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Asphalt Pavement Aging and Temperature Dependent Properties through a Functionally Graded Viscoelastic Model, Part-II: Applications

Eshan V. Dave[1,a], William G. Buttlar[1,b], and Glaucio H. Paulino[1,c]

[1]Department of Civil and Environmental Engineering, University of Illinois,
205 N. Mathews Avenue, Urbana, IL 61801, United States

[a]edave@illinois.edu, [b]buttlar@illinois.edu, [c]paulino@illinois.edu

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Abstract. This is the second article in a series of two papers describing simulation of functionally graded viscoelastic properties in asphalt concrete pavements. The techniques developed are applicable to other viscoelastic material systems with continuous, spatial grading of material properties. A full-depth asphalt concrete pavement has been simulated to demonstrate the applicability and importance of the graded viscoelastic analysis method. Based on the graded finite elements developed by Kim and Paulino[1], Buttlar et al. [2] used graded finite elements to determine typical responses to tire loading for an aged asphalt concrete pavement. In the current study, a similar pavement section is studied using the viscoelastic graded analysis (rather than elastic). Graded, layered and homogeneous material variations were used for a series of simulations, and the results from different approaches were compared.

Introduction

Asphalt concrete pavements are inherently non-homogeneous in nature. Property gradients are most severe across the thickness of the asphalt concrete layers. The main sources of non-homogeneity are:

(a) Aging
(b) Varying temperature profile

The viscoelastic graded analysis procedure described in the companion paper (Part-I) is the current method of choice for analyzing asphalt concrete pavements. In the current paper, an aged full-depth asphalt concrete pavement was simulated using the graded approach and comparisons were made with the results using layered and homogeneous assumptions.

Asphalt Concrete Pavements: Viscoelastic FGMs

There are over 2.2-Million miles of paved roads across United States, out of which 94% are surfaced with asphalt concrete [3]. Asphalt concrete is an engineered heterogeneous composite manufactured from asphalt binder (bitumen) and mineral aggregates (crushed stone). Asphalt binder is one of many products obtained through fractional distillation of crude oil or petroleum. Due to its organic nature, asphalt binder continuously undergoes oxidative aging. The effect of aging is most prominent in form of hardening or stiffening. The effect of aging creates graded material properties due to variation in the amount of aging across the depth of pavement. The Strategic Highway Research Program (SHRP) Project A-368 dealt with the chemical composition changes during the aging process of asphalt binders. The final report from this project identifies the process of age hardening as a non-reversible and continuous process that extends throughout the life of a pavement [4]. Age hardening can be divided into two stages - Mirza and Witczak [5] refers to them as *short term hardening*, which occurs during the mix production and construction; and *in-situ field aging* which occurs during the service life of a pavement. In-situ field aging or long-term aging is the source of property gradient through the pavement. Illustration of aging gradient through the asphalt concrete pavement thickness is shown in Fig. 1(a). The illustration is based on prediction made by the "Global Aging Model" used in American Association of State and Highway Transportation Officials Design Software [6] for an eight year old asphalt concrete pavement located at central Illinois in the mid-western part of the United States.

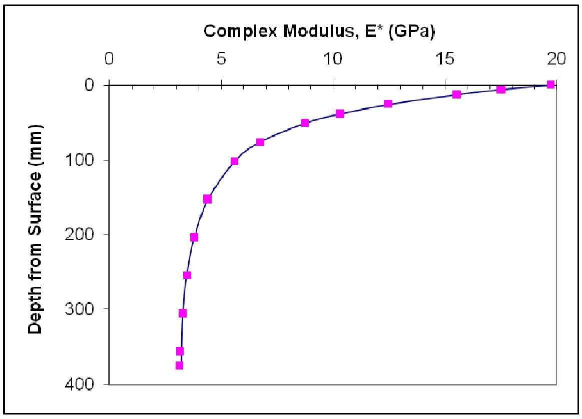


Fig. 1 Asphalt Concrete Complex Modulus for Pavement after Eight Years of Service

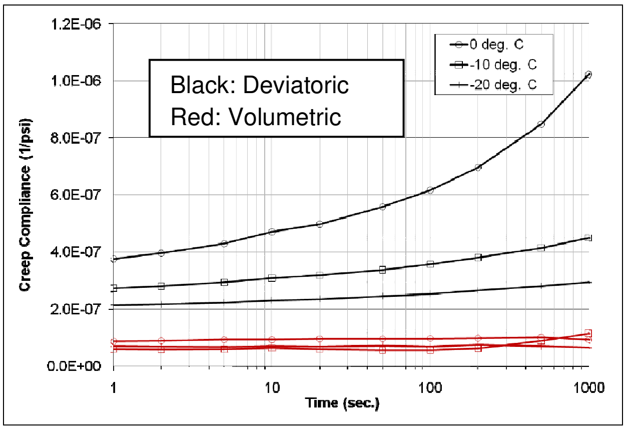


Fig. 2 Creep Compliance of a typical Asphalt Concrete at 0, -10, and -20°C

Constitutive properties of asphalt concrete are significantly temperature dependent. Asphalt concrete creep compliance varies significantly with temperature. Fig. 2 shows creep-compliances of an asphalt mixture at three test temperatures, where the testing was performed following the AASHTO T-322 [7] test specifications. Due to climatic variations the pavement structure undergoes transient thermal conditions. Due to temperature gradients, material property gradients are established within pavements.

Finite Element Analysis (FEA)

A series of finite element simulations were performed to study the response of a full-depth asphalt pavement under tire load condition. The simulations were performed for four material discretizations:

(a) Graded properties
(b) Layered properties
(c) Aged properties
(d) Unaged properties

This section describes the details of the finite element models used for the analysis.

Pavement Section. The pavement section studied in this paper is modeled after interstate highway I-155 near town of Lincoln, IL located in mid-western USA. The pavement is constructed as a full-depth asphalt concrete section on top of lime-stabilized clay subgrade. This pavement has been previously studied by Buttlar et al. [2] using graded finite-element technique. Fig 3. shows a schematic of the pavement section.

Asphalt Properties. The asphalt concrete properties for the simulations were approximated based on the laboratory test results reported by Apeagyei et al. [8, 9]. They have reported short and long term aged viscoelastic properties for asphalt mixtures. In order to simulate an aged pavement condition, it was assumed that short-term aged properties represent material at the bottom of asphalt concrete layer and long term aged properties represent material at the top of asphalt concrete layer (c.f. Fig. 3). The variation of the material properties is chosen similarly to that predicted by the Global Aging Model [5]. Fig. 4 shows the relaxation modulus variation with time and space (across asphalt concrete thickness). As anticipated, the material is significantly stiffer at the pavement surface and short loading times; and conversely, most complaint near the pavement bottom at longer loading times.

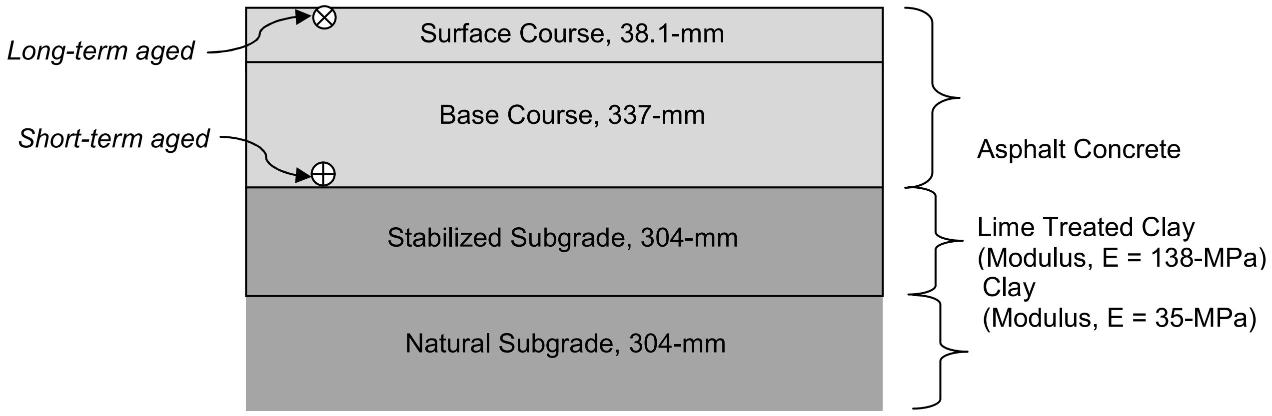


Fig. 3 Pavement Cross-Section

As mentioned previously four material distributions were simulated. Viscoelastic FGM analysis was performed by simulating the spatial and temporal material variation as shown in Fig. 4, and thus this material representation is labeled as "FGM" throughout the rest of this paper. Layered approximation was utilized to compare and contrast with the FGM approach; thus this representation will be labeled as "Layered" and two homogeneous materials were simulated representing short term aging properties ("Unaged") and long-term aging properties ("Aged"). The "Aged" and "Unaged" properties were similar to those shown in Fig. 4 at top (height = 375.1mm) and bottom (height = 0mm) of asphalt layer respectively. For layered approximation the surface course was divided into six layers (6.35mm each) and the base course was divided into sixteen layers (21mm). The property gradients are significantly steep near the top of asphalt concrete, thus finer resolution was utilized near the top.

Finite-Element Model. A two-dimensional axisymmetric model was used for the simulations. Two levels of mesh discretizations were utilized. Two meshes were generated, the first one was utilized for simulation of graded and homogeneous material properties, and the second one with higher refinement was utilized for performing simulations using layered approximation. A portion of the finite element meshes at the top portion of the asphalt layer are shown in Fig 5. The total nodal degrees of freedom for the coarser mesh were 72150, versus 129060 for the finer mesh utilized in the layered approach.

A single tire with 40-kN load and 758-kPa inflation pressure was simulated. The simulations were performed for quasi-static loading conditions with the loading times up to 1000-seconds. The load and displacement boundary conditions are shown in Fig. 5.

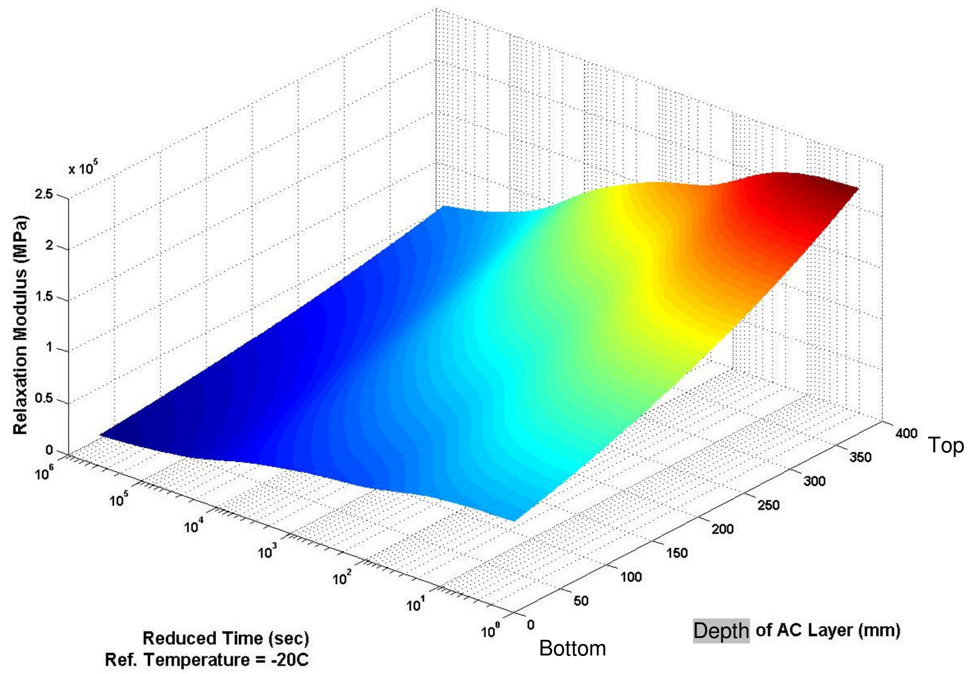


Fig. 1 Relaxation Modulus (Variation with Time and Height of Asphalt Layer)

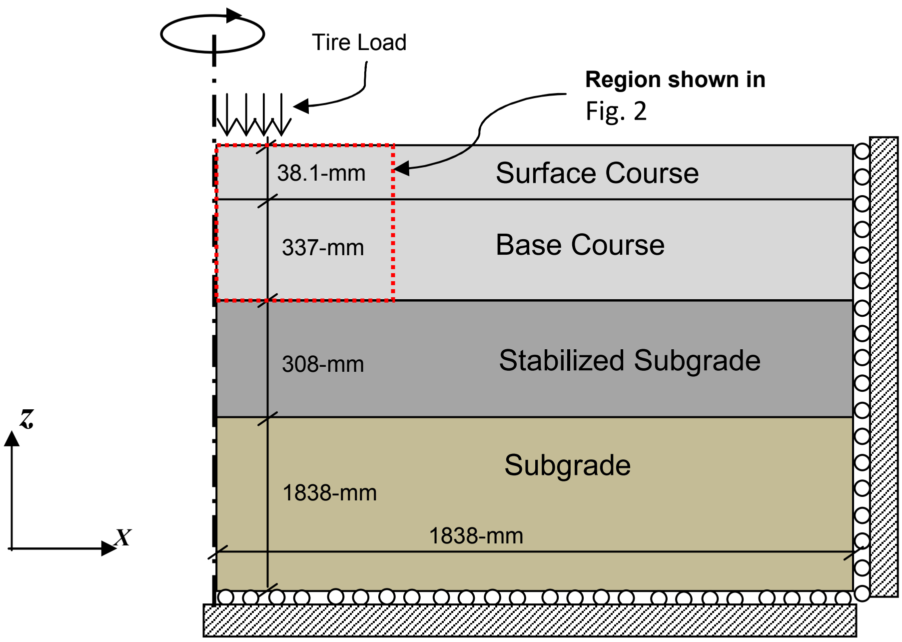
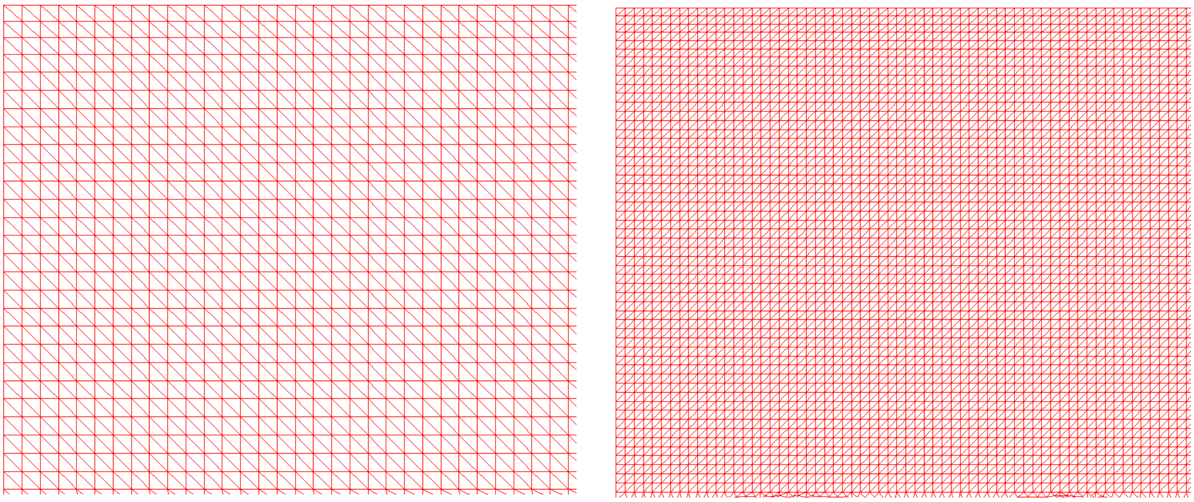


Fig. 5 Finite Element Model Schematic

Simulation Results

The pavement response parameters that are commonly utilized in analysis and design of asphalt pavements are: (1) Tensile strain at the bottom of asphalt concrete, (2) Compressive strain at the top of asphalt concrete and (3) shear strain at edge of tire load. The First two have been empirically related to pavement's fatigue and permanent deformation behaviors. The shear strain has been recently studied by several researchers to relate it with longitudinal cracking along the wheel path. These parameters for each of the material representation are shown in Fig. 7(a), (b), and (c).



(a) FGM and Homogeneous Material Distributions **(b) Layered Material Distribution**

Fig. 2 Mesh Discretization of Asphalt Layers for Different Material Distributions

The typical responses indicate that the layered approach provides reasonable approximation compared with the graded approach. However it should be noted that significantly higher mesh refinement was utilized for the layered analysis. In addition to this, the quantities in the plots were evaluated at either surface or bottom of asphalt concrete where the responses may have not been so sensitive to the material variation. The predictions from layered approaches are questionable at the interfaces of layers and this could lead to significant errors in the analysis, as illustrated by looking at a response at the interface of surface and base course within asphalt pavement. Fig 7(d) shows strains in Z-direction near the interface at 1000second loading time. It can be observed that as much as 20% error is incurred while utilizing layered approach, whereas the graded approach provides smooth predictions without jump in the strains. The following key points can be observed from the simulation results:

- It is important to consider effects of aging in the course of analysis; the unaged predictions made using unaged properties may be significantly different from those obtained with the consideration of aging.
- The viscoelastic FGM analysis procedure developed herein provides an accurate and efficient way of analyzing asphalt pavements.
- Layered approach may provide results with significant errors in derivative quantities at the layer interfaces.
- The most severe response observed for this limited study was the high magnitude of shear strains generated at the edge of tire load.

Summary

The viscoelastic FGM analysis procedure described in the companion paper has been successfully applied to the simulate asphalt concrete pavement. The results show superiority of the graded approach in comparison with layered approach. The advantage of the graded viscoelastic approach have been established for asphalt pavements, which are one of many applications of the analysis procedure developed and discussed here. Examples of other applications include polymer and plastic components commonly used in automobile and aerospace industries that undergo aging due to oxidation and ultraviolet radiations.

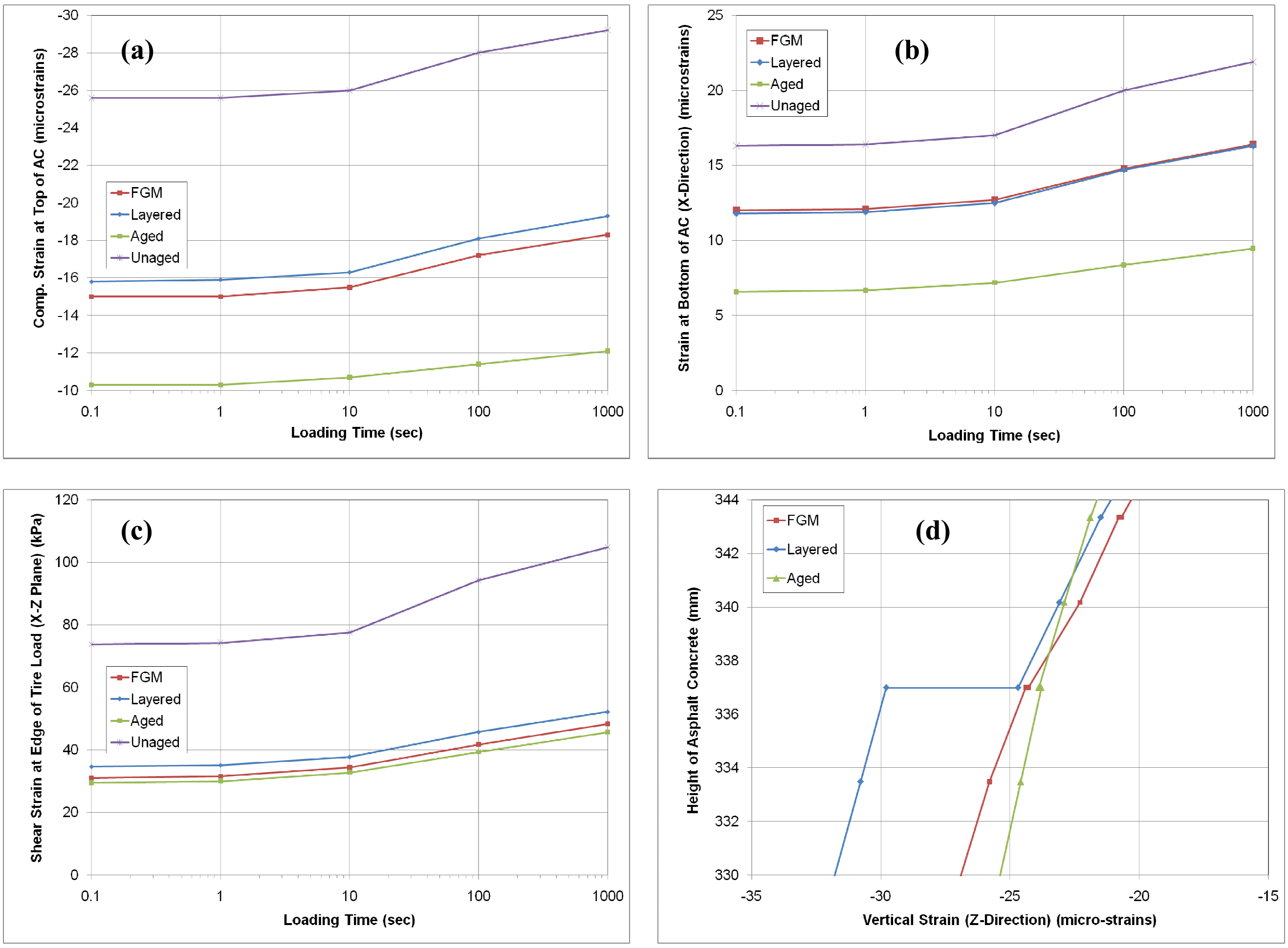


Fig. 7 Pavement Response under Tire Load (a) Horizontal Tensile Strain at Bottom of Asphalt Layer, (b) Vertical Compressive Strain on Surface, (c) Shear Strain at Edge of Wheel load, and (d) Vertical Strain near Interface of Surface and Base Course.

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