SLOVAK JOURNAL OF CIVIL ENGINEERING

Vol. XXI, 2013, No. 2, 15 – 20 DOI: 10.2478/sjce-2013-0008

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COMPARISON OF PAVEMENT LAYERS RESPONSES WITH CONSIDERING DIFFERENT MODELS FOR ASPHALT CONCRETE VISCOELASTIC PROPERTIES

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ABSTRACT

In this paper, a comparison between pavement responses is performed by considering two different models for the linear viscoelastic behavior of an asphalt concrete layer. Two models, the Maxwell model and the Kelvin-Voigt model, are generalized. The former is used in ABAQUS and the latter in KENLAYER. As a preliminary step, an appropriate structural model for a flexible pavement structure is developed in ABAQUS by considering linear elastic behavior for all the layers. According to this model, when the depth of a structural model is equal to 6 meters, there is a good agreement between the ABAQUS and KENLAYER results. In this model, the thickness of the pavement is equal to 30 centimeters, and the thickness of the subgrade is equal to 5.7 meters. Then, the viscoelastic behavior is considered for the asphalt concrete layer, and the results from KENLAYER and ABAQUS are compared with each other. The results indicate that the type of viscoelastic model applied to an asphalt concrete layer has a significant effect on the prediction of pavement responses and, logically, the predicted performance of a pavement.

KEY WORDS

- *Flexible pavements,*
- *viscoelasticity,*
- *ABAQUS,*
- *KENLAYER,*
- *FEM.*

1. INTRODUCTION

The mechanical responses of pavements are of primary importance in pavement analysis and design. This is especially significant for flexible pavements in order to determine the tensile strain at the bottom of the asphalt concrete layer and the vertical strain above the subgrade. For this purpose, different programs, each of which has specific hypotheses, have been developed to analyze asphalt pavements. Most of these programs have been developed by considering a multi-layered elastic system structure for a pavement, such as BISAR, KENLAYER and JULEA. However, several programs such as CAP 3D have used the finite element method to determine the strains and stresses in pavement layers. In this program, C++ programming language has been used and the finite element method incorporated to analyze pavements by considering linear and nonlinear behavior for granular materials (Holanda et al., 2005). Since the finite element method is advantageous when compared with the layered theory, it is useful for the analysis and backcalculation of pavement structures (Gopalakrishnan, 2009). In previous works, analyses of pavements by general finite element programs, such as ABAQUS, have been done. This research has considered either 2-dimensional or 3-dimensional models for a pavement structure. In research done by Hadi and Bodhinayake (2003), a model was made using ABAQUS software for a 4-layer pavement. In this model, the granular layers behaved in a nonlinear manner, and a 20 kN load was applied to the pavement's surface (Hadi and Bodhinayake, 2003). In other work done by Cho (1996), the effects of 2-dimensional and 3-dimensional models were scanned on the pavement responses by ABAQUS software (Cho et al., 1996). Also, hybrid methods have been used to determine deflections in pavement layers. For example, a combination of the finite element method and the artificial neural network method have been considered for the nonlinear behavior

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of a base layer using the New SDUFEM program (Saltan and Sezgen, 2007). Additionally, in order to consider the nonlinear behavior of granular layers, previous works have applied different models to compare the responses with each other (Sadrnejad et al., 2011).

An asphalt concrete layer in a flexible pavement behaves the same as elastoviscoplastic materials, but, under some circumstances such as during small strain magnitude, asphalt concrete can be considered as a linear viscoelastic material (Saltan and Sezgen, 2007). Thus, viscoelastic models are required to simulate the time-dependent behavior of a pavement. Different models are used to consider the asphalt viscoelastic properties. Therefore, attention to the differences between the responses from various models can be useful for a better understanding of the behavior of an asphalt layer as well as for more precisely determining the stresses and strains in pavement layers. In this area, the effect of the loading time on the dynamic response of a pavement has also been studied using the finite element method and considering the asphalt concrete layer with a viscoelastic property (Yin et al., 2008). In addition, in a new method for the design of a flexible pavement, i.e., the Mechanistic Empirical Pavement Design Guide (MEPDG), the viscoelastic properties of asphalt concrete have been characterized using a master curve, thereby capturing the dynamic response (NCHRP, 2004). Accordingly, the objectives of this paper are to compare the structural responses of flexible pavements by considering various models for the viscoelastic properties of asphalt concrete.

2. MATERIALS AND METHODS

The first step for a comparison of flexible pavement responses when considering various models for the viscoelastic properties of an asphalt concrete layer is to develop a structural model of a flexible pavement in ABAQUS, which uses the finite element method and considers the viscoelastic properties of an asphalt concrete layer. Then, the ABAQUS and KENLAYER results are compared. In other words, the ABAQUS and KENLAYER software consider the different material models for the viscoelastic properties of asphalt concrete and can show the differences between the results from each model. First of all, a structural model with appropriate dimensions must be developed for a three-layer flexible pavement in ABAQUS. This structural model is developed with the assumption of linear elastic behavior for the pavement layers, and the accuracy of the structural model is controlled by comparing the ABAQUS results with KENLAYER. Then, the viscoelastic behavior is considered for the asphalt concrete layer and others with a linear elastic behavior. In this manner, the ABAQUS results can be compared with KENLAYER.

3. VISCOELASTIC BEHAVIOR OF ASPHALT CONCRETE

When an asphalt binder as a viscous liquid is mixed with an elastic aggregate to make asphalt concrete, the mixture will have a viscoelastic behavior. Under the effect of traffic, if the loads exerted would not be of a high magnitude, the mixture would exhibit viscoelastic behavior instead of viscoplastic behavior. The following equation is used to show linear viscosity (Chen, 2009):

$$\sigma(t) = \eta \frac{d\varepsilon(t)}{dt} \tag{1}$$

in which $\sigma(t)$ and $\varepsilon(t)$ denote stress and strain, respectively, and η the viscosity.

Linear elasticity is shown by a spring model based on Hooke's law (Huang, 2004):

$$\sigma(t) = E\varepsilon(t) \tag{2}$$

$$\varepsilon(t) = D\sigma(t) \tag{3}$$

Where E and D denote the modulus and compliance of elasticity which are related by (Rowe et al., 2001):

$$\int E(\zeta)D(t-\zeta) = t \tag{4}$$

Generalized models have been developed to determine the relaxation modulus and creep compliance for viscoelastic materials. The generalized Maxwell model consists of a spring and M Maxwell elements connected in a parallel manner, as shown in Figure 1. The generalized Kelvin-Voigt model consists of a spring and N Kelvin elements connected in a series, as shown in Figure 2. The generalized Maxwell model is used in ABAQUS software and the generalized Kelvin-Voigt model in KENLAYER software.

The relaxation modulus for the generalized Maxwell model is presented by a Prony series written as (Chen, 2009):

$$\sigma(t) = \int_0^t E(t-s) \, {\partial\varepsilon}/{\partial t} \, ds \tag{5}$$

$$E(t) = E_e + \sum_{m=1}^{M} E_m e^{\left(-t/\rho_m\right)} \tag{6}$$

$$\rho_m = \frac{\eta_m}{E_m} \tag{7}$$

where ρ_m is the relaxation time.

It is necessary to input prony series coefficients in ABAQUS to consider the viscoelastic properties of asphalt concrete. Also, the data from a creep or relaxation test can be used.

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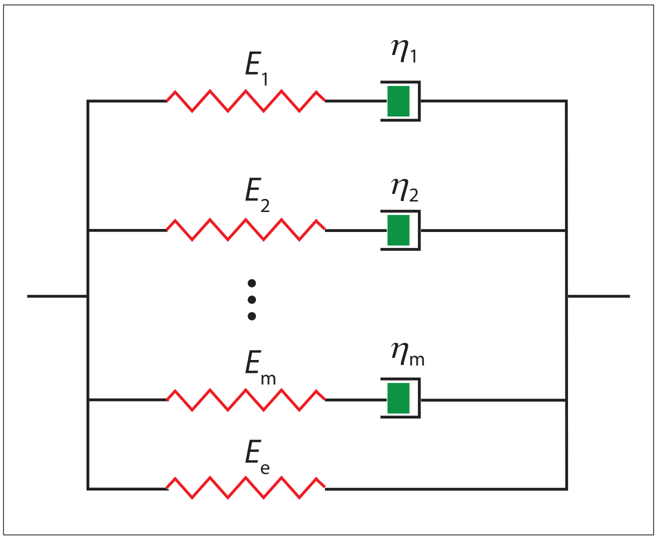

Fig. 1 *Generalized Maxwell model.*

In KENLAYER software, creep compliance is presented by a generalized Kelvin-Voigt model that can be written as (Huang, 2004):

$$D(t) = \frac{1}{E_0} + \sum_{i=1}^{n} \frac{1}{E_i}\left[1 - e^{\left(-t/T_i\right)}\right] \quad (8)$$

where T_i is the retardation time.

Equation (8) reveals that the creep compliance for the generalized Kelvin-Voigt model is similar to that for the generalized Maxwell model as in Equation (6), or in other words, the generalized Maxwell model and generalized Kelvin-Voigt model are equivalent to each other (Sargand, 2002).

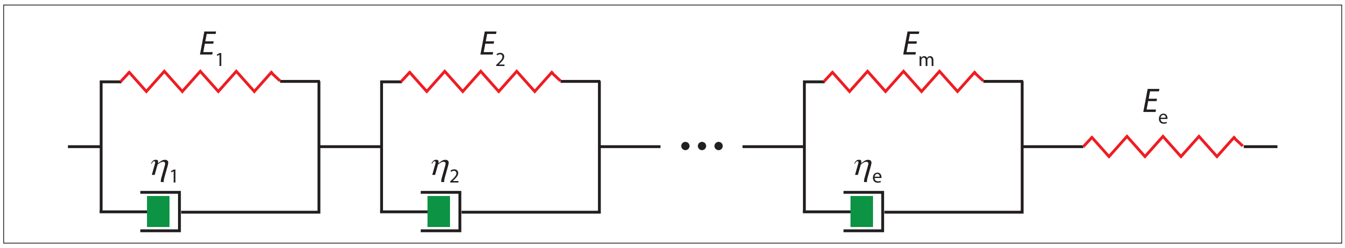

Fig. 2 *Generalized Kelvin-Voigt model.*

4. PAVEMENT STRUCTURE

The pavement structure selected for this study consists of an asphalt concrete layer as the surfacing course, a base layer and a subgrade layer at the bottom. The configuration of the pavement structure is shown in Table 1. As is shown, the pavement's thickness is equal to 30 centimeters. To model the viscoelastic properties of an asphalt concrete layer, the prony series coefficients have been gathered according to the asphalt mixture constructed in SHRP A-415 (SHRP, 1994). Table 2 shows these coefficients for an asphalt concrete layer.

Tab. 1 *Pavement configuration (Holanda et al., 2005).*

Layer Name	h	E	ν
	mm	MPa	–
AC	100	3500	0.35
Base	200	350	0.3
Subgrade	Varied	100	0.45

Tab. 2 *Viscoelastic properties of an asphalt concrete layer for a generalized Maxwell model (SHRP, 1994).*

i	E_i (kPa)	ρ_i
infinite	1172000	-
1	3100000000	2.20E-05
2	4310000000	2.20E-04
3	3460000000	2.20E-03
4	2020000000	2.20E-02
5	1270000000	2.20E-01
6	272000000	2.20E+00
7	65900000	2.20E+01
8	14500000	2.20E+02
9	1520000	2.20E+03
10	710000	2.20E+04
11	58800	2.20E+05

5. RESULTS

5.1 ABAQUS model for a pavement structure

For an analysis of a flexible pavement structure using ABAQUS

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software, a model was built with the following features:

- A 3-layer system was considered for a pavement with the above configuration.
- A quarter of the pavement section was considered for the modeling.
- The asphalt concrete layer was first assumed to have elastic behavior; then the viscoelastic properties of this layer was considered.
- The subgrade and base layers were assumed to have linear elastic behavior.
- This pavement was subjected to a loading equal to 20 kN. This load was exerted on a quarter of a circle with a 150 millimeter radius.
- It was essential to choose a domain size that gives the most accurate pavement responses from the FE analysis. Duncan et al. (1968) reported that reasonable pavement responses were obtained when the analysis boundary moved to 40 times the radius of the circular loading area (R) in the vertical direction and 12-times *R* in the horizontal direction (Duncan et al., 1968). According to this study, a domain size was selected equal to 3 meters for the width and length of the model and 6 meters for the vertical direction of the model. In other words, the pavement's thickness is 30 centimeters, and the subgrade's thickness is equal to 5.7 meters. Although Kim (2000) found that the influence of the boundary truncation was negligible for domains larger than about 150 times *R* in a vertical direction (Kim, 2000), there is a good agreement between the ABAQUS results with those of the KENLAYER by considering the above dimensions for the model as illustrated in Table 3.
- The finite element mesh generated for a three-dimensional model consisting of 3667 brick elements is shown in Figure 3. As can be seen, the area subjecting to the loading of the wheel has a finer mesh. Also, Figure 4 compares the linear interpolation order of the elements with the quadratic ones. As illustrated, there is a better agreement between the ABAQUS results with the KENLAYER results by considering the quadratic elements.
- The vertical displacements of the nodes on the bottom plane of the model were prohibited.
- The lateral displacements of the nodes in the symmetrical plane were prevented.

Therefore, the 3D FE model developed was deemed accurate enough to model the viscoelastic properties of the asphalt concrete next and to analyze the flexible pavement. The critical stresses and strains in flexible pavements are shown in Table 3, and there is an exact agreement between the ABAQUS and KENLAYER results.

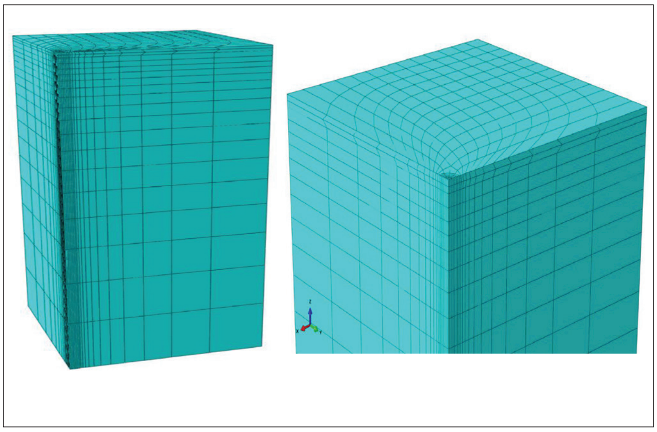

Fig. 3 *3-dimensional finite element meshes used for the selected domain size.*

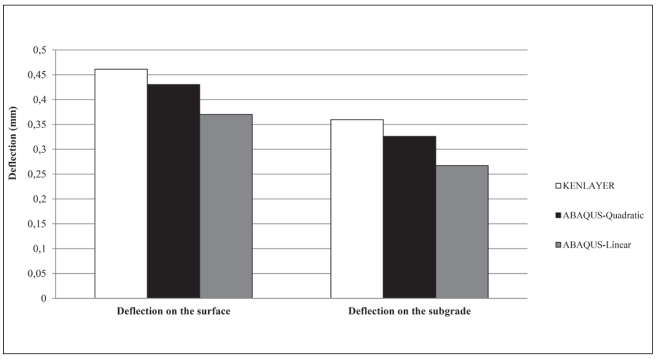

Fig. 4 *Comparing the ABAQUS results with the KENLAYER results by considering the quadratic and linear types for the geometric order.*

Tab. 3 *Results by considering the elastic behavior for the asphalt concrete layer.*

Specification	Unit	ABAQUS	KENLAYER	Difference (%)
Surface Deflection	mm	0.43	0.461	6.72
Tensile Strain at the bottom of AC layer	με	+216.93	+217.8	0.4
Tensile Stress at the bottom of AC layer	MPa	+1.0359	+1.036	0.01
Vertical Strain above Subgrade	με	–345.9	–363.9	4.95
Vertical Stress above Subgrade	MPa	–0.0595	–0.0653	8.88

+ Tension – Compression

5.2 Flexible pavement analysis considering the viscoelastic properties for the asphalt concrete layer

To consider the viscoelastic properties for an asphalt concrete layer, an interconversion between the relaxation modulus and the creep compliance must be done. By the equations (9) to (11), the coefficients of the generalized Maxwell model can be converted to the Voigt model (Kim, 2009; Park and Schapery, 1999). Then, equation (4) can be used to determine the creep compliances at a reference temperature (21 ^{0}C) for a number of time durations that can be used in KENLAYER to model the viscoelastic properties of an asphalt concrete layer. So, by considering the coefficients illustrated in Table 2 for the generalized Maxwell model and these equations, the coefficients of the Voigt model have been determined and shown in Table 4.

$$[A]\{D\}=\{B\} \tag{9}$$

$$A_{kj}=\begin{cases} E_e(1-e^{-\left(\frac{t_k}{\tau_j}\right)})+\sum_{i=1}^{m}\frac{\rho_i E_i}{\rho_i-\tau_j}(e^{-\left(\frac{t_k}{\rho_i}\right)}-e^{-\left(\frac{t_k}{\tau_j}\right)})when:\rho_i\neq\tau_j \\ or \\ E_e(1-e^{-\left(\frac{t_k}{\tau_j}\right)})+\sum_{i=1}^{m}\frac{t_k E_i}{\tau_j}(e^{-\left(\frac{t_k}{\rho_i}\right)})when:\rho_i=\tau_j \end{cases} \tag{10}$$

$$B_k=1-\left(E_e+\sum_{i=1}^{m}E_i e^{-\left(\frac{t_k}{\rho_i}\right)}\right)/\left(E_e+\sum_{i=1}^{m}E_i\right) \tag{11}$$

By considering models with the above properties, the ABAQUS and KENLAYER results can be compared when an asphalt concrete layer behaves in a linear viscoelastic manner. The deflections, strains and stresses obtained for the pavement layers by considering all the layers with linear elastic behavior and the asphalt concrete layer with viscoelastic behavior are shown in Table 5. These results indicate that the pavement responses obtained from ABAQUS are lower than those from KENLAYER. Also, the amount of the difference in the horizontal tensile stress at the bottom of the asphalt concrete layer is higher than the other results from these software products. The main reason for this difference is that the horizontal tensile stress at the bottom of the asphalt concrete layer is highly dependent on the asphalt concrete modulus and that the different models considered for the viscoelastic behavior of the asphalt concrete layer in these software products give a different modulus for asphalt concrete.

Tab. 4 *Viscoelastic properties of an asphalt concrete layer for the Voigt model.*

i	D_i (1/kPa)	τ_i
infinite	6.89E-11	-
1	8.41E-11	5E-05
2	1.20E-10	5E-04
3	1.50E-9	5E-03
4	2.69E-9	5E-02
5	4.30E-9	5E-01
6	5.56E-9	5E+00
7	1.43E-8	5E+01
8	4.85E-8	5E+02
9	3.52E-7	5E+03
10	4.21E-7	5E+04
11	5.39E-7	5E+05

6. CONCLUSIONS

To consider the viscoelastic behavior of asphalt concrete, different models can be used. Therefore, to compare these models with

Tab. 5 *Results by considering the viscoelastic behavior for the asphalt concrete layer (for 100 seconds).*

Specification	Unit	ABAQUS	KENLAYER	Difference (%)
Surface Deflection	mm	0.232	0.304	23.68
Tensile Strain at the bottom of AC layer	με	+62.17	+77.93	20.22
Tensile Stress at the bottom of AC layer	MPa	+1.41	+2.08	32.21
Vertical Strain above Subgrade	με	-149.45	-179	16.51
Vertical Stress above Subgrade	MPa	-0.0292	-0.0338	13.61

+ Tension – Compression

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each other, the ABAQUS and KENLAYER software products were used because two different material models are used in these software products to consider the viscoelastic behavior of asphalt concrete. According to the structural models constructed in ABAQUS, the 6-meter depth for the 3-D structural model with quadratic brick elements resulted in responses that better matched the layered elastic theory when all the pavement layers had linear elastic behavior. In this structural model, the thickness of the subgrade was considered equal to 5.7 meters, and the thickness of the pavement was equal to 30 centimeters. Also, when comparing the results from ABAQUS and KENLAYER for flexible pavement responses when the asphalt concrete layer had viscoelastic behavior, it was concluded that the pavement layers deflections, strains and stresses were fewer when the generalized Maxwell model was used for asphalt concrete than when the generalized Kelvin model was used. Therefore, the type of model used to characterize the asphalt concrete's viscoelastic properties has a significant effect on predicting pavement responses and damage from traffic loading, although they may be the same when considering elastic behavior for all the pavement layers. According to this research, it is recommended to use various models and software products when considering the viscoelastic properties of an asphalt concrete layer to design flexible pavements.

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