LOADING RESPONSES COMPARISON BETWEEN LABORATORY TESTING AND NUMERICAL MODELING FOR HOT-MIX ASPHALT SPECIMENS

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ABSTRACT

This paper presents the results of 3D finite element model for flexible pavement to investigate its response to various loading conditions. Because hot-mix asphalt is susceptible to time of loading and temperature changes, it is simulated as a viscoelastic material. Results from the 3D finite element method are compared to laboratory results. The laboratory specimen comprises of 50 mm of wearing surface, 150 mm of binder base, and 40 mm of neoprene, to simulate the base layer. The developed numerical model was capable of predicting the hot-mix asphalt specimen response to loading. This will allow the optimization use of reinforcements in flexible pavement as to its location and type.
Keywords: Flexible pavement, FE modeling, viscoelasticity.

1. INTRODUCTION

The presented work is part of an ongoing research. The objective of the research is to study the effects of various interlayer reinforcement, placed in the flexible pavement system at different depths, on the structural capacity of the pavement as well as its capability to reduce reflective cracking. In this paper, 3D finite element (FE) models were developed and the analysis results were compared to laboratory testing data. The purpose of the modeling is to allow examining loading and response parameters that could not be applied or measured in the laboratory due to limitation in time and/or resources. A centered force-controlled compressive test was conducted on a square specimen (500x500mm). The test is intended to simulate simplified pavement tire loading. The loading area is related to the tire-pavement contact area.

Three dimensional finite element method (FEM) is quite common for engineering applications, such as pavement design and analysis. The basic concept in the physical FEM is subdividing the simulated system into disjoint components of simple geometry called *finite element*. Each element possesses a set of distinguishing points called *nodal points* in order to define their geometry. The response of each element is expressed in terms of a finite number of degrees of freedom (DOF) characterized as the value of an unknown function, or functions, at a set of the nodal points. The response of the model is then considered to be approximated by a discrete model obtained by connecting or assembling the collection of all elements. Because of its versatility, one of the most popularly used FE software is Abaqus.

1.1 Material characterization

Prior to pavement modeling, hot-mix asphalt (HMA) was characterized to determine the properties needed for the numerical simulation. Complex modulus and phase angle were found using the MEPDG method [Pellinen et al. 2002]. A 100-mm diameter and 110-mm high HMA cylinders were obtained by coring from HMA slabs. The slabs were prepared in the same methods as the ones used for the testing. The sigmoidal master curve to obtain the complex modulus at various temperatures was developed (Fig. 1).

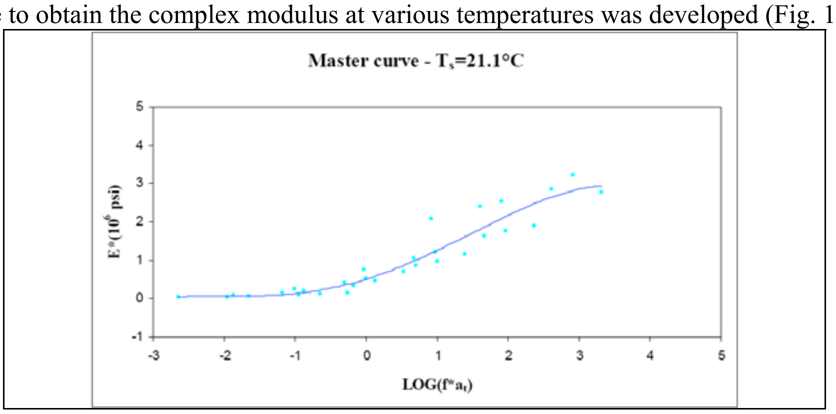

Figure 1 Master Curve of binder base

In order to simulate the viscoelastic behavior of HMA, a generalized Maxwell model was used. The corresponding expression of this theory is presented in a *"Prony series"* [ABAQUS 6.6]:

$$g_R(t) = 1 - \sum_{i=1}^{N} g_i \left[1 - e^{-t/\tau_i}\right] \qquad \text{(Eq. 1)}$$

where:
g_R = shear relaxation modulus (dimensionless);
g_i = Prony series parameters
N = the number of parameters in the series;
t = time (second);
τ_i = reduced time (second).

This approach allows reproducing the viscoelasticity in a time domain. The Hirsh model was used to calculate the needed parameter of $|E^*|_{max}$ from the complex modulus testing [Von Quintus, 1994 and Christensen et al., 2003]. HMA volumetric characteristics were obtained including VTM (air void in total mix), VMA (voids in the mineral aggregates) and VFA (voids filled with asphalt) in accordance with AASHTO T 166-93 [AASHTO 1998] and a binder modulus of 1 GPa was assumed to limit the maximum modulus.

The calculated elastic moduli were converted into shear moduli and then normalized with respect to the instantaneous shear moduli associated with the instantaneous modulus of elasticity (E_0). During the conversion, the shear moduli [G(t)] variation with time was estimated assuming that Poisson's ratio (υ) has a relatively small effect on pavement behavior and does not change with time (assuming that the material is isotropic and homogeneous and that the resulting strain is small) [Elseifi et al. 2006]. The Poisson's ratio was chosen from literature [Montepara et al. 2005a].

The model was then validated. The Complex modulus was conducted at 21.1°C and at 0.1 Hz, 0.5 Hz and 1 Hz. This temperature was the closest to that used when the centered compressive test was conducted,18°C. Low frequency was selected to simulate the laboratory loading frequency at which the HMA viscoelastic characteristics are manifested. In order to reproduce the same sinusoidal wave in Abaqus, Fourier series was used:

$$a = A_0 + \sum_{i=1}^{n} \left[A_n \cos n\omega(t - t_0) + B_n \sin n\omega(t - t_0)\right] \qquad \text{(Eq. 2)}$$

where:
ω = angular frequency;
A_n, B_n = Fourier coefficient;
t = time;
A_0 = initial amplitude.

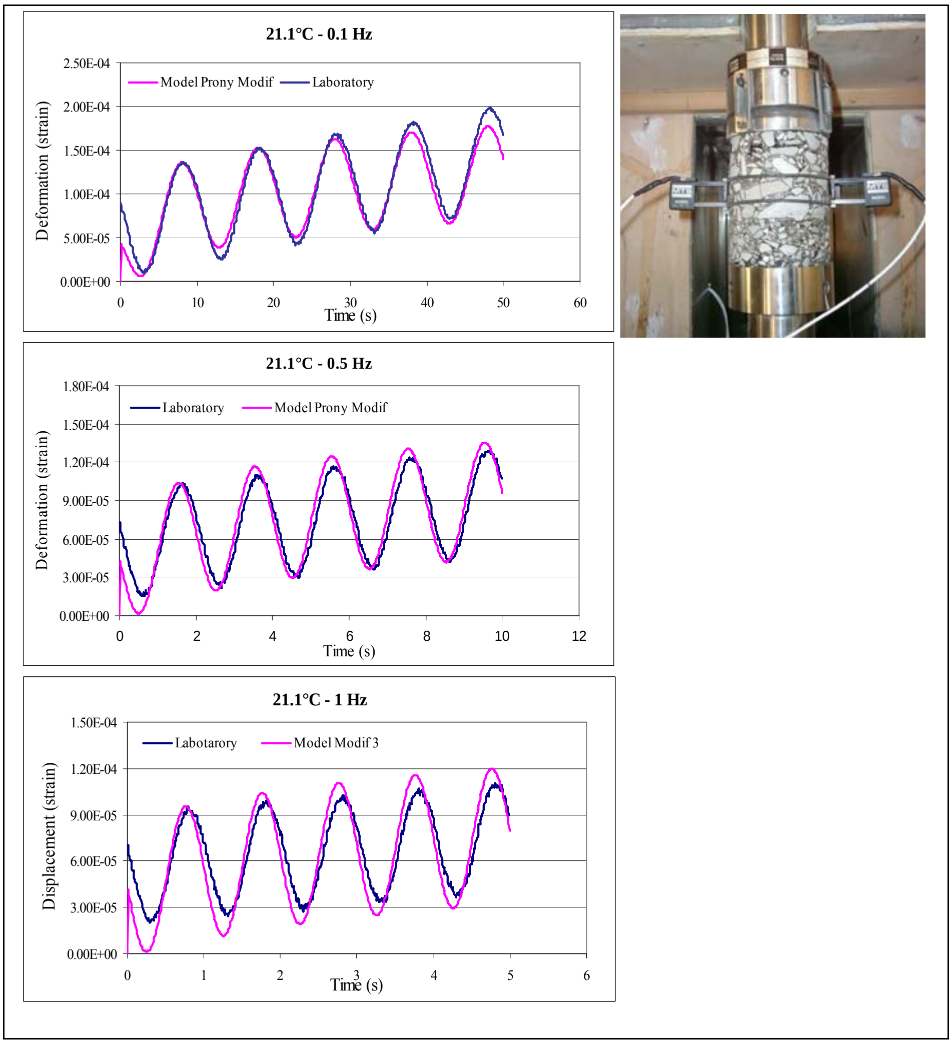

Figure 2 Extensimeter on the cylinder and comparison between strains in laboratory and in the modeling at various frequencies

This approach allows expressing all the continuous periodic functions with T period (2π), which are a linear combination of sin and cos. In this case the wave is a sin function; hence, the parameters needed for Abaqus input can be determined.

During the HMA cylinder testing of the complex modulus, two extensimeter were placed on the lateral surface of the cylinder. The vertical displacements with a precision of 10^{-4} mm were measured. Modeling and laboratory results compared as presented in Fig. 2. It is evident that the laboratory and modeling results are in agreement and have similar trends.

1.2 Experimental evaluation

The laboratory tests were conducted using square specimen (500x500 mm) and 200-mm-thick. The pavement was composed of a 50 mm wearing surface layer and 150 mm binder base. At the bottom of the specimen, the subbase was simulated by placing a 40 mm neoprene layer. The specimen size was selected in order to reduce any edge effects during loading. It was reported that the effect of vehicle tire is within 500 mm of the tire loading center, Fig. 3 [Montepara et al. 2005, b].

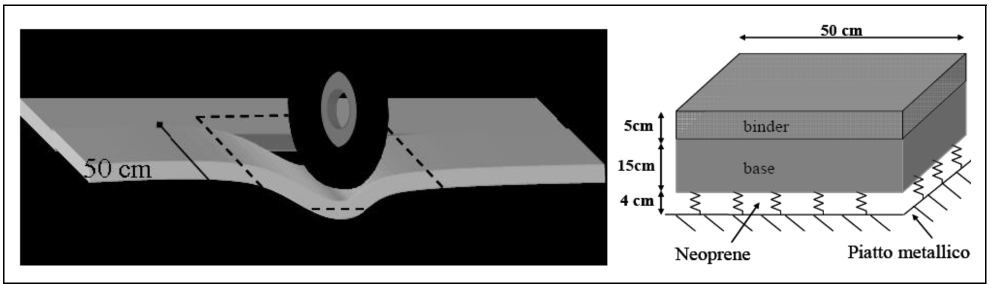

Figure 3 Specimen size and pavement system layers

For specimen preparation, a compactor capable of simulating field compaction was used [Montepara et al. 2005,a]. The specimen was loaded using a force-control test. The loading pattern included two “loadings” for 15 sec (from 0-5 kN and 5-10 kN), two rest periods of 3 min and an unloading period of 30 sec (Fig. 4). Extensimeter was used to measure horizontal displacements close to the loading area (Fig. 5).

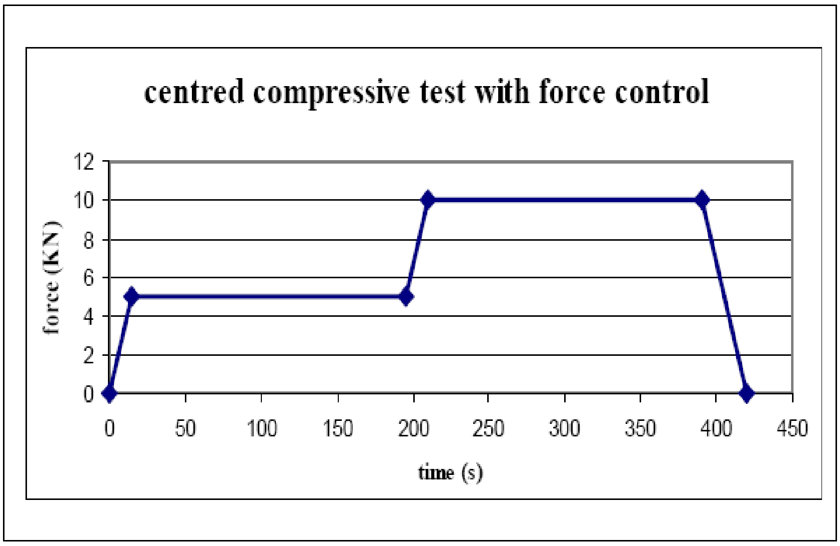

Figure 4 Load curve in the centred compressive test

Figure 5 Extensimeter applied around the load mark

A FE model was developed using Abaqus 6.6. 3D deformable solids were used, and all layers (wearing surface, binder base, and neoprene layers) have the equivalent geometrical characteristics. For each layer, hexahedron-shape elements were chosen, although the sizes may differ. A fine mesh was used under the loading, and a coarser mesh was used away from the loading area (Fig. 6).

For HMA layers (wearing surface and binder base layers), the elastic parameters, Young's modulus and Poisson's ratio, were used in addition to the viscoelastic characteristics utilizing the Prony series. For the neoprene layer, only elastic characteristics were used. Loading simulated the one applied in laboratory was used. Various "loading amplitudes" were simulated. In each steps, it was necessary to establish the initial boundary condition. Therefore, the vertical movements at the bottom of the specimens were halted. Similar conditions were utilized in the laboratory where a steel plate is positioned under the neoprene layer.

In order to simulate the loading ramp, a pressure was applied to the center of the wearing surface layer. An isotropic Coulomb friction model was selected between layers to simulate the tangential and normal behavior at interfaces. The friction parameter μ was set equal to 1 [Al-Qadi et al. 2004; Romanoschi, 2001].

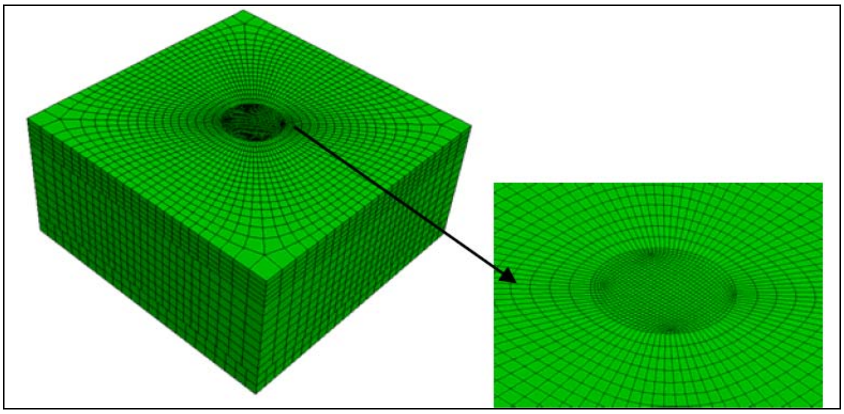

Figure 6 Finite element mesh of the wearing surface layer

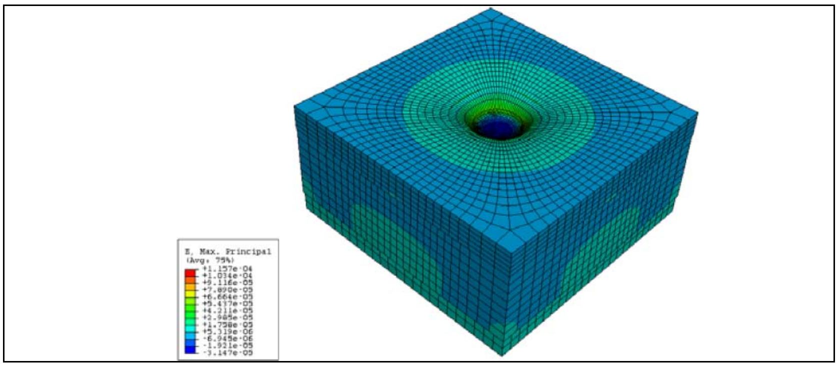

Figure 7 Trend of strain in the specimen

Fig. 7 shows typical strain trends during loading. Fig. 8 presents a comparison between modeling and laboratory results of the horizontal displacements in the wearing surface layer. Therefore, it is clear that the developed model is capable of predicting the laboratory testing. The greatest difference in horizontal displacements in the model and in laboratory is 0.0024 mm.

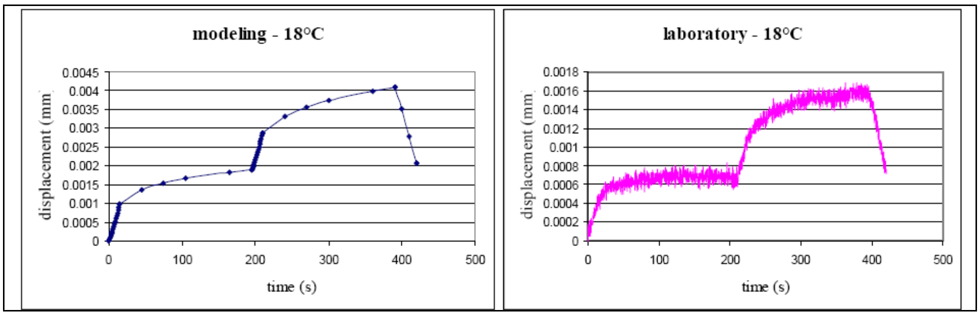

Figure 8 Horizontal displacement in laboratory and modeling at 18°C

SUMMARY

This paper presents results from ongoing research to develop a numerical model capable of predicting reinforced flexible pavement response to loading. The proposed model simulates HMA as a viscoelastic material and makes use of the Prony series. Good agreement was achieved between the pavement response using the developed model and the laboratory testing data. It also shows that the developed model is capable of predicting reinforced flexible pavement behavior. The model will be used to optimize the reinforcement type and position in the flexible pavement system.

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