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Roadway Pavement Design Methods, Structural Approaches and Relevant Computer Algorithms: A Critical Review

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Abstract: Transport and international agencies invest millions of dollars on road projects to support countries develop their infrastructure; therefore, it is important to ensure longer service life and value for money. The primary function of the pavement structure is to keep distresses, including fatigue cracking and permanent deformation, to an acceptable limit so that the pavement can withstand applied vehicle load and repetitions during the service duration. Furthermore, the layered structure of the pavement is intended to ensure that the vehicle contact pressure is distributed in such a way that critical responses at the bottom layer of the pavement are low enough to avoid severe damage. Two typical procedures associated with roadway pavement design are empirical-based and structural analysis methods. However, the empirical-based methods have significant shortcomings, as predicting the mode and extent of pavement performance becomes a major challenge. Alternatively, the structural analysis methods have advanced extensively with computers since they consider crucial factors such as traffic loads, material characteristics and environmental conditions. The imputation of these parameters into the computer algorithm contributes to a better understanding of the mechanical performance of constituent pavement material responses. The predicted responses enable highway engineers to select appropriate pavement compositions that will deteriorate at a satisfactory level during the time of service. The most common structural analysis approaches are analytical modelling and numerical simulation. On the other hand, differences in analysis results generation using these approaches have been a notable concern. This review article presents a synopsis of typical pavement design methods and the problem connected with them; structural approaches to identify factors influencing their accuracy. Furthermore, computer algorithms use due to their usefulness, and the assumptions of layered theories employed in pavement structural design are discussed to uncover potential drawbacks for future upgrades.

Keywords: Highway Pavements, Design Methods, Structural Approaches, Computer Algorithms, Pavement Distresses

1. Introduction

Several transport agencies employ a variety of pavement design methods. However, two typical procedures used for pavement design are empirical-based and structural analysis methods. The empirical methods include experience-based, design charts, and AASHTO design procedures, while the structural methods include analytical and numerical approaches with computer algorithms [1-3]. The empirical methods are mainly based on experience and simple correlations between traffic loading, subgrade soil and pavement performance evaluation observation developed from the AASHO Road Test [4, 5]. Using these methods, the selection of pavement composition has raised concerns since they ignore critical factors such as pavement layer material properties and distress interpolations [6].

Meanwhile, the structural methods have become a bridge that supports the empirical methods. Despite its complexity and challenges, it has emerged as a potential method for pavement structural design due to its approximate solution outputs and, more importantly, evaluating pavement performance based on mechanistic interpretations [7, 8]. On the other hand, the difference in outputs applying the structural methods have pushed researchers to develop various computer algorithms to fit local conditions. The structural approaches using computer algorithms involve analytical modelling (close-form) and numerical analysis (FEM) [9]. Both approaches result in a short and long computing time with comparative differences. As a result, the most pressing issue is to employ the appropriate computer algorithm that produces more rational results for highway and pavement engineers.

The article review defines pavement design methodologies, concepts, benefits, and pavement composition selection problems. The second portion delves into the two most common structural approaches and the factors affecting their correctness. The last part includes a brief discussion of the contribution among several widely used computer algorithms and the layered theories employed in pavement design, and perhaps some shortcomings that could be improved to make pavement analysis more accurate.

2. Methods of Pavement Design

Various transport agencies have developed methods to design flexible and rigid pavements. These procedures are both basic and advanced. However, there are two typical pavement design methods: empirical and structural. The empirical methods have been identified to have drawbacks due to the inability to explain the mechanical behavior of pavement performance. At the same time, the structural methods involve estimating the thickness of pavement layers based on pavement responses; as such, it becomes possible to predict the severity of traffic load and environment-related failures, including fatigue cracking and permanent deformation.

2.1. Empirical Methods

2.1.1. Experience Based Approach

Some road agencies have adopted the concept of pavement sections design based on road categories/types. Such standard is primarily based on previous experience and does not apply to environmental conditions [10]. Several agencies have used this method for longer because of its simplicity and lack of study and design costs. The reliability and evaluation of pavement performance of this kind of concept may not be dependable. The method does not identify important factors that influence pavement behavior. On the other hand, if traffic conditions and other conditions change, there is no way to alter the design, which happens to be a significant disadvantage [11].

2.1.2. Soil and Traffic Based (Design Chart) Approach

The design chart approach relies on empirical correlations between the required pavement thickness and soil classification and simple strength tests, such as the California Bearing Ratio (CBR). This approach is widely used since it implies that the prepared subgrade takes most of the traffic load, while pavement layers are primarily for smoothness and dust control. Similar to the previous approach, this method is simple, have low design costs, and is reliable under certain conditions. The disadvantage of this method does not recognize the varying serviceability and associated pavement factors [11]. The chart shows the thicknesses of the pavement composition about traffic data in equivalent single axle load known as ESAL for short and the California bearing ratio commonly known as CBR value of the subgrade layer [12]. Nevertheless, pavement performance concerning responses becomes a major outstanding problem since pavement composition and layer type depends on only two factors (subgrade strength and traffic information).

2.1.3. AASHTO 1993 Pavement Design Approach

Road tests study by the American Association of State Highway Official (AASHO) in the late 1950s formed the foundation for most pavement design approaches used in many countries today [13, 14]. The test track involved the full-scale pavement sections considering different categories of load spectrums. The AASHTO Interim Guide for Designing Flexible and Rigid Pavements, first published in 1961, modified in 1972, and finally authorized in 1993, was mainly based on the experience of analyzing well-performing and poorly-performing pavements. The relationship between traffic loading and pavement performance obtained from the AASHO road test simulation in the United States and linking it to other countries has been inadequate. Importantly, this method has served as the basis for approximating pavement structural numbers typical known as SN [15, 16]. However, because of other factors, some road transport agencies worldwide have used different methods to design flexible and rigid pavements throughout the years, to suit their local conditions rather than solely relying on the AASHTO 1993 Structural Design Guide, which is highly valued.

2.2. Structural Methods

These methods are more fundamental than all others because they use computer algorithms to calculate principal pavement structural responses. The primary goal of pavements is to reduce tensions on the subgrade so that the prepared subgrade does not deform due to traffic and environmental conditions. Rutting or permanent deformation in the wheel path and fatigue cracking are examples of pavement distress associated with axle load and temperature variance [17, 18]. These failure modes are then simulated as critical pavement responses (strains). They are further used to determine other permissible parameters, including fatigue and rutting design life, maximum damage, pavement life span concerning the number of years. The highway designer can evaluate the pavement compositions and layer thicknesses for a particular road category so that the pavement would last for the expected design period without rapid distresses. This method also incorporates a portion of the empirical phenomenon on a small scale [11, 19].

3. Structural Approaches

The load-carrying capacity of pavements is determined primarily by distributing surface stresses in the underlying layers over an increasingly broader area in the analysis and design. The layering enables the computation of structural responses based on analytical solutions and numerical simulations (1D, 2D, and 3D), respectively [20]. These approaches have provided engineers with a convenient and often highly accurate solution to pavement structures. Boussinesq vertical stress and vertical stress coefficient, Burmister stress theory, Westergaard equations, and the FEM ideas have aided in analyzing and designing pavements [21, 22]. These principles and theories depict a pavement system with single to many finite-thickness layers such as the asphalt concrete, base, and subbase layers, sitting on an infinite subgrade layer. In pavement and design performance evaluation, the mechanical responses of vehicle stresses on the pavement surface are significant. Software programs have been developed based on a simplified model, and they are now routinely used in pavement evaluations [23].

3.1. Concept of Analytical Approach (Closed-form)

The simple method based on concepts developed by researchers to estimate engineering parameters is utilized in some computer programs for pavement design. In a nutshell, the closed-form analysis looks at how traffic loads affect pavement responses. The theories for stress computations by some scholars was captured in this review.

3.1.1. Boussinesq's Principle

In 1985, Boussinesq gave the computation equation of stress and strain at any depth when a concentrated load acts on the horizontal boundary surface of an elastic, weightless, semi-infinite body referred to as half-space. He assumed pavement materials as either homogenous, isotropic, or linear elastic. The mathematical equations determine stresses, strains, and deflections of homogeneous, isotropic, linear elastic, and semi-infinite space under a point load [24, 25]. Equation (1) to equation (5) showed Boussinesq computation equations for stresses.

Vertical Stress:

$$\sigma_z = \frac{3P}{2\pi R^2}\cos^3\beta \quad (1)$$

Radial stress:

$$\sigma_t = \frac{P}{2\pi R^2}\left(3\sin^2\beta\cos\beta - \frac{1-2\mu}{1+\cos\beta}\right) \quad (2)$$

Tangential stress:

$$\sigma_\theta = \frac{P}{2\pi R^2}(1-2\mu)\left(-\cos\beta - \frac{1}{1+\cos\beta}\right) \quad (3)$$

Shear stress:

$$\tau_{rz} = \frac{3P}{2\pi R^2}\sin\beta\cos^2\beta \quad (4)$$

Deformation below the surface:

$$\delta = \frac{(1+\mu)P}{2\pi RE}\left(2-(1-\mu)+\cos^2\beta\right) \quad (5)$$

Where:
δ, the deformation
μ, the Poisson's ratio
E, the elastic modulus of the half-space
R, the radial distance
B, the angle

3.1.2. Burmister's Principle

Burmister published the analytical stress and displacement equation in 1943. The expression deems limiting the critical strains that occur in pavement compositions. Because all of the loads are in the same direction, vertical or z-direction, the vertical tension and displacement caused by them may be easily calculated by adding them together. Each load's radial, tangential, and shear stress cannot be added directly. As a result of the load, the three stresses in the x and y directions are resolved into components [26, 27]. Equation (6) to equation (10) showed Burmister's computation for stresses and strains.

Three principal stresses σ_1, σ_2 & σ_3:

$$\begin{aligned}&\sigma^3 - \left(\sigma_x+\sigma_y+\sigma_z\right)\sigma^2 + \left(\sigma_x\sigma_y+\sigma_y\sigma_z+\tau_{yz}^2-\tau_{xz}^2-\tau_{xy}^2\right)\\&\sigma - \left(\sigma_x\sigma_y\sigma_z+2\sigma\tau_{yz}\tau_{xz}\tau_{xy}-\sigma_x\tau_{yz}^2-\sigma_y\tau_{xz}^2-\sigma_z\tau_{xy}^2=0\right)\end{aligned} \quad (6)$$

The predominant strains $\varepsilon_1, \varepsilon_2$ & ε_3 are then calculated as:

$$\varepsilon_1 = \frac{1}{E}\left[\sigma_1 - \upsilon\left(\sigma_2+\sigma_3\right)\right] \quad (7)$$

$$\varepsilon_2 = \frac{1}{E}\left[\sigma_2 - \nu\left(\sigma_3+\sigma_1\right)\right] \quad (8)$$

$$\varepsilon_3 = \frac{1}{E}\left[\sigma_3 - \nu\left(\sigma_1+\sigma_2\right)\right] \quad (9)$$

The horizontal principal tensile strains calculated from:

$$\varepsilon_t = \frac{\varepsilon_x+\varepsilon_y}{2} - \sqrt{1\left(\frac{\varepsilon_x-\varepsilon_y}{2}\right)^2+\gamma_{xy}^2} \quad (10)$$

3.1.3. Westergaard Theory

Westergaard made the first proposal to analyze and design rigid pavement structures. His idea is still used in many design techniques to compute load-induced stresses. The pavement structure was represented as a homogeneous, isotropic, elastic, thin slab on a Winkler foundation, similar to a flexible pavement structure but with various foundation fractions [11].

The temperature on top of the slab becomes higher than the bottom slab when the environment changes. The slab bombs up by the compression springs on the outside edge. The springs in the interior, on the other hand, are in tension and draw the slab down [26]. Based on the plate theory, Westergaard derived equations for estimating stresses in concrete pavement. The following equations demonstrate the general equation for predicting stresses in concrete at three (3) different locations [28]. Equation (11) to equation (13) showed Wastergaad computation equations for stresses in three (3) locations of the slab (interior, corner and edge).

Interior Stress,

$$\sigma_t = \frac{E\alpha Vt}{2}\left[\frac{C_x + \mu C_x}{1-\mu^2}\right] \quad (11)$$

Edge Stress,

$$\sigma_t = \frac{CE\alpha Vt}{2} \quad (12)$$

Corner Stress,

$$\sigma_t = \frac{E\alpha\Delta t}{3(1-\mu)}\left[\sqrt{\frac{\alpha}{1}}\right] \quad (13)$$

Where:

E, the modulus of elasticity of concrete

μ, the Poisson's ratio of concrete

α, the coefficient of thermal expansion

$C\text{-}C_x$ and C_y, correction factors

A, is the radius of the circular contact area applied at the corner

ℓ, defined as the radius of relative stiffness

3.1.4. Analytical Modelling of Pavement

In the analytical model (theories of mathematics) approach, the layered elastic concept to analyze and design pavement due to a load acting at a specified point in any layer. This concept's standard design input includes pavement composition and thickness, layer properties, traffic loading, and environmental conditions [23, 29]. A most recent brief review of commercial software tools uses the analytical approach in pavement design [30]. These include AASHTOWare pavement, PAVERS, CIRCLY, PAKPAVE, IITPAVE KENPAVE PaveXpress, Win P.A.S. 12 and Street Pave, of their benefits in Table 1.

However, one of the drawbacks of the analytical approach is the difficulty of modelling or simulating pavement in 2D and 3D. Therefore, to incorporate the present pavement system's complex behavior, current axles load configuration, change of material properties in the horizontal direction, consideration of a more realistic analysis is required [31, 32].

Table 1. *Analytical software tools and their benefits in pavement design [30].*

Software tools	Description
PAKPAVE	Evaluate the thickness of layers, the design life, and the relevant damage factor for the various environmental condition.
IITPAVA	Determines pavement responses in asphalt pavement
KENPAVE	Predicts pavement responses and beyond
PaveXpress	Is sued to determine the necessary pavement thickness
AASHTOWare	Pavement responses are predicted based on traffic, material, and climate parameters.
PAVERS	Use for pavement design, construction evaluation, and maintenance.
CIRCLY	Calculate the cumulative damage by the total traffic, including any combination of vehicle types and loads.

3.2. Concept of Numerical Approach (FEM)

The finite element method (FEM) as a numerical analysis technique used to calculate stress-strain and deflection in pavement layers [33]. The US Army Corps of Engineers developed the tools. It has evolved into a sophisticated and adaptable analysis tool to solve many engineering challenges. The FEM provides the feasibility of investigations of various engineering structures with complex geometry and loading condition. On the other hand, the accuracy of FEM outputs is primarily determined by the mesh patterns. The iterative solution techniques improve the estimated solution's precision with each iteration, resulting in a close approximation to the accurate (precise) but unknown resolution [34]. The idea of the FEM divides structures into many small, interconnected subregions, which are very small with field distribution such as stress and displacement can then be approximated with various types of modelling functions. The equations governing engineering phenomena are usually derived from equilibrium equations and constitutive laws with strain-displacement relations and prescribed boundary conditions. The FEM method mathematically represents an approximate solution of a boundary value problem described by differential equations. Henceforth, the discretization techniques are usually arranged by many approaches [35].

3.2.1. Boundary Condition

A boundary condition in finite element modelling is a set of constraints on nodal coordinates at the virtual domain's boundaries. It is the condition that a solution to a different equation must satisfy. Constrains can be in the x, y, and z axes and different rotating frames. In numerical analysis simulations, a particular region or contact zone of interest is selected, and the area-defined boundaries associated with it consider the point of intersection and the materials. A boundary value may be used to build a representative volume element with appropriate boundary conditions, the amount in which periodic boundary condition is the most efficient in terms of convergence rate, to forecast the effective properties of materials using the FEM approach [36-38]. However, every FEM solution is connected with specifying the behaviours/conditions of the nodes at the domain's boundaries, referred to as the FEM model's boundary conditions. In the instance of ABAQUS, the graphic depicts typical load and boundary condition sub-divisions that are widely utilized in the FEM solver's boundary condition module [39], as shown in Figure 1. Additionally, the method for analyzing each Representative Volume Element (RVE) separately with prescribed boundary conditions, needing just the expense of solving a single RVE was studied [4]. The boundary conditions are iteratively adjusted during the process, allowing the REV iteration to occur by solving the FEM problem on the entire domain using the coarse mesh technique, which also involves an accurate selection of boundaries.

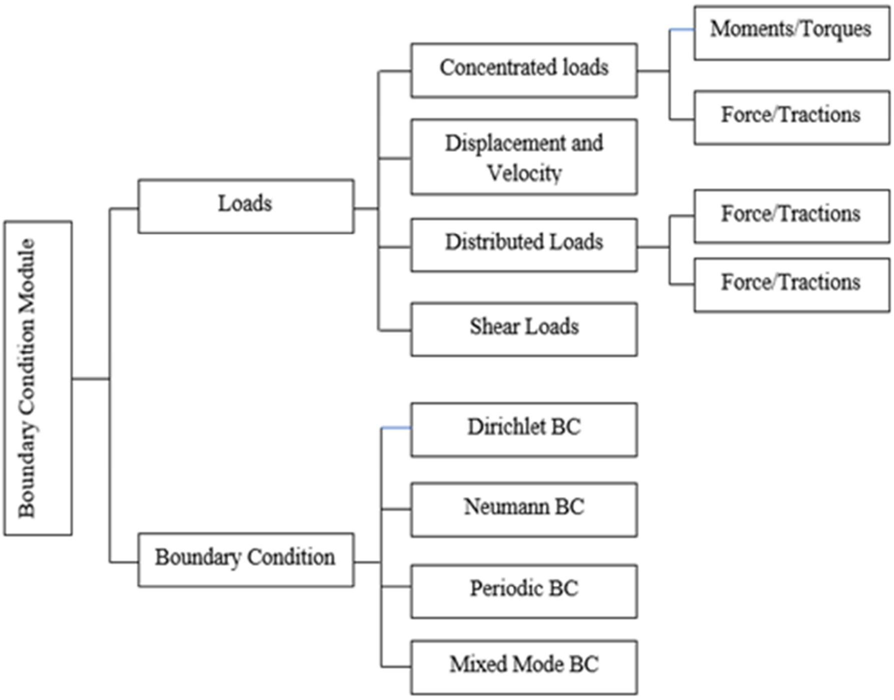

Figure 1. *Illustrates loads and boundary condition module [39].*

3.2.2. Meshing

Meshing in FEM is one of the main points for accurately achieving the analysis solution. The basic idea of meshing is to make calculations precise at only a few points and then interpolate the entire surface or volume results. Any continuous region has infinite degrees of freedom, and it is impossible to solve the problem as a whole as in actual structure. Besides, users may not know that getting a model to mesh and obtaining reliable results are two different phenomena. However, meshing an object to achieve more adequate results is eventually considered by using enough small subregions at a specific stress point estimated over each one and then sewing all the answers together. Then a smooth and reasonable solution is obtained [41-43]. On the other hand, advances in effective meshing modification techniques have been studied by researchers using the modelling of fine and coarse mesh patterns [44]. The alternative and generation of fine meshing sometimes do not require re-meshing due to promising outputs or results.

Meanwhile, the smaller the mesh size, the more precisely the analysis design solution is better across the geometry but solving time is extended. Fine mesh is considered to reasonably approximate the stress variation at various points on the structure [45, 46]. On the contrary, coarse meshing does not require extra solving hours to simulate with a minor or dense mesh, provided the required result is achieved. Nevertheless, mesh patterns remain the powerhouse of simulation to obtain accurate results in FEM, which is one major issue.

3.2.3. Numerical Simulation of Pavement

The numerical simulation software tools use the finite element method to analyze and design flexible and rigid pavement structures. In designing pavements using the FEM, similar analysis factors for the analytical approach are considered. All of these conditions simulate 3D-dimensional finite element analysis. Because of the processes involved, the analysis is computationally expensive. The pavement structure, on the other, is discretized into uniform elements, and the pavement responses are divided by loading a mesh configuration [47, 48]. The model can accommodate the loading-dependent stiffness of the road layers, granular, and subgrade materials thanks to the usage of FEM. The linear elastic theory is still used in most models to form relationships. It is also generally accepted that the behaviour of acceptable materials can be described more appropriately by a nonlinear equation. The tool computations indicate a reasonable solution. Popular FEM computer codes such as ANSYS, ABAQUS, and EverStresssFE are user-friendly 3D for simulating the responses of flexible asphalt systems subjected to wheel loads [49-51]. The techniques would also simulate different pavement structures [33, 52, 53].

4. Computer Algorithms

The development of software tools to facilitate the calculation of pavement behavior has gained permanent compared to other design methods. They have gradually become more sophisticated in handling different materials such as linear elastic, elastoplastic, nonlinear, different loading configurations, and two to five multiplayer systems of pavement cross-sections. Modelling the pavement structure with a multilayer or finite element method is possible. The essential element of modelling a pavement structure, whether using a layered elastic or finite element method, is that simulation should interpret the representations of the pavement behavior in the field. Current structural design computer algorithms also use the mechanistic-empirical approach [54]. However, some computer tools such as AASHTOWare, KENPAVE, IITPAVE, BISAR, ANSYS, ABAQUS, and EVERTRESS are professional programs that engineers use to compute critical pavement responses in the x, y and z directions of the pavement structure [28].

4.1. Mechanistic-empirical Pavement Design

The Mechanistic-Empirical Pavement Design Approach is a modified version of the AASHTO pavement design method that employs the AASHTOWare Pavement ME Design software for advanced pavement design. The approach aims at identifying traffic-induced stresses and calibrating them against observed pavement performance. The program considers various inputs, superior to other pavement design computer algorithms. Before applying theories to estimate essential pavement responses, the approach considers various input groups, including climate, advanced traffic characteristics, and material properties [55].

The AASHTOWare design method, on the other hand, is primarily based on essential distress functions for pavement performance prediction: fatigue and rutting strains [56]. Additionally, the program's sophistication for multiple data imputations makes it challenging for users and will need to be more adjustable to fit other local conditions.

4.2. KENPAVE

The KENPAVE computer program for pavement analysis and design relies on the analytical approach/principles that calculate stresses, strains, and deflections due to individual wheel load such as Tandem and Tridem in flexible and rigid pavement structures. Yang Huang, a professor emeritus of civil engineering at the University of Kentucky in the United States of America, developed the computer tool in 1993. The program is often used to model pavement systems based on ideas and theories as other analytical applications. Both English and SI systems of measurement are used in the program. KENLAYER and KENSLAB are the two portions of the KENPAVE computer program. KENPAVE's main screen has two input boxes at the top containing specifications for asphalt and concrete and ten (10) command windows [26].

The KENLAYER of KENPAVE algorithm is a Semi-Mechanistic-Empirical (ME) program applied to flexible pavements which use the concept of an elastic multi-layered system under a circularly loaded area. It is used based on Burmister's multi-layered elastic theory (closed-form) based on an analytical approach. The tool contains many data sections, including 19 layers with 25 different radial and 19 vertical coordinates.

One attractive section of the KENLAYER is the way material properties are handled. Materials can be linear-elastic, nonlinear elastic, viscoelastic or a combination thereof. Interestingly, each layer material can be imputed for each seasonal variation [26, 57].

Traffic load groups can be treated separately and analyzed in one goal. The critical location of failure modes in the pavement can be specified and computed [24, 58]. The computer algorithm can also calculate the damage caused by 2 to 3 axles load groups with the accurate simulation of vehicle loading geometry in the plan.

Fatigue cracking is based on tensile strain at the bottom of the asphalt layer, and permanent deformation is based on compressive strain on top of the subgrade according to the damage analysis for pavement design life prediction [59]. The Asphalt Institute provided one of the damage coefficients. Because the unit is dimensionless, the estimated identical strain can be utilized for both systems of units.

However, one of the downsides of the KENLAYER algorithms is that the user can only change the modulus values of each layer in the vertical direction. Besides, the modulus is supposed to be constant throughout the layer, which is not always the case due to material resilient modulus variation in the horizontal direction. Furthermore, the programme exclusively employs the collocation approach to assess the viscoelastic behaviour of HMA. By measuring creep compliances from creep tests across eleven (11) various time durations. However, limiting the characterization of the material's viscoelastic nature to one alternative is insufficient. As mentioned in ANSYS, additional alternatives would allow users to choose either a mechanical model or an experimental investigation.

4.3. IITPAVE

IITPAVE computer algorithms uses the analytical approach and is an improved version of FPAVE developed from a research project of R-56 of MORTH in India. The program uses the multilayer analysis approach to design and analyze the flexible or bituminous pavement using the IRC: 37-2012 guidelines. The program's essential input parameters are layer thicknesses, loads applied over the pavement surface, tire pressure, spacing between the wheels, elastic modulus, and Poison's ratio. After the imputations of those parameters, the program then calculates the actual horizontal tensile and vertical compressive strains at the critical location in the pavement compositions [60]. A good pavement design can rest assured through an iterative process, thereby varying the layer thickness or changing the material type of pavement composition. A research study was conducted entitled: Analysis of the Flexible Pavement Structure using falling Weight Deflectometer for Indian National Highway Road network. Various tools, such as the Falling Weight Deflectometer (FWD) and KGBACK, were employed in the research to assess the performance of a road stretch on the National highway by examining the deflection caused by load application. Moreover, the resulting in-situ elastic moduli were used in the IITPAVE tool for pavement overlay design [61].

However, the program is operated to design flexible pavement solely using the layered elastic theory. Material evaluation theories such as viscoelastic, nonlinear, damage models are not incorporated to increase the computational accuracy of results. Furthermore, maximum layer inputs are up to four (4) levels. Asphalt layers are combined as a single layer with the same elastic and Poison ratio. Combining the asphalt layers is not reasonable because surface and binder layers reaction to temperature varies. Therefore, it is vital to include varying parameters to increase the confidence of analysis outputs.

4.4. BASIR

BISAR Shell computer algorithm is a linear elastic multilayer program used to model flexible pavement. Because of its capacity to add shear spring compliance as an input factor, Shell Research Gate developed the program in 1970. It is the most extensively used tool. Pavement responses computation in the BISAR program generates complete calculation results in a pavement structure due to various loading categories and predictions of pavement structures. To further expand on the program's accuracy, a comparison of BISAR and EverStressFE was carried out to investigate the interlayer bounding problem of the asphalt pavement system [62]. The output of the results indicated that both programs' discrepancy in analyzing the mechanical response of the asphalt pavement interlayer problem does not provide any significant difference, and further concluded that the professional tools are excellently useful. Also, the BISAR and Egyptian environmental and pavement materials conditions were used to predict the tensile strains that commonly occur beneath the AC layer and over the subgrade due to the effect of axle load, in addition to assessing the program's accuracy [63-65]. Pavement engineers have successfully used the program as a more analytical tool for pavement design.

4.5. ANSYS

ANSYS is a 2D and 3D FE analysis powerful and universal computer program for linear and nonlinear pavement responses to traffic load and environmental elements. The modelling of pavement structure considered creating a geometrical simulation, the assignment of material properties (viscoelastic, plasticity, elastic), the application of loading (force or pressure), mesh contacts, and the appropriate boundaries. Pavements can be analyzed using either the APDL or the workbench options. Meanwhile, the program is an approximately analytical procedure whose accuracy solely depends on the discretization of mesh pattern, as in ABAQUS and all other FEA programs. The use of the FEM in road pavement design gives one much flexibility when analyzing the pavement stress-strain condition and establishing the pavement and roadbed bearing capacity. The number of layers, location, and material type used to calculate pavement reactions using such a tool is not limited [66, 67]. A pool of researchers has been using the 3D FE program for many years.

ANSYS was used to compute and analyze the foundation of a flexible base asphalt pavement system with various elastic moduli and thicknesses. As a result, a response regarding pavement structure for the base foundation was obtained, serving as a design reference [68]. Also, a comparison of the season-dependent equal temperature to the effect of seasonal temperature changes on the fatigue strength of flexible and semi-rigid pavement systems of flexible and semi-rigid pavement systems at the yearly equivalent temperature of 10℃was performed [69]. The strain and stress states were obtained using the ANSYS mechanical tool.

However, the key disadvantage of performing FE analysis to predict pavement responses is that it can be costly and time-consuming, mainly if a mix of pavement material parameters are used as input.

4.6. ABAQUS

Abaqus is a two-dimensional and three-dimensional computer program that uses the number approach (FEM) and has been widely utilized in the structural analysis of flexible and rigid pavement systems. The software generates some realistic pavement representations based on an axisymmetric idealization-based method. The tool can create, edit, monitor, diagnose, and display quickly and efficiently. Furthermore, the tool is flexible, with CAD interfaces, and a finite element model can be created based on input data. Many highway and pavement researchers have used Abaqus extensively [70, 71]. The computer algorithm can treat nonlinear material in a more rational way practically. A research effort by the University of Illinois studied the analysis of flexible pavements having nonlinear, stress-dependent pavement foundations. The study's goal was to do three-dimensional FE analyses considering the nonlinear resilient characterization of geomaterials. The ABAQUSFE program and the GT-PAVE were compared. The result between the two computer codes for the nonlinear axisymmetric analysis was in good agreement [72].

On the other hand, the ABAQUS and the Semi-Analytical Finite Element Method to evaluate the dynamic characteristics of asphalt pavement under moving loads was examined. The SAFEM outperformed the ABAQUS in terms of computational accuracy, supporting that the SAFEM can reliably identify the dynamic responses of asphalt pavement under moving loads [73].

4.7. EverStressFE

The program is a user-friendly 3D finite element analysis (FEA) numerical tool for simulating the flexible pavement structure responses due to the subjection of loading. The program was developed by the University of Maine supported by the Washington State Department of Transportation in the United States of America. The stress properties of granular materials can be considered by repeatedly modifying the layer moduli using the stress modulus relationship. The analysis of a flexible structure using three (3) case studies CBR methods, the Asphalt Institute, the National Crushed Stone Association, and the Nigerian CBR methods were carried out to evaluate critical pavement responses such as fatigue strain and rutting deformation [50].

However, the FEM model through EverStressFE allows the model to accommodate the load-dependent stiffness of the road layers granular and subgrade materials. Put another way, the application can only analyze flexible pavement systems with maximum four (4) layers. Furthermore, loading conditions are restricted to single and tandem axles.

5. Conclusion and Recommendations

Adequate design-based method using computer algorithm provides a framework of efficient and effective analysis engine which better interpret the short and long-term performance of pavement structure mainly to characterize its responses. This review herein briefly discusses and summarizes with bullet points typical pavement design methods, well-known structural approaches, and some relevant computer algorithms.

1) The development of pavement design based on empirical methods such as experience-based, design charts and AASHTO 1993 continues to cast doubt on pavement structural performance prediction. These procedures do not consider theories or principles. For example, the experience-based approach selects pavement structural composition only based on road category; method based on design charts incorporates two elements (CBR value and design ESAL); method based on AASHTO 1993 design evaluates pavement based on SN due to the AASHO road test implemented in the United States. Meanwhile, the structural method has proved to provide a meaningful image of pavement responses via a mechanical interpretation to compute pavement distresses. However, both empirical and structural methodologies could be employed concurrently to assess the accuracy of pavement composition and performance prediction.
2) Widely use structural approaches (analytical model) and (numerical simulation) rationally calculate pavement structural responses in the x, y and z directions, respectively, using theories and principles. These approaches consider material type, traffic loads, and environmental elements as essential inputs factors. Each theoretical base approach describes and analyses the material layer in different ways. For example, the analytical model based on layered elastic analysis and integral solutions assumes linear, nonlinear, and viscoelastic material. One major disadvantage is its inadequacy to analyze material property nonlinearly accurately. While the numerical simulation approach, however, can incorporate advanced features of material behaviour though considering a variety of material properties as an alternative. On the other hand, the difficulty with the approach accuracy is that it is dependent on its capacity to provide suitable boundary conditions, mesh, and computing time is subject to additional material attributes description. In comparison, the numerical approach is superior to the analytical approach. As previously stated, most analytical model computer algorithms do not consider the characteristic of material properties as nonlinear and viscoelastic. Therefore, it is essential to incorporate different features of material properties to increase the accuracy of results.
3) The review selected the analytical approach (MEPD approach, KENPAVE, IITPAVE & BISAR) and numerical approach (ANSYS, ABAQUS, & EverStressFE. The selected computer programs have seen much pavement analysis and design application. Unlike other analytical programs, the KENPAVE program is user-friendly to model flexible and rigid pavements with adequate input variables. The tool, for example, can treat each layer in the pavement system as either linear elastic, nonlinear elastic, or viscoelastic. Single, dual, tandem, and tri-axles load groups and applications can be used in a single analysis run. Remarkably, the tool can analyze damage over a year, reacting differently due to varying material properties in each loading period concerning temperature. The difference in numerical and analytical programs is ideal for correctly evaluating granular material characteristics. However, nonlinear material features were also included in three ways by KENPAVE. Similarly, the three (3) numerical method FEM programmed discussed in this study are extensively used and have nearly identical configurations. Though, ANSYS promises to be more effective due to the imputation of additional variables and its ability to incorporate nonlinear material. On the other hand, one key issue of the program is that the likelihood of analyzing complex materials is expensive, and analysis timing is highly delayed. As a result, using a hard-speeding device would shorten the analytical process.

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