating this solution over a circular area, it effectively represents the tire's contact area. To improve this analysis, Burmister and colleagues developed a solution for layered systems, where the half-space is made up of several surface layers resting on a semi-infinite base. This layered solution serves as a foundational analytical approach to predict the mechanical response of flexible pavements.

Given these points, it becomes essential to carefully select appropriate material models for each pavement layer, as the chosen model directly influences the accuracy of the mechanistic response.

The asphalt layer, being the top and strongest layer that carries the load, is typically modeled in one of three ways: as elastic, viscoelastic, or viscoelastoplastic. The elastic model assumes a straightforward linear relationship between stress and strain. In viscoelastic models, the material exhibits time-dependent strain under constant stress, capturing the asphalt's viscous behavior. Common models used to describe this include the Kelvin and Maxwell models. More advanced approaches consider viscoelastoplastic behavior, which accounts for both time-dependent deformation and permanent changes in shape. Research on hot mix asphalt, particularly used in flexible pavements in Western Australia, has further explored these material characteristics and their specific properties.

3.Discussion

This review highlights the significant evolution of pavement design methodologies, moving from early empirical approaches grounded primarily in observation and experience to the more sophisticated mechanistic-empirical (ME) framework that integrates fundamental engineering principles with empirical evidence. Historically, empirical methods, such as those based on soil classification systems and the California Bearing Ratio (CBR), provided practical solutions for pavement thickness design. However, these methods exhibit inherent limitations, notably their heavy reliance on historical data and their inability to fully capture the complex mechanical behavior of pavement materials under varying load and environmental conditions.

The ME approach addresses these limitations by combining mechanical analysis with empirical correlations. This method enables the calculation of stresses, strains, and displacements within pavement layers, which are then linked to performance indicators such as fatigue cracking and rutting. The ability to incorporate material models ranging from elastic to viscoelastic and viscoplastic behavior allows for a more accurate representation of pavement responses over time. Consequently, ME design offers improved predictive capabilities and adaptability to diverse pavement structures and loading scenarios.

Furthermore, the layered nature of flexible pavements necessitates precise material modeling for each stratum. Solutions such as Burmister's layered elastic theory provide a foundational analytical framework, though the accuracy of pavement response predictions ultimately depends on the selection of appropriate material models. Advances in characterizing hot mix asphalt and granular subgrade materials have been crucial in refining these models.

Fatigue cracking and rutting remain the primary distress modes affecting flexible pavements. Fatigue initiates at the bottom of the asphalt layer due to tensile stresses and propagates upwards, resulting in interconnected cracking patterns commonly referred to as alligator cracking. Rutting manifests as surface depressions in wheel paths caused by permanent deformations in the asphalt layer or underlying subgrade. Despite extensive research, the definition of fatigue failure varies across testing methods, indicating an ongoing need for standardized failure criteria.

In conclusion, the integration of improved material characterization and mechanistic modeling within the ME framework represents a critical advancement in pavement design. These developments enable more reliable, durable, and context-sensitive pavement structures capable of withstanding modern traffic demands and environmental challenges.

Conclusion

Pavement design has transitioned from traditional empirical approaches to the mechanistic-empirical method, which offers a more rigorous and scientifically grounded framework. While empirical methods such as those based on CBR provided foundational guidelines, their limitations in addressing complex material behavior and varying conditions have become increasingly apparent.

The mechanistic-empirical approach enhances pavement design by calculating internal stresses and strains and relating them to pavement distress mechanisms. This integration allows for more precise prediction of fatigue cracking and rutting, thereby facilitating the design of longer-lasting and more resilient pavements.

Central to the success of this method is the accurate representation of material behavior across different pavement layers. Asphalt materials exhibit elastic, viscoelastic, and viscoplastic characteristics that must be adequately modeled, while granular materials require consideration of their nonlinear and time-dependent responses.

Future research should continue to refine these material models and incorporate them into advanced mechanistic frameworks to further improve design accuracy. Ultimately, the adoption of these scientifically informed methods will contribute to the development of pavement systems that better withstand the demands of traffic loading and environmental variability, promoting sustainable and cost-effective infrastructure solutions.

References.

1. American Association of State Highways and Transportation Officials (AASHTO). 1986. Guide for the Design of Pavement Structures. Washington D.C.: American Association of State Highways and Transportation Officials.
2. --------. 2002. Guide for Mechanistic Empirical Design of New and Rehabilitated Pavement Structure. Washington D.C.: American Association of State Highways and Transportation Officials.
3. Adu-Osei, A., D. N. Little, and R. L. Lytton. 2001. Cross-anisotropic Characterization of Unbound Granular Materials. Transportation Research Record: Journal of the Transportation Research Board 1757 (1): 82-91.
4. Ahmed, S. B., and H. G. Larew. 1962. A Study of the Repeated Load Strength Moduli of Soils. 1962, International Conference on the Structural Design of Asphalt Pavements. 203(1).
5. Al-Khateeb, G., and A. Shenoy. 2004. A Distinctive Fatigue Failure Criterion. Journal of the Association of Asphalt Paving Technologists 73: 585-622.
6. Al-Qadi, I. L., M. A. Elseifi, and P. J. Yoo. 2004. In-situ Validation of Mechanistic Pavement Finite Element Modeling. In Proc. 2nd Int. Conf. on Accelerated Pavement Testing, 2004.

7. Al-Qadi, I. L., H. Wang, and E. Tutumluer. 2010. Dynamic Analysis of Thin Asphalt Pavements by Using Cross-Anisotropic Stress-Dependent Properties for Granular Layer. Transportation Research Record: Journal of the Transportation Research Board 2154 (1): 156-163.
8. Allou, F., C. Chazallon, and P. Hornych. 2007. A Numerical Model for Flexible Pavements Rut Depth Evolution with Time. International Journal for Numerical and Analytical Methods in Geomechanics 31 (1): 1-22.
9. Allou, F., C. Petit, C. Chazallon, and P. Hornych. 2009. Influence Of The Macroscopic Cohesion On The 3D FE Modeling Of A Flexible Pavement Rut Depth. Bearing Capacity of Roads, Railways and Airfields. 8th International Conference (BCR2A'09).
10. Araya, A. A., M. Huurman, L. J. Houben, and A. A. Molenaar. 2011., Characterizing Mechanical Behavior of Unbound Granular Materials for Pavements. Transportation Research Board 90th Annual Meeting. No. 11-0407.
11. Araya, A. A., M. Huurman, A. A. Molenaar, and L. J. Houben. 2012. Investigation of the Resilient Behavior of Granular Base Materials with Simple Test Apparatus. Materials and Structures 45 (5): 695-705.
12. Arnold, G., D. Alabaster, and B. Steven. 2001. Prediction of Pavement Performance from Repeat Load Tri-axial (RLT) Tests on Granular Materials. PLACE OF PUBLICATION: PUBLISHER.
13. Attia, M., and M. Abdelrahman. 2011. Effect of State of Stress on the Resilient Modulus of Base Layer Containing Reclaimed Asphalt Pavement. Road Materials and Pavement Design 12 (1): 79-97.
14. Austroads. 2004. Pavement Design – A Guide to the Structural Design of Road Pavements. Sydney, Australia: Austroads.