Comparison of Elastic and Viscoelastic Modeling for Asphalt Concrete Surface Layer

Fouzieh Rouzmehr, Mehdi Mousavi

***Abstract*—**Hot mix asphalt concrete is a viscoelastic material, and its stress-strain relationship depends on the loading duration and the strain rate. To investigate the effect of elastic and viscoelastic modeling under traffic load, asphalt concrete pavement is modeled with both elastic and viscoelastic properties and the pavement performance is predicted. The differences of these two models are investigated on fatigue cracking and rutting problem which are the two main design parameters in flexible pavement design. Although the differences in rutting problem between two models were negligible, in fatigue cracking, the viscoelastic model results were more accurate. Results indicate that modeling the flexible pavement with elastic material is efficient enough and gives the acceptable results.

***Keywords*—**Flexible pavement, asphalt, FEM modeling, viscoelastic, elastic, ANSYS.

I. INTRODUCTION

HOT mix asphalt concrete (HMAC) is a mixture of aggregates and bitumen. The primary ingredient that determines the mechanical properties of HMAC is the bitumen in it, which displays viscoelastic behavior under normal service conditions. For simplicity, asphalt concrete is considered as an elastic material, but this is far from reality at high service temperatures and longer loading times. Viscoelasticity means that the material's stress-strain relationship depends on the strain rate and loading duration.

In the measurement of the physical properties of bitumen, primary emphasis is generally given to the characterization of the rheological behavior of the material. In this context, rheology is defined as the study of the deformation or flow properties of materials whether in liquid, melted or solid form, in terms of the materials' elasticity and viscosity [1], [2]. In terms of its rheology, bitumen can be classified as a thermoplastic, viscoelastic liquid that behaves as a glass-like elastic solid at low temperatures and/or during rapid loading (short loading times – high loading frequencies) and as a viscous (Newtonian) fluid at high temperatures and/or during slow loading (long loading times – low loading frequencies). As a viscoelastic material, bitumen exhibits both elastic and viscous components of response and displays both a temperature and time dependent relationship between applied stresses and resultant strains. The rheology of bitumen is consequently defined by its stress-strain-time-temperature response [3].

In this study, asphalt modeling has been performed in completely similar conditions, both elastic and viscoelastic, so that these two models can be compared and the degree of elastic closeness to viscoelasticity can be compared with the diagrams and numbers obtained from the software.

The goal of this project is to simulate mechanical response of flexible pavements using linear elastic and viscoelastic modeling of asphalt concrete and predict pavement performance. Falling Weight Deflectometer (FWD) load will be simulated and the results for elastic and viscoelastic modeling will be evaluated. The viscoelastic simulation is performed by prony series, which will be modeled by using ANSYS software.

Fatigue cracking and rutting are the major distresses of the flexible pavement. The surface distresses by fatigue cracking and rutting are shown is Figs. 1 (a) and (b). Asphalt pavement is engineered to support a specific volume of vehicles and vehicles within a specified weight range. Calculations for foundation thickness and asphalt depth are based on the loads that the pavement is expected to withstand. If the paving is heavier than what is built to support it, it can cause fatigue cracking.

Rutting is the surface depression in the wheel path. Ruts are particularly noticeable after rain when the wheel paths are filled with rain. Basically, there are two types of rutting in the flexible pavement: subgrade rutting and mix rutting. When the subgrade has not rut yet, but the pavement surface exhibits wheel path depressions, we have compaction/mix design problems. Subgrade rutting occurs when the subgrade exhibits wheel path depressions due to loading. In this case, the pavement settles into the subgrade ruts causing surface depressions in the wheel path.

Horizontal tensile strain at the bottom of asphalt layer is a predictor of fatigue life, which is shown in Fig. 2 (a), and the vertical compressive strain at the top of subgrade is a predictor of rutting, as it is shown in Fig. 2 (b).

II. STRUCTURAL ANALYSES OF PAVEMENT

The structural responses of flexible pavement due to the application of FWD load were evaluated using 3-dimensional finite element program, ANSYS. Fig. 3 shows the overall geometry of the analysis model and the location of applied load is at the center of the surface, the dimension of the model is 80-in × 80-in in X and Z direction and the dimensions in Y direction for all layers are shown in the figure. The pavement has five different layers: asphalt, base, subbase, compacted

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subgrade and subgrade (native soil). The assumption is that the soil layer at a certain depth is assumed fixed with no impact due to traffic load.

Fig. 1 (a) Fatigue cracking

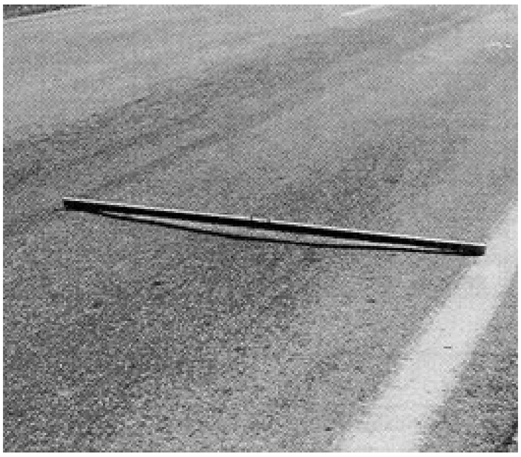

Fig. 1 (b) Rutting

Elastic Modeling

In flexible pavement, it is important to have a good stiffness ratio (3 to 5) between the top layer and the bottom one. To evaluate the effect of stiffness ratio for the layers, two different material properties were selected to model the elastic material. Table I shows the material property for the layered pavement without considering the good elastic modulus ratio for the layers and Table II shows the material property with considering the good stiffness ratio between layers.

TABLE I
PROPERTY 1 OF PAVEMENT LAYERS

	Elastic Modulus (ksi)	Poisson's ratio
HMAC	400	0.35
Base	50	0.35
Subbase	12	0.4
Subgrade	12	0.4
Native soil	7.5	0.42

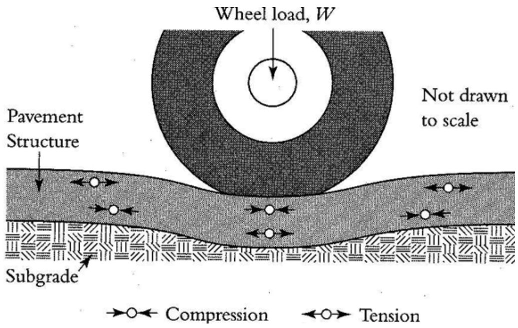

Fig. 2 (a) Fatigue cracking predictor

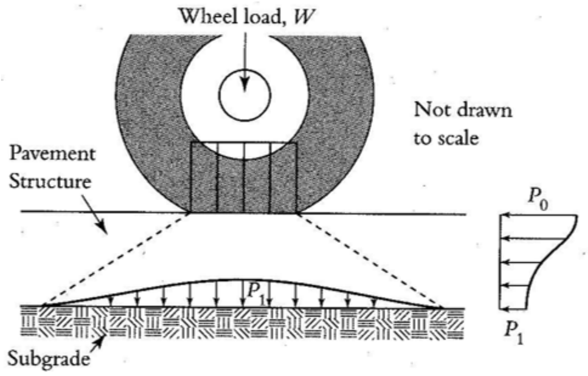

Fig. 2 (b) Rutting predictor

TABLE II
PROPERTY 2 OF PAVEMENT LAYERS WITH GOOD STIFFNESS RATIO

	Elastic Modulus (ksi)	Poisson's ratio
HMAC	400	0.35
Base	80	0.35
Subbase	16	0.4
Subgrade	12	0.4
Native soil	7.5	0.42

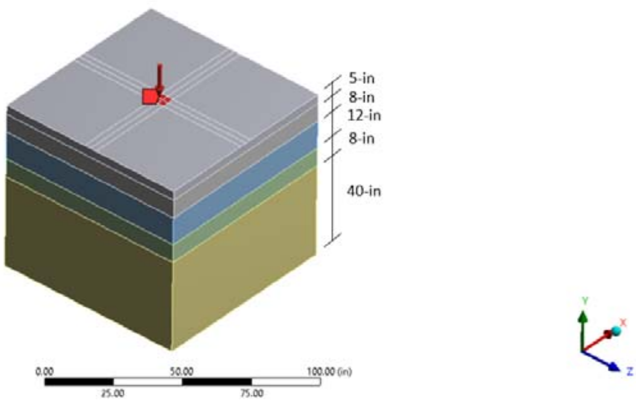

Fig. 3 Geometry of the model in ANSYS

In flexible pavement design, tensile strain at the bottom of surface layer and compressive strain at the top of last layer play an important role in structural response of the pavement and they will imply the number of loads for fatigue (N_f) and rutting (N_d) respectively. Therefore, the amounted of these values are compared with the two material properties from Tables I and II. The results are collected in Table III.

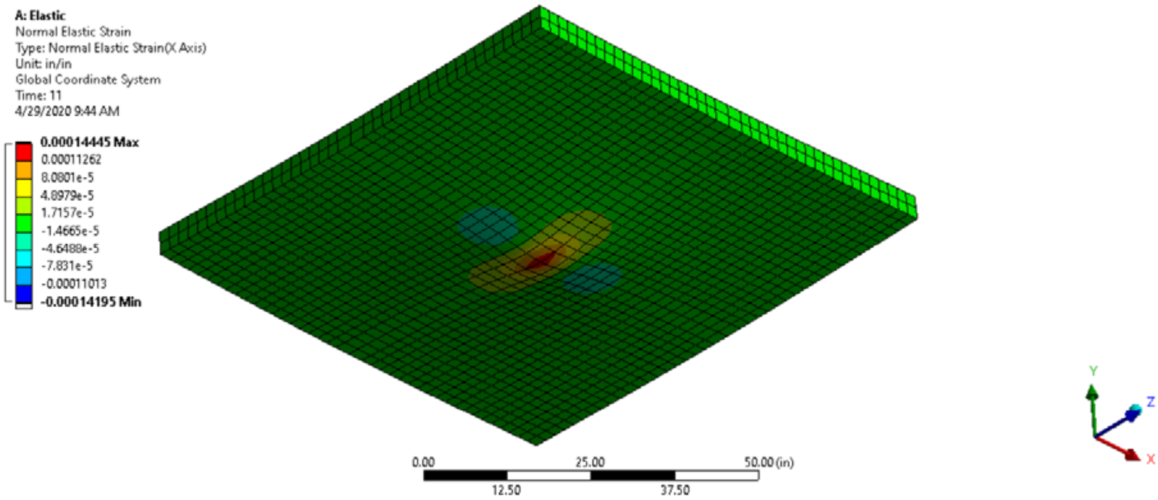

Fig. 4 Strain result of HMAC

TABLE III
COMPARING THE RESULTS OF ELASTIC MODELING WITH PROPERTY 1 AND PROPERTY 2

	Property 1	Property 2
Tensile stress at the bottom of surface layer (micro strain)	144	114
Compressive strain at top of the last layer (micro strain)	109	99

From Table III we can see that the strains coming from a good-ranged stiffness ratio is less and it shows that good stiffness ratio is very important for flexible pavement. Therefore, the property shown in Table II has been chosen for the flexible pavement.

Viscoelastic Modeling

Asphalt binders have been shown to undergo significant time-dependent stiffening when stored at low temperatures. This phenomenon, often referred to as physical hardening, has a significant impact on the laboratory performance of asphalt binders. Glass relaxation happens in a range of temperature during transition from equilibrium to super cooled liquid. The viscoelastic model can be applied to simulate glass behavior during the glass transition phase and to predict the glass deformation and stress evolution. Viscoelasticity displays both viscous and elastic characteristics when deformation happens [4].

The theory of viscoelasticity includes two types of phenomenon: stress relaxation and structural relaxation. Structural relaxation describes the time-dependent volume change due to temperature change and thermal history.

In this paper, a framework of materials manufacturing model is developed for implementing a complete viscoelastic model with structural relaxation and stress in Ansys.

Williams-Landel-Ferry Shift Function

The Williams–Landel–Ferry Equation (or WLF Equation) is an empirical equation associated with time–temperature superposition of asphalt as a continuous function of conditioning time and temperature. The idea behind this model is that the input thermal strain can be divided into small increments for which the relaxation response can be easily computed and added in time to obtain the total thermal stress [4]. T_0 is the reference temperature and C1 and C2 are the constants [5].

$$log\alpha T = -\frac{C1(T-T0)}{C2+(T-T0)}$$

Previous researchers have shown that the C1 and C2 values for unaged and aged bitumen can be taken as 19 and 92, respectively [6]. However, the values of C1 and C2 are inconsistent from one sample to the next. Generally, the WLF equation does not fit bitumen rheological data with the same set of constants above and below the softening point, where |G*| (complex shear modulus) is increasingly dominated by viscous and elastic effects, respectively. The complex shear modulus can be considered the sample's total resistance to deformation when repeatedly sheared, while the phase angle (δ) is the lag between the applied shear stress and the resulting shear strain. Based on this argument, one might expect poor superposition of |G*| data taken over a frequency interval sufficiently wide as to include both glassy and viscous asymptotes for the master curve [7]. In addition, Chailleux et al. [8] attempted to link the WLF coefficients to the physicochemical state of bituminous binders. They found the C2 parameter was linked to the thermal dependency of the materials with an increase in C2 value with ageing. The constants C1 and C2 were chosen 16 and 126 respectively from the maximum and minimum range, which are collected in a table by Yusoff et al. for aged and unaged bitumen materials [5]. A shift function widely used in glass simulation is the one proposed by Narayanaswamy [9], which considers the influence of fictive temperature.

Modeling Viscoelastic Behavior

In ANSYS mechanical solutions, viscoelasticity is applied with a Prony series. The Prony-series representation of shear modulus G(t) is used for the time-dependent behavior of viscoelastic materials. The shear and volume responses are separated, and there are well-known relationships between the shear modulus G and the bulk modulus K.

$$G = \frac{E}{2(1+\nu)}$$

$$K = \frac{E}{3(1-2\nu)}$$

Instead of having constant values for G and K, these are provided by the Prony series viscoelasticity, in which G and K are function of t, and t starts from zero. The material has the full stiffness at time zero and the stiffness will decrease by increasing the time. For simplicity only G(t) is considered in the modeling [10].

Fig. 5 (a) shows a Maxwell element, with a spring and a dashpot to represent the elastic and viscoelastic behavior. In this model strain will increase over time and is not instantaneous.

For asphalt mixes, there is evidence that a simple model is not enough to describe the viscoelasticity behavior, it is necessary to use generalized Maxwell element. Generalized Maxwell element consists of a number of spring and dashpot in parallel [10].

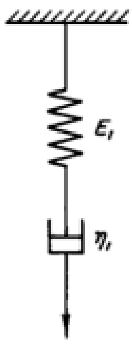

Fig. 5 (a) Maxwell model

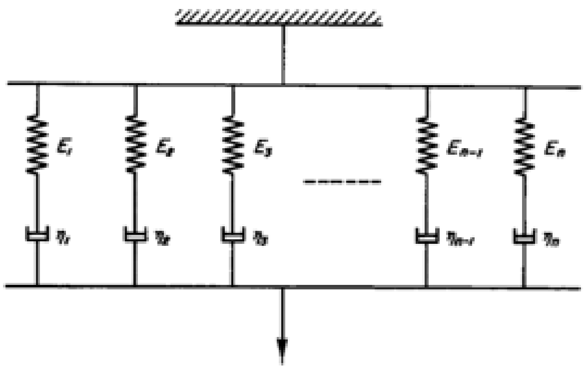

Fig. 5(b) Generalized Maxwell model

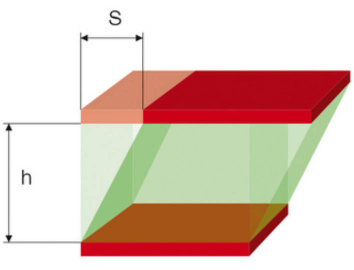

Fig. 6 Shear deformation

Shear Modulus

The relation between shear modulus G, shear stress τ, and shear strain or shear deformation γ [12] is according to:

$$G = \tau/\gamma$$

$$\gamma = S/h$$

Shear Modulus Data

Asphalt binders can be considered as thermo-rheologically simple material. For such materials, the change of properties at a constant loading time due to temperature change may be achieved with a change of loading times at constant temperature. Material property curves at different temperatures are translated parallel to the time axis if loading time is altered. By shifting a range of material property curves along the loading time or temperature axis at a reference temperature or loading time respectively, a "master curve" of the material property may be generated [4].

One of the primary analytical techniques used in analyzing dynamic oscillatory data involves the construction of master curves using the interrelationship between temperature and frequency (time) to produce a continuous rheological parameter curve at a reduced frequency or time scale [3].

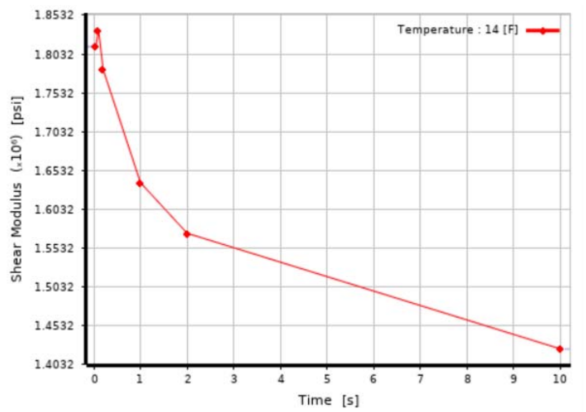

Fig. 7 (a) Shear modulus data for viscoelastic material for 14 °F

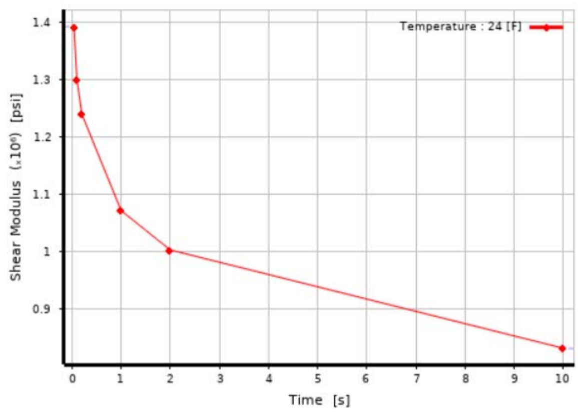

Fig. 7 (b) Shear modulus data for viscoelastic material for 24 °F

World Academy of Science, Engineering and Technology
International Journal of Civil and Environmental Engineering
Vol:16, No:11, 2022

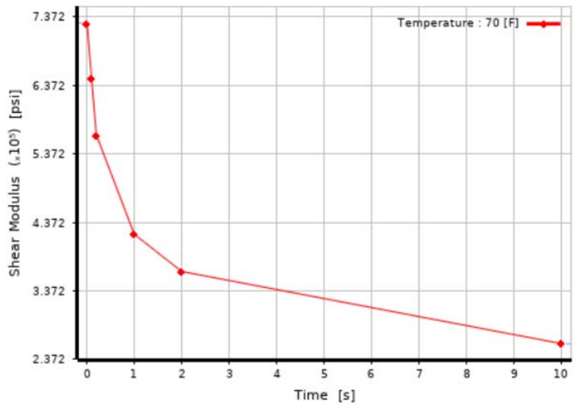

Fig. 7 (c) Shear modulus data for viscoelastic material for 70 °F

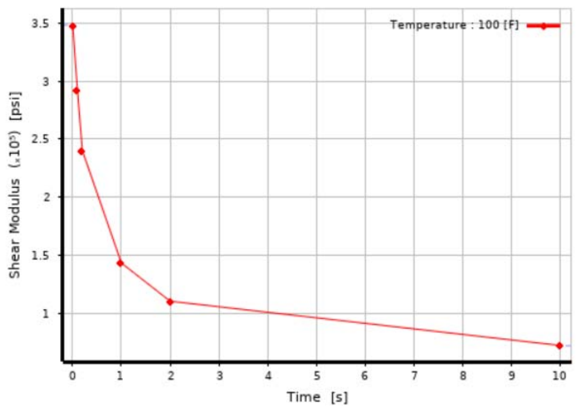

Fig. 7 (d) Shear modulus data for viscoelastic material for 100°F

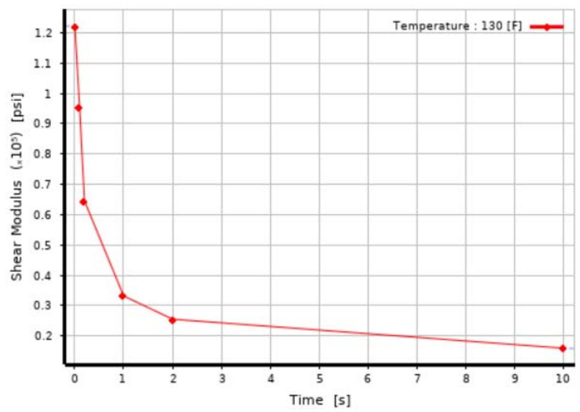

Fig. 7 (e) Shear modulus data for viscoelastic material for 130 °F

Load is applied in 10 seconds. Five different temperatures are considered for the asphalt (14, 24, 70, 100 and 130 degrees Fahrenheit) and for each temperature, shear data are written during the 10 second, which is divided in six different phases. Shear modulus is decreasing with time for a constant temperature and shear modulus is changing with temperature as it is shown in Figs. 7 (a)-(e). The environmental temperature considered for this model is 50 degree Fahrenheit.

III. Results and Conclusions

In flexible pavement design, tensile strain at the bottom of surface layer and compressive strain at the top of last layer play an important role in structural response of the pavement and they will imply the number of loads for fatigue (N_f) and rutting (N_d) respectively as the Asphalt Institute [13] represents them by:

$$N_f=0.0796\,(\varepsilon_t)^{-3.291}(E_1)^{-0.854}$$

$$N_d=1.365\times10^{-9}\,(\varepsilon_c)^{-4.477}$$

According to these equations, N_f and N_d are function of tensile strain at the bottom of surface layer and compressive strain at top of the last layer respectively.

With comparing the results from ANSYS collected in Table IV, we can say that compressive strain on top of the last layer has not changed much (99 and 100 micro strain); therefore, the resulting N_d is not very different by modeling the HMAC as elastic or viscoelastic material. In addition, the strain at the bottom of the HMAC layer has changed by almost 8% (114 and 123 micro strain).

TABLE IV
Comparing the Results of Elastic and Viscoelastic Modeling of HMAC

	Elastic	Viscoelastic
Tensile strain at the bottom of surface layer (micro strain)	114	123
Compressive strain at top of the last layer (micro strain)	99	100

For fatigue cracking, if we consider viscoelastic material the result varies and it will be more accurate, but for rutting problem it does not change the results very much. However, since the change in the results is negligible, modeling the HMAC as an elastic material would be the easier approach and it is acceptable.

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