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Pavement Analysis with the Consideration of Unbound Granular Material Nonlinearity

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Abstract: Accurate pavement design and evaluation requires the execution of response analysis. Pavement materials' behavior does not necessarily conform to the assumptions of the multi-linear elastic theory usually adopted during pavement analysis. In particular, the unbound granular materials located in the base and sub-base layers behave in a nonlinear elastic manner, which can be captured through advanced constitutive modeling of their resilient modulus. The finite element method enables us to code constitutive models and quantify potential variations in pavement responses because of different mechanistic assumptions. In this study, variations in response are investigated for a typical structure of a flexible pavement considering the nonlinear anisotropic behavior of the unbound materials together with their initial stress–strain state. To demonstrate the impact of their behavior on the outcome of pavement analysis, variable asphalt concrete layer thicknesses and moduli are assumed, such that they cover a large spectrum of roadways. It was found that pavement responses can be calculated up to 3.5 times higher than those retrieved from the conventional linear analysis. This comparison means that the alterative mechanistic modeling of the unbound granular materials can be proved to be more conservative (i.e., leading to higher strains) in terms of pavement design and analysis. From a practical perspective, this study alerts pavement scientists and engineers engaged in pavement design to a more reliable performance prediction, which is needed to bridge the gap between advanced modeling and routine analysis.

Keywords: pavements; base layer; granular materials; constitutive modeling; finite element analysis; nonlinearity

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1. Introduction

1.1. Overview

Pavements' performance prediction is challenging for pavement scientists and engineers engaged in both the design of new structures and the condition analysis of existing ones [1]. To assess a pavement's structural adequacy, knowledge is required about the critical responses to vehicular loading and the expected mechanical performance of pavement materials. In this context, the selection of input material parameters during the design phase is rather critical. This aspect is exacerbated considering that, during the implementation phase, material variability or construction variability can lead to uncertainties in the actual mechanical responses of a pavement, making it difficult to perform pavement quality control [2,3].

As a routine practice, the simplified assumptions of multi-linear elastic theory (MLET) are assumed for all pavement materials [4–6]. While much documentation exists regarding the need to consider the viscoelastic behavior of asphalt concrete (AC) mixtures more representatively [7–9], the actual behavior of the unbound granular materials located in the base and sub-base layers is usually overlooked. Multiple studies over the years have recognized the significance of the behavior of unbound granular materials [10–12], which is normally nonlinear elastic. Other studies have additionally focused on the base material cross-anisotropy [13–15], as well as on the joint modeling of the unbound materials' nonlinear and anisotropic behavior [16–20]. As per the subgrade materials, a greater variance is also present because of the high engineering spectrum of soil material properties [21]. Soil elasto-plasticity, although tedious, can also be considered to improve the results of pavement design and analysis.

In this study, the focus is being put on the base/sub-base materials. Consistent research interests are observed that investigate correlations between inputs during the design of the unbound materials and pavement performance. To this end, the use of finite element method (FEM) tools is an efficient approach to investigate pavement responses' sensitivity with respect to variations in several geometric or material parameters that affect pavement design [10,22,23]. Considering that during a pavement's construction process, deviations between the design and the as-built values of either the pavement's geometric or material properties frequently occur, leading to additional short-term or long-term costs for the road agencies, it always remains challenging to access efficient tools to accurately predict the impact that such deviations may potentially have on future pavement responses. Indeed, FEM can be considered as a robust analysis tool that serves the need for a more complicated analysis of pavement structures and acts as an accurate-as-possible assessment tool of both new and in-service pavements.

1.2. Background on the Granular Layers' Performance

The contribution of the unbound materials' behavior is important since they provide the foundational support to the pavement structure and dissipate the stresses induced by traffic loading to the underlying subgrade [24]. Their actual response to wheel loading is known to be nonlinear elastic. In fact, they are not completely elastic, as some non-recoverable deformation takes place after each load application [25]. This plastic deformation occurs during the early stages of a pavement's service life and remains nearly constant afterward. A good construction quality can keep plastic deformation due to post-compaction effects at minimum levels, which explains why the component of plastic deformation is usually ignored [25].

As such, a representative stiffness modulus for the unbound pavement materials is the resilient modulus M_R, which considers only recoverable deformation. The resilient modulus (M_R) of base course materials is considered as an important material input for pavement design, and the determination of the M_R is achievable through laboratory testing [26]. Despite being dependent on classical laboratory testing, its importance continuously revives since new materials and gradients appear as alternatives, like the reclaimed asphalt pavement (RAP), which is also used widely in the AC layers [27–29]. So, existing testing methods and models for the granular materials are worthy of investigation and/or recalibration.

In this context, various constitutive models incorporating laboratory-determined coefficients have been developed to closely represent the material behavior for the estimation of the stress-dependent resilient modulus. The development and existence of these models, along with advances in computing, permit the further modeling of pavement responses through numerical simulation, e.g., FEM, which can become an even more robust analysis tool with the incorporation of computer coding of the material behavior through constitutive laws that closely resemble the mechanical behavior of the pavement materials [30]. Apart from FEM analysis for pavement design, related research on the prediction of pavement performance has also been extensively performed with the main challenge of the in situ validation of the predicted responses. FEM enables the consideration of complex behaviors; Tarefdar et al. [31] examined the effects of the nonlinear and cross-anisotropic nature of the unbound materials on the stress–strain response of pavement and concluded that more conservative results can be obtained compared to a conventional analysis.

In addition, modeling only a single pavement cross-section can hinder the wide applicability of FEM, preventing us from gaining a more in-depth understanding of the joint impacts of different variables, e.g., the nonlinearity of unbound materials, the type of constitutive model, the pavement structure (i.e., material properties and thicknesses, etc.).

Indeed, Al-Qadi et al. [18] stated that as the thickness of the AC layers is reduced, the effects of stress-dependency of granular materials can become more pronounced. As such, variable pavement thicknesses have a direct impact on the predicted responses. In this context, Sahoo and Reddy [32] proved that consideration of the granular material's nonlinearity resulted in increased pavement responses, and the increased rates ranged from 35% to 44% considering the vertical subgrade strains and the surface deflections, respectively. Over the years, limited investigation efforts have focused on the combined effects of both the unbound material nonlinearity and varying pavement cross-sections.

1.3. Study's Objective

On these grounds, the purpose of the current study is to consider multiple pavement cross-sections with variable AC thicknesses and investigate how the potential variations in flexible pavement responses at critical locations could affect the outcome of pavement analysis in the context of pavement design, which is normally conducted according to MLET. A focus is also placed on low-volume roads (LVRs) since granular layers constitute the main structural contributor to these roads. The investigated responses include surface deflections, horizontal tensile strains at the bottom of the AC layer, and vertical compressive strains at the top of the subgrade. Variable analysis cases are considered with different modeling assumptions in the FEM environment related to the mechanical performance of the unbound materials, and multiple combinations of AC thickness and AC modulus are also assumed. Performing sensitivity analysis is arguably an effective means to investigate the weight of impact of several input parameters and enables pavement engineers to accurately select values for design and analysis purposes. Thus, routine analysis and decision-making procedures can be more reliably improved.

In this study, input values for thicknesses and moduli are based on current experience from pavement design and construction such that they cover a wide spectrum of relevant practices in pavement engineering. The mechanistic behavior of the unbound materials is considered through a User-defined MATerial subroutine (UMAT), as was presented and validated in [33]. The impact of the analysis type on the predicted responses is outlined in terms of quantification of variations, to assist pavement design optimization and enhance performance prediction of existing structures.

2. Resilient Modulus

The unbound materials respond to axial wheel loading in a nonlinear elastic manner. During the early stages of loading, the unbound materials face some plastic deformation. As shown in Figure 1, the plastic deformation rises slowly during the first load repetitions and remains nearly constant, irrespective of further load repetitions. Araya et al. [34] showed that after the first few load applications, the increment of non-recoverable deformation is much smaller compared to the increment of resilient/recoverable deformation. As such, plastic deformation can be considered negligible under normal conditions in the case of transient traffic loads.

Considering elastic deformation, the most appropriate stiffness modulus to capture the mechanical behavior of the unbound materials is the resilient modulus M_R. It is defined as follows:

$$M_R = \frac{\sigma_d}{\varepsilon_r} \tag{1}$$

where

- $\sigma_d = \sigma_1 - \sigma_3$, the deviator stress.
- ε_r, the recoverable strain.

The resilient modulus can be determined by utilizing triaxial testing in the laboratory, which is conducted by applying a repeated axial cyclic stress of fixed magnitude, load duration, and cycle duration to a cylindrical test specimen [35,36].

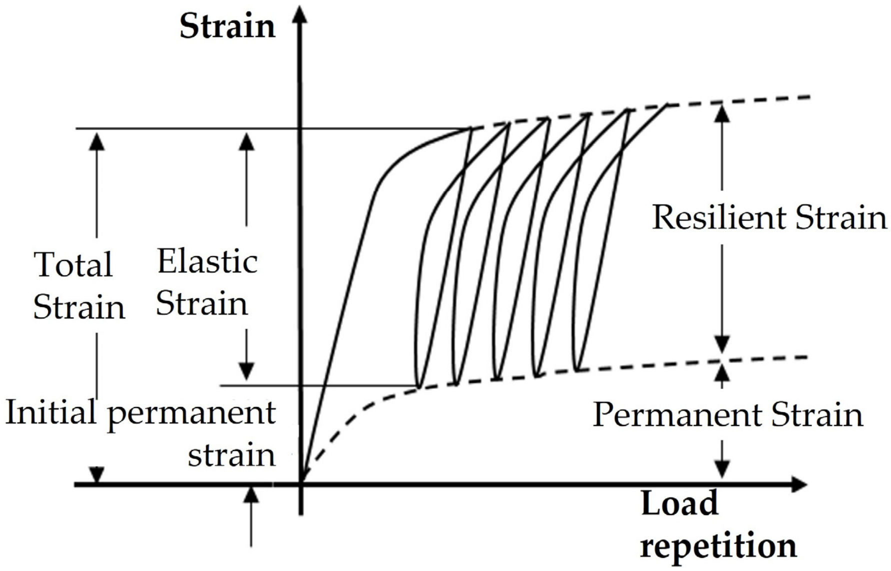

Figure 1. Deformation pattern of unbound granular materials.

With data from triaxial testing serving as inputs, a multitude of constitutive models have been developed to model the stress–strain dependency of the resilient modulus. In the current study, the Mechanistic-Empirical Pavement Design Guide (MEPDG) model is used to define the *MR* according to the following equation:

$$M_R = k_1 \cdot p_a \cdot \left(\frac{\theta}{p_a}\right)^{k_2} \cdot \left(\frac{\tau_{oct}}{p_a} + 1\right)^{k_3} \tag{2}$$

where

- θ, the bulk stress in kPa (calculated as $\sigma_1 + 2\sigma_3$).
- p_a, the atmospheric pressure in kPa.
- k_1, k_2, k_3, regression constants.
- τ_{oct}, the octahedral stress in kPa, calculated through the principal normal stresses as follows:

$$\tau_{oct} = \frac{1}{3} \cdot \sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_1 - \sigma_3)^2 + (\sigma_2 - \sigma_3)^2} \tag{3}$$

The MEPDG model is suitable for both the unbound materials and soil materials used for the base and subgrade layers, respectively. An advantage of this model is that it considers the hardening effect of bulk stress, as well as the softening effect of shear stress. Thus, for the unbound granular materials, k_2 is expected to be positive and k_3 is expected to be negative.

3. Methodology

3.1. Description of the Developed Model

In the current study, a typical flexible pavement structure is simulated (Figure 2), including the following:

(i) A unified AC layer with variable thicknesses to cover many cases from roads serving lower traffic volumes to more heavily trafficked pavements. The interest in low-volume roads (LVRs) is well-grounded based on other international studies linking the impact of material nonlinearity with this type of road, e.g., [18,32].
(ii) A 25 cm thick unbound granular base (crushed stone material).
(iii) A semi-infinite layer for the subgrade consisting of natural gravel.

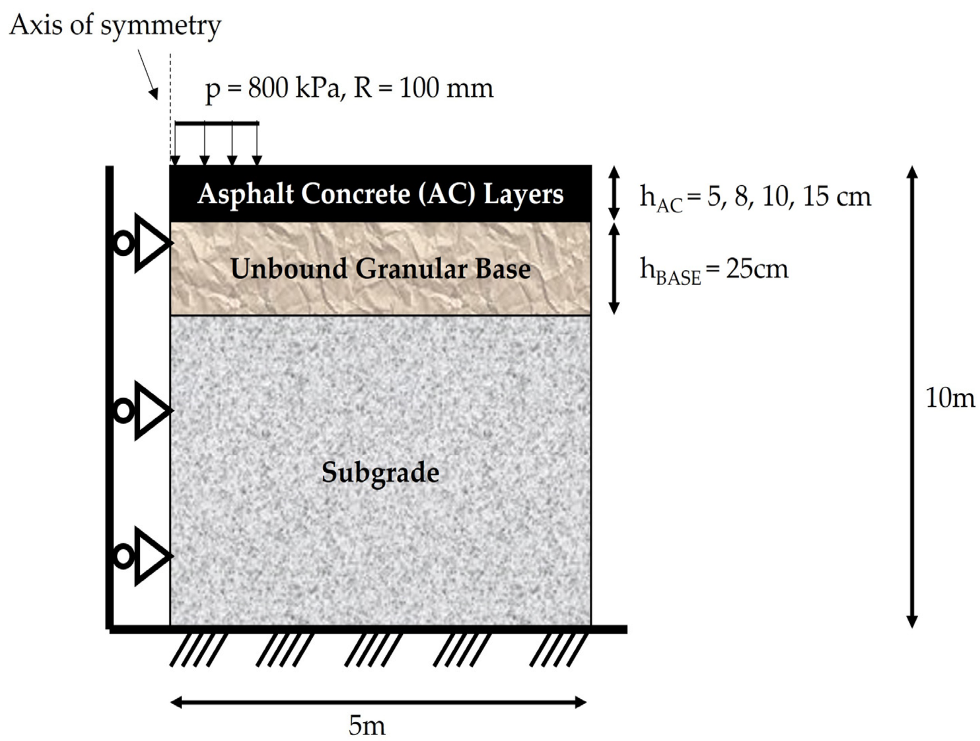

Figure 2. Pavement structure: 2D axisymmetric model.

The illustrated structure corresponds to a 2D axisymmetric model, which is generally preferred during routine analysis procedures since a single-axle loading (with one wheel in each part) corresponds to axisymmetric loading conditions, too. There is also no need to model the whole pavement structure. Thus, efficiency is achieved in both time and computation efforts.

Overall, the model dimensions in Figure 2 (i.e., length: 100 R, height: 50 R, R: radius of loading) were selected such that they eliminate boundary effects. With higher model dimensions, the impact of a rigid bottom (i.e., because of the fixed-end constraint shown at the bottom of the model, disabling any kind of displacement of rotation) tends to be absent. This means that the pavement structure is free to respond to the effect of wheel loading. Moreover, there is no need to add a restriction at the right part of the model if the width of the model is selected to be high enough. The left part of the model includes a simple roller constraint (shown in Figure 2) because of the axisymmetric conditions.

With respect to the mechanical properties of pavement materials, the values shown in Table 1 were used following relevant experience from pavement engineering design and construction processes, e.g., [37].

Table 1. Material properties.

Layer	Modulus (MPa)	Poisson's Ratio
AC	2000, 4000, 8000	0.35
Base	400	0.40
Subgrade	40	0.45

AC and subgrade layers were assumed to consist of linear elastic materials, to exclusively investigate the impact of the behavior of the unbound granular materials on pavement analysis. The constitutive model of the MEPDG was used to consider the unbound materials' characterization.

3.2. Response Calculations and Modeling Phases

The model shown in Equation (2) was coded in a subroutine and incorporated into a FEM model in ABAQUS. The flowchart of the FEM analysis with the UMAT subroutine is shown in Figure 3. The considered load was assumed to be static (uniform pressure of 0.8 MPa) from a single circular wheel, but it was imposed incrementally. The nonlinear analysis was based on the modified Newton's method with secant stiffness. The meshing of the model structure was carried out with quadratic elements of 8 nodes (CAX8R). Denser elements were considered near the area of loading, whereas a coarser meshing was applied for the rest of the structure (Figure 4). Finally, all of the layer interfaces were assumed to be fully bonded.

The critical locations for pavement response prediction included the surface deflection (u_{22}), the tensile strain (ε_{11}) at the bottom of the AC layer related to fatigue cracking, and the compressive strain (ε_{22}) at the top of the subgrade related to rutting phenomena.

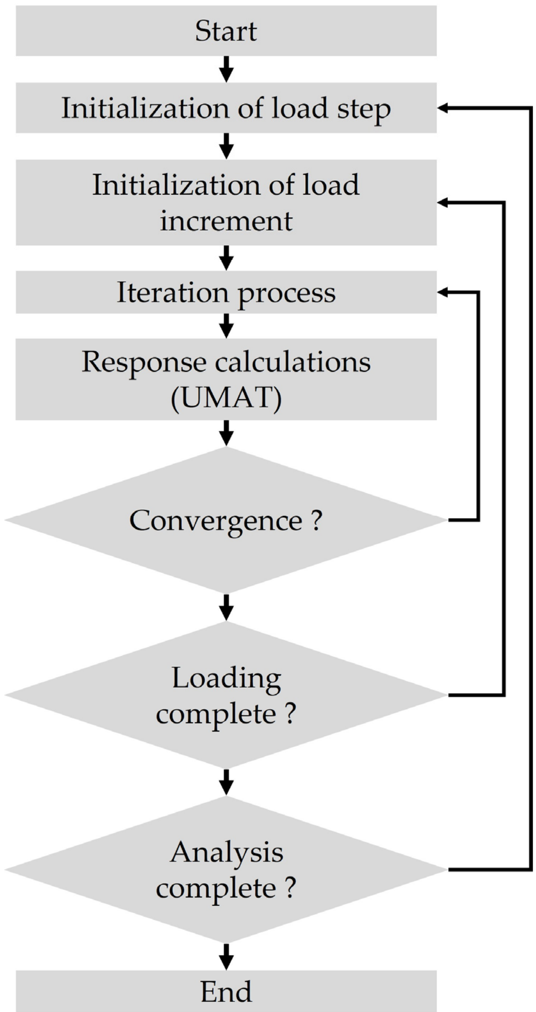

Figure 3. Analysis flowchart.

To support the interpretation of the results, the present investigation is separated into two phases. In phase A, a sensitivity analysis of pavement responses to the unbound materials' mechanical behavior is presented through five different cases, as per Table 2.

These cases were chosen to represent a wide range of assumptions that can be implemented, and to investigate which one seems more indicative for the next phase of the analysis. For cases 3 and 5, an anisotropic factor of n = 0.5 was assumed, indicating a 50% stiffness decrease horizontally. Initial loading included overburden stress of materials' self-weight and the initial compaction process. A uniform density of d = 2.2 ton/m^3 was assumed for the overall pavement structure. MEPDG regression constants in Equation (2) (k_1 = 0.918, k_2 = 0.91, and k_3 = −0.64), required for cases 2–5, were assumed, as per [38].

In phase B, a sensitivity analysis of the predicted pavement responses depending mainly on the AC modulus and thickness is presented (recall Table 1). Layer thicknesses and material properties for both phases of analysis were considered as per Figure 2 and Table 1, too. In phase B, only results from cases 1 and 5 were evaluated based on the justification provided in the following subsections.

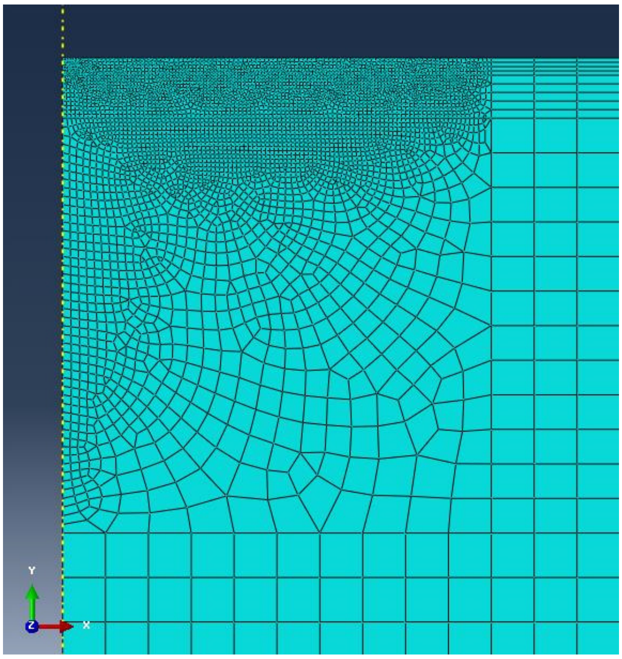

Figure 4. Mesh of the pavement structure (upper left part, near the loading area).

Table 2. Cases under investigation for the base layer material.

Case	Assumptions for the Unbound Materials
1	Linear analysis, Isotropic material
2	Nonlinear analysis, Isotropic material, No initial loading
3	Nonlinear analysis, Anisotropic material, No initial loading
4	Nonlinear analysis, Isotropic material, With initial loading
5	Nonlinear analysis, Anisotropic material, With initial loading

4. Results and Discussion

4.1. Analysis—Phase A

Full experimental results from the pavement response analysis are given in Tables 3–5. Variations can be seen during performance prediction as well as a significant underestimation of pavement responses through linear analysis in comparison to the other investigated cases. Overall, case 3 leads to higher predicted values for both the deflections and the strains. Yet, case 5 seems to be more realistic, since the initial stress–strain state within the structure is considered, thereby leading to a slight decrease in the estimated responses.

It can be argued that the presented differences in Tables 3–5 could affect the outcome of pavement analysis and design-based decision-making. This makes sense, considering that the use of more advanced mechanistic principles for material characterization can affect the selection of an analysis type or a constitutive model over another one by the engineers in charge. Design variations also have techno-economic implications, raising the interest in the accuracy of mechanistic modeling.

Figures 5–7 present predicted deflections and strains for the whole range of AC layer thicknesses from 5 to 15 cm. In particular, maximum deflections are predicted to be 1.39–1.98 times greater in case 5 than in the corresponding linear analysis. The ranges of ratios for tensile and compressive strain prediction are 1.63–2.61 and 1.62–3.23, respectively.

As expected, variations in predicted responses become greater with a progressive reduction in the AC thickness, highlighting the increased sensitivity of the unbound materials' nonlinear analysis to AC thickness during performance prediction, especially for LVR.

Table 3. Results for the surface deflections (μm).

Case	h_{AC} = 15 cm	h_{AC} = 10 cm	h_{AC} = 8 cm	h_{AC} = 5 cm
1	−0.383	−0.469	−0.518	−0.616
2	−0.526	−0.743	−0.885	−1.185
3	−0.538	−0.77	−0.925	−1.258
4	−0.52	−0.725	−0.858	−1.156
5	−0.533	−0.755	−0.899	−1.220

Table 4. Results for the tensile strains—AC bottom (μm/m).

Case	h_{AC} = 15 cm	h_{AC} = 10 cm	h_{AC} = 8 cm	h_{AC} = 5 cm
1	135	204	240	264
2	217	380	488	627
3	222	397	517	716
4	213	366	465	612
5	219	384	495	690

Table 5. Results for the compressive strains—top of the subgrade (μm/m).

Case	h_{AC} = 15 cm	h_{AC} = 10 cm	h_{AC} = 8 cm	h_{AC} = 5 cm
1	−250	−376	−451	−571
2	−374	−679	−923	−1462
3	−424	−775	−1193	−1975
4	−373	−678	−902	−1426
5	−404	−803	−1145	−1869

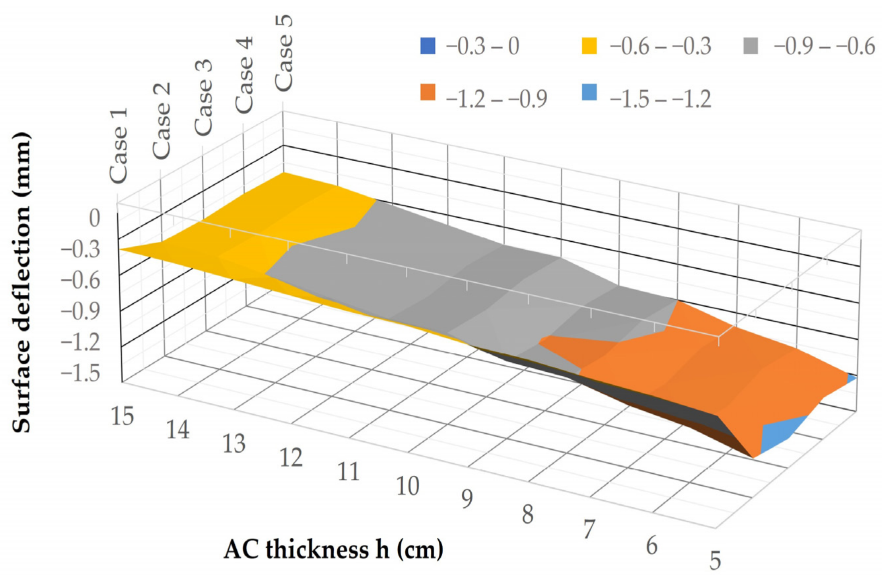

Figure 5. Variations in the predicted surface deflections.

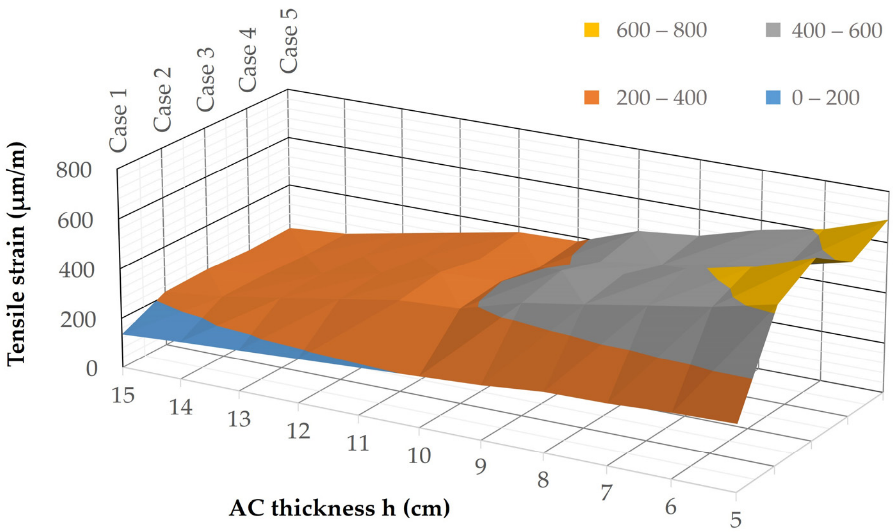

Figure 6. Variations in the predicted tensile strains at the AC bottom.

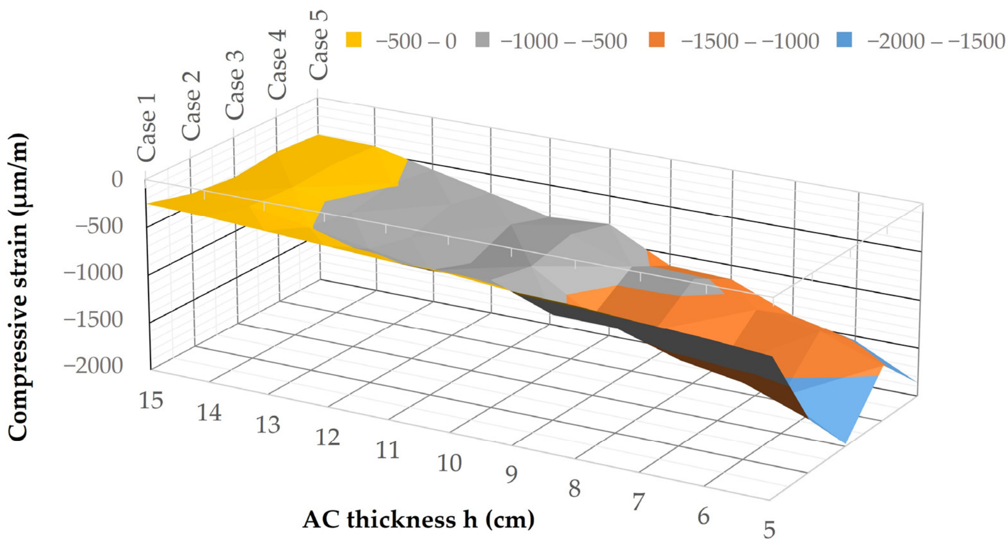

Figure 7. Variations in the predicted compressive strains at the top of the subgrade.

Considering relevant findings from the international literature [14,18,32], case 5 seems more realistic and capable of predicting the actual stress–strain state within a base layer with granular materials. Of course, the issue of uncertainties during the pavement performance prediction is always a challenge despite any kind of validation procedure. This is because the use of different assumptions for material characterization varies the predicted pavement responses. Although uncertainties in the actual pavement condition can be solved through instrumentation, this approach might only provide location-specific information and, most importantly, it is a laborious process. Problems and challenges related to the equipment's installation and the data acquisition process or interpretation force the related engineers to optimally combine existing analysis procedures to yield reliable conclusions about the pavement design and analysis needs.

Nevertheless, based on the results so far, it was decided to further compare the results from cases 1 and 5. Normalized values from case 5 (anisotropic material with initial loading) compared to case 1 (linear elastic analysis) are presented in Figure 8, to highlight the large variations observed with changes in the AC thickness. The other cases exhibited similar trends; thus, they are not presented in Figure 8.

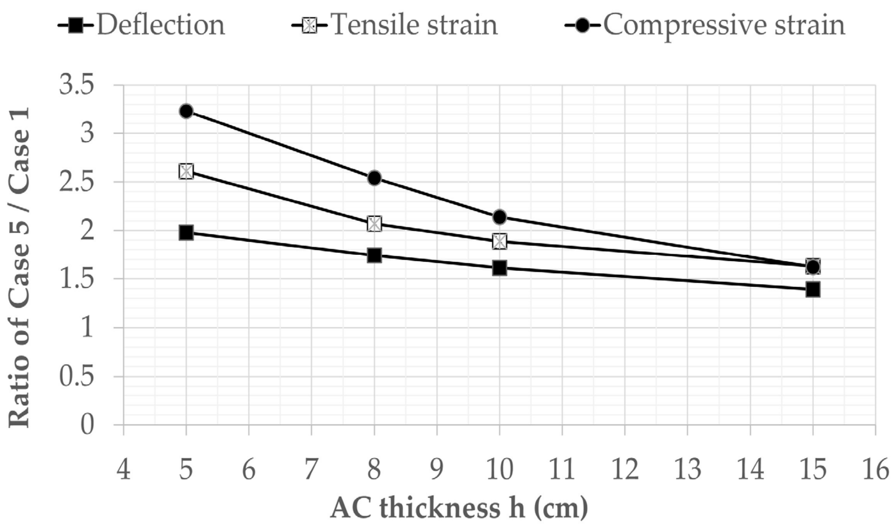

Figure 8. Comparison of cases 1 and 5 for surface deflection and critical strains.

For the AC thickness of 5 cm, the differences are most pronounced, with the results from the nonlinear analysis up to 3.5 times greater than those calculated from the linear analysis, which is the conventionally adopted approach during pavement design. Indeed, Table 5 shows that the compressive strain in case 5 was predicted to be 3.3 times higher than in case 1 for the section with an AC thickness of 5 cm. This provides evidence for the underestimation of predicted responses for thin AC layers when performing linear analysis.

From a practical perspective, considering that the majority of secondary road networks are often under-designed with small AC thicknesses, the performance of existing structures is usually poor, followed by insufficient maintenance planning, especially if the actual behavior of the unbound materials is ignored during pavement analysis. This suboptimal scenario can be magnified considering that secondary or mountain roadways are usually subject to extremely overloaded vehicles making journeys relating to emergent needs (e.g., transport of wind turbine blades), which can accelerate the deterioration rate of the roadway structure. As such, the conventional analysis type, i.e., case 1, is rather insufficient for pavement design and evaluation procedures.

Nevertheless, even for the largest AC thickness under investigation (15 cm), the differences in all predicted responses are still considerable. Thus, there is a margin for necessary improvements and optimization in the way pavement design takes place, which is further supported by the findings presented in Section 4.2.

4.2. Analysis—Phase B

In this stage, only cases 1 (Linear—L) and 5 (Nonlinear—NL) were examined. From the results shown in Figures 9–11, it can be seen that the most critical combinations (high ratios) were for low values of both the AC thicknesses and moduli.

For the section with an AC thickness of 5 cm and an AC modulus of 2000 MPa, the compressive strain on the top of the subgrade was estimated to be more than 3.5 times greater through nonlinear analysis in comparison to a linear analysis, indicating potentially increased deviations between the designed and the expected rutting life. This finding is in agreement with the international literature, e.g., [32], where it has been reported that linear elastic analysis can result in unsafe designs for LVR.

Indeed, in many areas worldwide, the focus of roadway engineering during design, evaluation procedures, and pavement management is erroneously put solely on highway pavements, which usually consist of thick AC structures. However, this is not the majority of the road network. Secondary roadways mainly serving lower traffic volumes are often under-designed when the conventional elastic analysis is followed, as this is a less conservative approach. In addition, secondary or mountain roadways are usually subject to extremely overloaded vehicles; because, in these cases, granular base material forms the main structural layer that carries the traffic load, the impact of the analysis type can be detrimental, as explained in the current study.

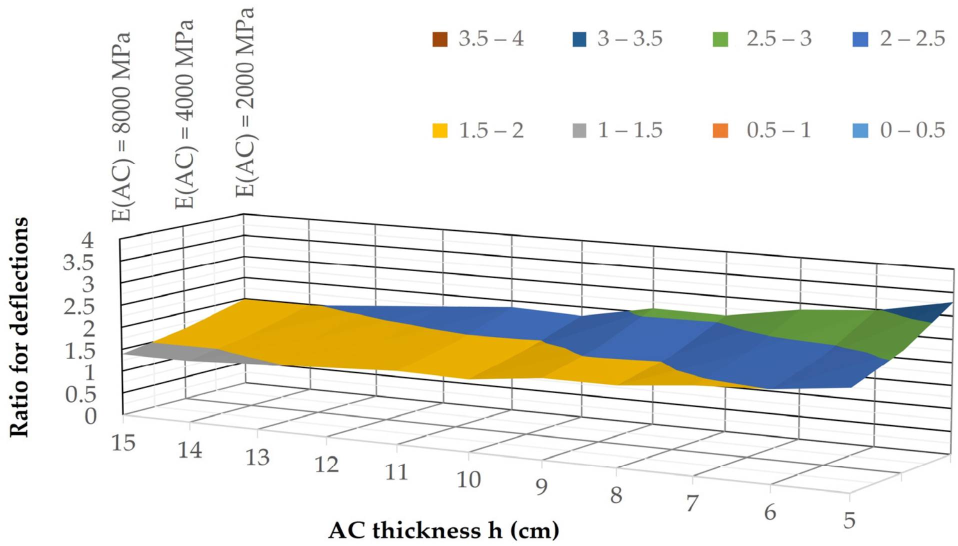

Figure 9. Sensitivity of deflections to AC modulus and thickness.

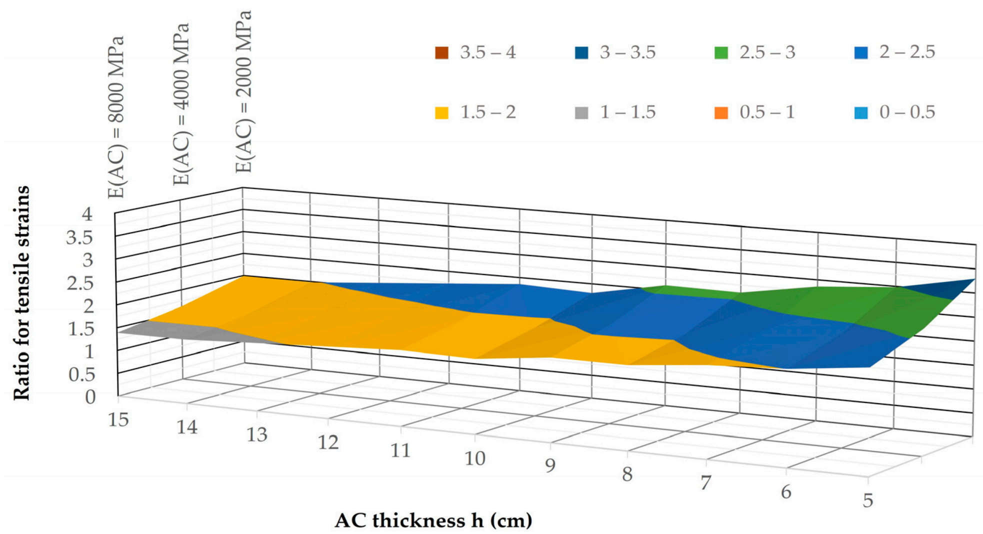

Figure 10. Sensitivity of tensile strains to AC modulus and thickness.

On the contrary, for a combination of high AC modulus and high AC thickness, the differences between linear and nonlinear analysis are less severe, yet they are still kept at considerable and significant levels. Although the focus of the current study was on the variation in AC thickness, variations in AC modulus are also expected, depending on the climatic conditions in a specific area. For example, during the summer months in Southern Europe, increased temperatures within the AC layers can soften the AC materials, thereby leading to a reduced modulus that can exacerbate the impact of granular material nonlinearity during the pavement response analysis, based on the indications from Figures 9–11.

It becomes evident that through a FEM sensitivity analysis, preliminary indications can be provided when there is a need to compare the design values with the as-built values and further estimate deviations in the expected pavement responses, thereby enabling a rough estimation of how fatigue or rutting life is affected based on the predicted strains.

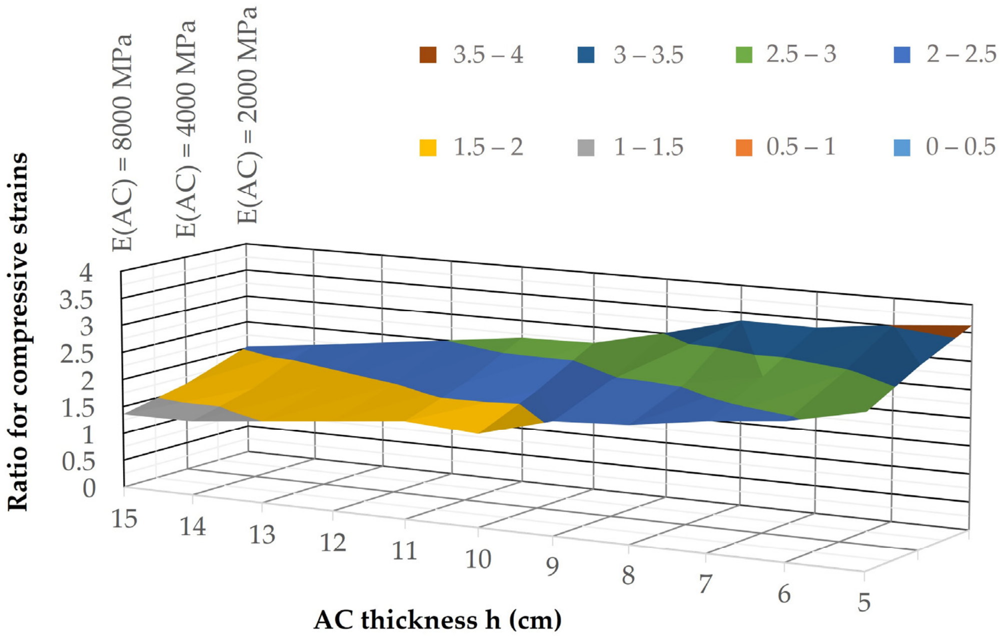

Figure 11. Sensitivity of compressive strains to AC modulus and thickness.

5. Conclusions

Incorporating material behavior in the pavement design to improve and optimize performance prediction is promising. Assuming linear elastic behavior of all pavement materials may lead to underestimated predictions of the expected responses, leading to improper pavement design and construction assessment. Among several cases investigated in a FEM environment to capture road materials' variability, the nonlinear analysis of the unbound materials considering their anisotropic behavior, but with no initial loading, caused the greatest predicted responses for all critical locations. Yet, the nonlinear analysis with anisotropic unbound materials and initial loading (self-weight) resulted in slightly reduced responses at critical locations. This case may lead to a more accurate calculation of responses due to the consideration of the initial self-weight of the materials.

Significant variations in the predicted mechanical responses were also indicated through the sensitivity analysis depending on different AC thicknesses and moduli, and these variations seem to cause uncertainties within pavement design or evaluation if they are not fully understood and taken into consideration. This problem can become more noticeable in pavements designed for LVR that present increased susceptibility to the AC thickness and modulus, highlighting the need to fully include the unbound materials' nonlinearity during performance prediction in these types of roads. From a practical engineering perspective, the design, the evaluation procedures, and the pavement management of LVR need to be systematically improved and become more conservative in favor of safety, to produce long-lasting and sustainable structures.

Overall, knowledge of variations in the predicted responses was found to be necessary for the rational design of road structures protected against either rutting or fatigue cracking. To that extent, pavement numerical simulation and performance modeling may potentially act as an optimization and risk assessment tool, to assist reliable performance prediction in a way that bridges the knowledge gap between advanced modeling and routine analysis. From a practical perspective, this can provide road agencies with the capability of comparing what is constructed with what is designed.

A limitation of the proposed method is the computational and time resources required to execute the related analysis, a factor that could make the related pavement engineers and road stakeholders reluctant to widely apply mechanistic approaches to base material characterization during pavement design or analysis. A future research prospect that should be highlighted is the need to formulate a large database with a variety of regression constants for different materials, so that consideration of material nonlinearity can become more feasible in other cases and conditions through advanced modeling techniques, e.g., artificial intelligence (AI), etc. Performing extensive sensitivity analysis will enable a vast database to be created, ideally for alternative materials and under the effect of different constitutive models, an aspect that could support the application of AI during the design process of roadway pavements based on more mechanistic assumptions for the unbound materials.

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