International Journal of Scientific Research & Engineering Trends
Volume 9, Issue 4, Jul-Aug-2023, ISSN (Online): 2395-566X

Numerical Simulation of Inverted Pavement Systems

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Abstract- Conventional pavements rely on stiff upper layers to spread traffic loads onto less rigid lower layers. In contrast, an inverted pavement system consists of an unbound aggregate base compacted on top of a stiff cement-treated base and covered by a relatively thin asphalt concrete layer. The unbound aggregate interlayer in an inverted pavement experiences high cyclic stresses that incite its inherently nonlinear granular media behavior. A physically sound, nonlinear elastoplastic material model is selected to capture the unbound granular base in a finite-element simulator developed to analyze the performance of inverted pavement structures. The simulation results show that an inverted pavement can deliver superior rutting resistance, as compared with a conventional flexible pavement structure with similar fatigue life.

Keywords- Pavement modeling; Constitutive model; Inverted pavement; Particulate media; Finite element; Resilient modulus.

I. INTRODUCTION

Pavement analysis and design combines mechanistic theories and empirical relationships. Layered linear and nonlinear elasticity concepts guided the development of the AASHTO 1972 interim design guide and its subsequent 1993 revision. More recently, underlying concepts are explicitly recognized in the latest mechanistic-empirical pavement design guide developed under the National Cooperative Highway Research Program (NCHRP) Project 1-37A.

In this guide, pavement structures are analyzed in two steps. First, the structural response is determined using mechanistic and constitutive material models developed from as-built layer properties; the key results from this analysis are horizontal tensile strains at the bottom/top of the bound aggregate layers and compressive vertical stresses within the unbound layers. Then, these values are used as input parameters to distress prediction models based on accumulated empirical field data, from which the expected pavement life is determined.

Inverted pavement systems consist of an unbound aggregate base compacted on top of a stiff cement-treated base, covered by a relatively thin asphalt concrete layer. Large cyclic stresses develop within the unbound aggregate layer under service loading, which translate into large transient variations in stiffness during loading-unloading. Linear elastic analyses cannot accommodate the stiffness-stress dependency of unbound aggregate layers and may yield erroneous stress and strain predictions in inverted pavement structures.

The analysis of pavement structures using the finite element method allows for the implementation of constitutive models that can properly capture the nonlinear behavior of unbound aggregate layers. The use of finite elements in the analysis of pavement structures started in the 1960s and led to case-specific. A summary of material models used in previous finite element analyses of flexible pavement structures is presented. The general-purpose finite element program ABAQUS has been used to study pavement conditions such as multiple wheel loads, unbound aggregate nonlinear behavior, and anisotropy. However, material models built in ABAQUS are not suitable to capture the resilient behavior exhibited by unbound aggregate layers.

The objective of this manuscript is to document the development of an ABAQUS-based simulator to analyze the response of inverted pavement systems, including the numerical implementaltion of a robust constitutive model for the unbound aggregate layer. The simulator is used to guide the selection of the domain size, to reveal the implications of simplifying assumptions, and to identify key differences in the mechanical performance between inverted and conventional flexible pavements.

II. PAVEMENT MATERIALS: BEHAVIOR AND MODELING

1. Asphalt Concrete:

The stress-strain behavior of asphalt concrete is determined by the loading frequency, duration and amplitude, temperature, stress state, aging, and moisture. Asphalt concrete deforms slowly and permanently at low strain rates and high temprelatures and becomes stiffer and brittle at high strain rates and low temperatures. The tensile strength and strain at failure depend on both temperature and the fraction of air filled void space. Asphalt concrete strength values reported vary between 3.6 and 5.4 MPa at 10°C and 0.9 to 1.6 MPa at 21°C; the strain at failure is on the order of 1×10^{-4} to 3×10^{-3}.

Aggregate shape and compaction during construction result in inherent and stress- induced anisotropy; thus, asphalt concrete exhibits cross-anisotropic material properties. The response of asphalt concrete to service load can be represented by a viscoelasto- plastic model.

2. Cement-Treated Base:
The long-term behavior of lightly cemented aggregate bases exhib- its three distinctive stages: (1) precracked phase, (2) the onset of fatigue cracking, and (3) advanced crushing. During the precracked phase, the layer behaves as a slab with horizontal plane dimensions larger than the layer thickness; the elastic modulus during this stage corresponds to that measured immediately after construction. At the onset of fatigue cracking, the initial elastic modulus reduces rapidly as the layer breaks down into large blocks with dimensions in the horizontal plane on the order of magnitude of the layer thickness. Finally, in the advanced crushing state, the layer reduces to a granular equivalent with blocks smaller than the layer thick- ness. At this stage, the originally cemented aggregate now behaves nonlinearly and with stress-dependent stiffness.

This evolution in mechanical behavior of the cement-treated base results in rearrangement of stresses and strains within the entire pavement structure. Therefore, while deterioration of the cemented aggregate itself is not considered a critical mode of distress, it has serious implications on the distress evolution of more critical layers, especially the asphalt concrete layer.

3. Unbound Aggregate Base and Subgrade Layers:
Unbound aggregates exhibit inherently nonlinear behavior. Within a characteristic range of stresses, plastic deformations decrease with the number of load repetitions until only elastic strains are present in the material response, i.e., plastic shakedown. The resilient modulus is defined as the ratio of the repeated load amplitude to the recoverable elastic strain. Experimental studies have established that the resilient response of the granular base is controlled by stress level, density, gradation, particle size, maximum grain size, mois- ture content, stress history, load duration, and load frequency.

In the plastic shakedown regime, the permanent strain rate per load cycle after the compaction period decreases until the response becomes entirely resilient.

III. NUMERICAL SIMULATOR

1. User-Defined Material Subroutine:
A cross-anisotropic nonlinear elastoplastic material model is imple- mented in Fortran to be inserted as a subroutine in the commercial finite element software ABAQUS. Note that ABAQUS 6.8 uses Fortran 77 code for user subroutines and custom postprocessing applications. Two types of elements are used in the simulations: CPE8R (two-dimensional plane strain) and CAX8R (axisymmetric). Both elements have eight nodes for displacements, and a two-by-two integration point scheme. The notation used in this manuscript follows. Underlined lowercase letters denote second- order tensors, e.g., a aij (the second-order tensor 1 δij is the Kronecker delta). Underlined uppercase letters denote fourth-order tensors, e.g., A Aijkl; here the I δikδjl δilδjk =2 is the unit fourth-order tensor. The symbol “:” denotes the inner product of two tensors; thus, a b ¼ aijbij, 1 1 ¼ δij, δij ¼ 3, and A a ¼ Aijklakl. Finally, the symbol denotes the juxtaposition of two ten- sors, e.g., a b aijbkl.

The constitutive equations in linear elasticity are represented by the generalized Hooke’s law, which can be expressed as σ De ε, where σ σij is the stress tensor, ε εij the strain tensor, and De Deijkl is the fourth-order material stiffness tensor. In cross- anisotropic materials the elastic properties in any direction within

2. Constitutive Model:
Robust model predictions start with the physically guided selection of the material model to satisfy experimental observations. While a large number of model parameters favors data fitting, we follow Ockham’s rule of parsimony, i.e., the simplest model that properly justifies the data (Santamarina and Fratta 2005); hence, we seek a physically sound, simple model that can adequately justify the data. In particular, the selected model must capture (1) the Hertzian-type stress-dependent stiffness of unbound granular bases and (2) the skeletal softening caused by deviatoric loads that approach failure. The model initially proposed by Huurman (1996) and later modi- fied by Van Niekerk et al.

The limiting failure strength qf is recognized in the model so that modeled loads result in a state of stresses compatible with failure conditions. Here, the Drucker-Prager failure criterion is applied to determine the boundary between elastic and perfectly plastic deformations, which follow an associated flow rule. The failure A conventional flexible pavement structure is modeled using the isotropic linear elastic properties reported in simulations by Young’s modulus and Poisson’s ratio values for the different layers are presented in Predicted vertical stresses along the centerline caused by a 103 kPa uniformly

3. Multilayered Cross-Anisotropic Linear Elasticity:
Predictions using the new code for cross-anisotropic linear behavior are compared to published results obtained with GT-Pave The asphalt concrete and the subgrade are modeled as isotropic linear elastic layers using The three verification studies show that the predictions made using the proposed user-defined material model subroutine agree with closed-form solutions and established multilayered linear elastic isotropic and cross-anisotropic simulators.

4. Model Calibration:
Constant confinement cyclic triaxial test results for a crushed Georgia granite aggregate reported in Tutumluer

(1995) are used to assess the ability of the model to reproduce the physical response of unbound aggregate layers. Tests were conducted at five different cell pressures and three deviatoric stress increments for each cell pressure. The procedure followed for the determination of the con- stitutive model ki parameters satisfies physical constraints derived from soil mechanics; ki values are summarized in Table 2. There is very good agreement between numerical model predictions and the experimental data, as shown in Fig. 3.

5. Domain Size and Boundary Conditions:

Previous numerical and experimental studies show that zero dis- placement boundaries must be far from the loaded area to minimize boundary effects A numerical investigation was conducted to assess boundary effects on the predicted mechanical response of an inverted pavement structure. Following the recommendations of the guide for mechanistic- empirical design of new and rehabilitated pavement structures a 550 kPa tire contact pressure spread over a circular area of radius 0.15 m is used. The domain dimensions and material properties of individual layers are summarized in.

The pavement section is modeled using a 3D axisymmetric mesh that replicates the geometry of the inverted pavement structure shown in It is assumed that there is no slip at the inter- faces between layers. Results presented in show the sensi- tivity of critical design parameters including effects on maximum tensile strains in the asphalt concrete and cement-treated base and maximum vertical compressive stresses in the unbound aggregate base and subgrade to variations in the horizontal domain R.

The influence of the lateral boundary was assessed by imposing a zero-lateral-displacement boundary along the edge of the model for all layers and only along the unbound aggregate base and subgrade layers. There are only minor differences in the magnitude of the parameters studied in part due to the prescribed no-slip interfaces. In both cases, boundary effects are minimal when R=r > 20. There is a 30% difference in predicted maximum tensile strains in the cement-treated base and a 15% difference in the predicted maximum compressive stress in the subgrade between R=r 10 and 20.

The proximity of the wheel to the road often creates a range of physically meaningful domain sizes between R=r 5 and 10. Re- sults in show that simulations with a domain size R=r 20 can lead to a 140% underestimation of the maximum compressive stress in the subgrade, a 60% overestimation of the maximum tensile strain in the cement-treated base, and a 6% overestimation of the maximum tensile strain in the asphalt concrete layer. Con- sequently, predictions made using R=r 20 would underestimate subgrade rutting, the fatigue resistance of the cement-treated base and the fatigue life of the asphalt concrete layer. The rest of the study is conducted with an intermediate value of R=r ¼ 10.

6. Modeling of Anisotropy:

The influence of anisotropic material properties is examined via a parametric numerical study of triaxial and zero-lateral-strain load- ing simulations. Anisotropic elements are created using three values for the initial vertical to horizontal stiffness. progressing toward a particular asymptotic value at large strains (εz > 1 × 10−3).

IV. SIMULATION STUDIES AND RESULTS

Three simulation studies are conducted to explore the mechanical performance of an inverted pavement structure, to study the impact of simplifying assumptions, and to identify an equivalent conven- tional flexible pavement structure for a preselected inverted pavement.

1. Mechanical Performance of an Inverted Pavement Structure:

This simulation study is conducted to determine the mechanical response, stresses and strains, of the inverted pavement structure depicted in Following the findings on domain size reported previously, we model the load on the pavement as a 550 kPa tire contact pressure spread over a circular area of radius r 0.15 m with a domain size R 10 r 1.50 m. Material properties and layer thicknesses are summa- rized in The pavement structure is modeled using a 3D axisymmetric edge biased mesh, with zero-lateral-displacement boundaries at the edge of the pavement, zero vertical displacement at the lower boundary, and no-slip between the layers.

The resulting vertical, radial, and shear stress distributions along the centerline and under the wheel edge are presented in Vertical stresses along the centerline and the wheel edge are compressive throughout the full depth of influence of the load and become negligible within the cement-treated base. Radial stresses along the centerline and wheel line for the asphalt concrete and cement-treated base layers range from compression at the top to diminishes with depth; the peak vertical stress on the subgrade is less than 4% of the vertical stress applied on the surface.

Slices of the horizontal and shear stress fields at different depths are presented in Figs. 7(b and c). Radial tensile stresses in the asphalt layer are greatest along the bottom of the layer, reaching a maxi- mum at the load centerline. The unbound aggregate base cannot sustain tensile stresses; therefore, the constitutive model correctly predicts compressive stresses along the bottom of the unbound aggregate base. Tensile stresses at the bottom of the cement-treated base also reach a maximum at the centerline. The shear stresses along the asphalt concrete surface show a peak at the wheel edge, where there is a large discontinuity in vertical stresses. In the un- bound aggregate layer, shear stresses increase slightly with depth along the wheel edge. The cement-treated base considerably re- duces the wheel-induced shear stresses on the subgrade.

2. Linear Elastic Unbound Aggregate Layer Modeling Implications:
The use of linear elastic models for the analysis of conventional pavement structures, i.e., with decreasing layer stiffness with depth, predicts tensile stresses at the bottom of the asphalt concrete layer, the unbound aggregate base, and the subbase. However, linear elas- tic analysis of inverted pavement structures does not predict tensile stresses in the unbound aggregate base because the stiffness profile characteristic of inverted pavement structures results in the devel- opment of compressive stresses along the full thickness of the unbound aggregate base.

Additional implications of using simple linear elastic models to represent the unbound aggregate base in the analysis of an inverted pavement structure are identified by comparing the results of the nonlinear elastoplastic material model (NLEP) with two linear elastic models: (1) LE1 has a Young's modulus of 230 MPa cor- responding to the in-situ measured unloaded unbound aggregate base stiffness, and (2) LE2 has a Young's modulus of 500 MPa corresponding to the model predictions for the state of stresses at mid-depth in the unbound aggregate base, under a 550 kPa wheel load.

The results of the three analyses are shown in Fig. 8; differences between linear and nonlinear analyses follow:

- The maximum tensile strain at the bottom of the asphalt concrete layer is underestimated by 33% when the maximum elastic modulus is used and overestimated by 5% when the minimum elastic modulus is used.
- The maximum tensile strain at the bottom of the cement- treated base is underestimated by 4% when the maximum

3. Equivalent Conventional Flexible Pavement Study:
We use successive forward simulations to identify a conventional flexible pavement of similar mechanical performance to the studied inverted pavement. The simulation assumes that the material prop- erties of individual layers are the same in the conventional and inverted sections (Table 3). The mechanical response is compared in terms of the critical design parameters for fatigue failure analysis (i.e., maximum tensile strain at the bottom of the asphalt concrete) and rutting failure analysis (i.e., maximum vertical stress on the subgrade).
The mechanical response of the studied inverted pavement and three conventional flexible pavement structures are compared in Fig. 9. To facilitate the comparison, we keep the thickness of the unbound aggregate base constant in all of the conventional pavement structures. Simulation results show that a conventional pavement section with asphalt concrete thickness tAC 0.17 m and an unbound aggregate base thickness tUAB 0.3 m sustains similar maximum tensile strain in the asphalt concrete layer as the inverted pavement. However, the inverted pavement is more efficient in redistributing the vertical compressive stresses trans- ferred to the subgrade.

V. DISCUSSION

1. Mechanical Performance:
The vertical stress profile presented in shows that the com- pressive vertical stresses along the centerline decrease from the applied wheel load 550 kPa on top of the asphalt concrete, to 190 kPa at the top of the cement-treated base. The maximum tensile radial stress is 1380 kPa at the bottom of the asphalt concrete and 330 kPa at the bottom of the cement-treated base

2. Linear Elastic Unbound Aggregate Material Models:
The stiffness profile characteristic of an inverted pavement struc- ture prevents the generation of tensile stresses in the unbound aggregate base regardless of the material model assigned to the unbound aggregate base (linear or nonlinear elastic). A linear elastic analysis based on the maximum expected modulus yields conservative unbound aggregate base rutting predictions, but non- conservative asphalt concrete and cement-treated base fatigue pre- dictions. A linear elastic analysis based on the minimum expected stiffness leads to better asphalt concrete and cement-treated base fatigue predictions but significantly overestimates subgrade rutting.

3. Equivalent Section:
Limited comparative results of equivalent sections show a superior performance of the inverted pavement in terms of subgrade rutting prevention (lower peak vertical stress on the subgrade) for the same maximum tensile strain in the asphalt concrete layer.

VI. CONCLUSIONS

The unbound aggregate layer in an inverted base pavement expe- riences large cyclic stresses under service loading; this translates into large transient variations in stiffness during load-unload cycles. The analysis of pavement structures using the finite element method allows for the implementation of constitutive models that can properly reproduce the observed behavior of unbound aggre- gate layers. The selected model captures the Hertzian-type stress- dependent stiffness of unbound granular bases and the skeletal softening caused by deviatoric loads that approach failure. It is fit- ted to data using four physically meaningful and experimentally accessible constitutive parameters.

Simulation results show that the stiffness profile in inverted pavement structures prevents the development of tensile stresses in the unbound aggregate base even if a linear model is used to represent it. While linear elastic analyses cannot accommodate the stiffness stress dependency of unbound aggregate layers, limiting conditions can be simulated using an elastic response by adopting the in-situ stiffness before load application and the stiffness under maximum load.

The maximum vertical compressive stress in the subgrade of an inverted pavement is lower than the value predicted for a conventional flexible pavement structure designed to experience the same maximum strain in the asphalt concrete layer. Thus, the inverted pavement will deliver superior rutting resistance. The presence of a stiff cement-treated base facilitates the compaction of the unbound aggregate base so that the as built stress- dependent stiffness of the unbound aggregate base will be higher in inverted pavements than in conventional flexible pavements.

Numerical results show that the tensile stresses in the asphalt concrete layer and in the cement-treated base, as well as the compressive stress on the subgrade, decrease as the stiffness of the unbound granular base increases.

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