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Effects of cross-anisotropy and stress-dependency of pavement layers on pavement responses under dynamic truck loading

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ABSTRACT

Previous studies by the authors have determined pavement responses under dynamic loading considering cross-anisotropy in one layer only, either the cross-anisotropic viscoelastic asphalt concrete (AC) layer or the cross-anisotropic stress-dependent base layer, but not both. This study evaluates pavement stress–strain responses considering cross-anisotropy in all layers, i.e. AC, base and subbase, using finite element modeling (FEM) technique. An instrumented pavement section on Interstate I-40 near Albuquerque, New Mexico was used in ABAQUS framework as model geometry. Field asphalt cores were collected and tested in the laboratory to determine the cross-anisotropy (n-values) defined by horizontal to vertical modulus ratio, and other viscoelastic parameters as inputs of the model incorporated through user defined material interface (UMAT) functionality in ABAQUS. Field base and subbase materials were also collected and tested in the laboratory to determine stress-dependent nonlinear elastic model parameters, as inputs of the model, again incorporated through UMAT. The model validation task was carried out using field-measured deflections and strain values under falling weight deflectometer (FWD) loads at the instrumented section. The validated model was then subjected to an actual truck loading for studying cross-anisotropic effects. It was observed that horizontal tensile strain at the bottom of the AC layer and vertical strains in all layers decreased with an increase in n-value of the asphalt layer, from $n < 1$ (anisotropy) to $n = 1$ (isotropy). This indicates that the increase in horizontal modulus caused the decrease in layer strains. It was also observed that if the base and subbase layers were considered stress-dependent instead of linear elastic unbound layers, the horizontal tensile strain at the bottom of the asphalt layer increased and vertical strains on top of the base and subbase also increased.

1. Introduction

Pavement damage, i.e. fatigue or permanent deformation, is dependent on pavement responses such as horizontal and vertical strains due to repeated traffic loads. These strains are dependent on the stiffness of pavement layers, which are typically assumed to be equal in every direction. In reality, pavement is constructed by compacting pavement layers in the vertical direction, which may result in unequal material stiffness, i.e. defined by the modulus of elasticity, E, in horizontal and vertical directions (Tutumluer and Seyhan, 1999). Asphalt concrete (AC) can be considered isotropic if its stiffness (i.e. E-value) is the same in every direction; otherwise it is anisotropic. If AC's E-values are the same on a horizontal plane, the AC is called cross-anisotropic material. The ratio of horizontal to vertical moduli is called degree of cross-anisotropy, n-value. Thus, AC is isotropic if $n = 1$; otherwise, it is cross-anisotropic.

The study of cross-anisotropy was mostly concentrated on the unbound granular aggregate layer before 2000 (Lo and Lee, 1990; Tutumluer and Seyhan, 1999). The possible presence of anisotropy in AC was first studied by Masad et al. (2002). This study was performed based on an AC test specimen compacted by a SuperPave (SP) gyratory compactor in the laboratory. Wang et al. (2005) performed a study to determine the degree of cross-anisotropy on a field-collected AC sample using a triaxial test. Later, Motola and Uzan (2007) conducted a dynamic modulus test on AC samples to determine the degree of cross-anisotropy. The tests were conducted on AC samples along both vertical and horizontal directions. The test results indicated that the degree of cross-anisotropy was 40%.

In previous studies, pavement materials were mostly assumed as isotropic during the finite element modeling (FEM) of multi-layered pavement structure under dynamic loading (Uddin and

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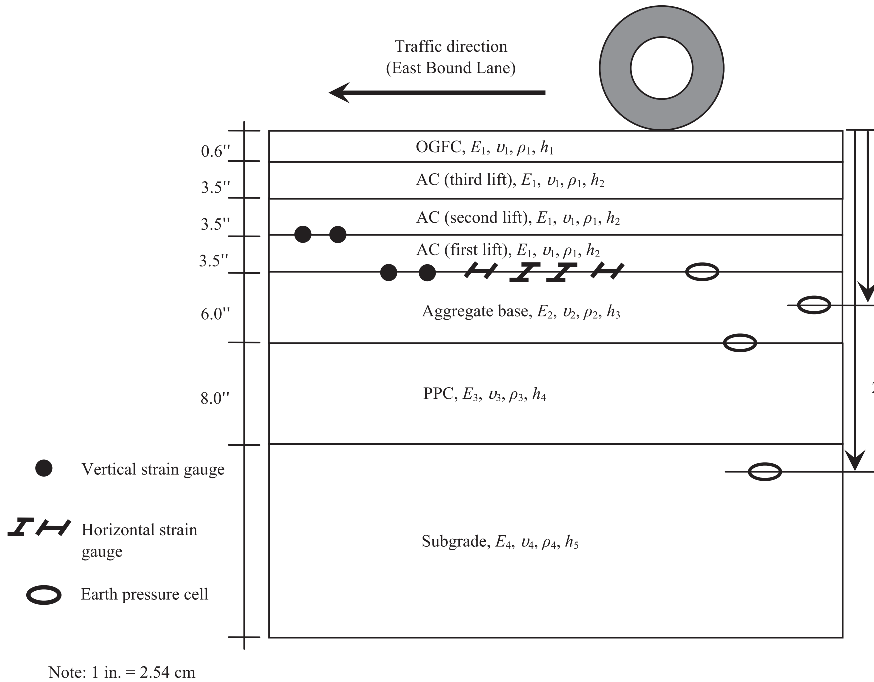

Fig. 1. Instrumented section at MP 141 on I-40, Rio Puerco, New Mexico.

Garza, 2010; Tarefder and Ahmed, 2013). Cross-anisotropy was incorporated only to unbound layers, such as base, subbase, and subgrade (Al-Qadi et al., 2010). It is known that a higher amount of stress is distributed over the AC layer due to traffic load. Therefore, ignoring AC's cross-anisotropy may cause significant error during predicting critical strains, which are related to fatigue damage or permanent deformation predictions of a pavement.

The effects of AC's cross-anisotropy on horizontal and vertical strains were investigated in recent studies (Ahmed et al., 2013, 2015). In another study by these authors, cross-anisotropy was only incorporated to the unbound layers in the presence of stress-dependent nonlinear elastic base layer (Ahmed et al., 2014). However, stress-dependency in subbase was not within the scope of that study.

From the above discussions, it is understood that cross-anisotropy was incorporated only to the AC or unbound layers in the FEM of a pavement structure under dynamic loading. Stress-dependency was incorporated only to the base layer instead of assigning it to multilayers, such as base and subbase together. This study is initiated to combine cross-anisotropy variation in all layers as well as incorporating stress-dependent nonlinear elastic unbound layers for investigating the effects of cross-anisotropy on pavement response.

2. Objectives

The main objective of this study is to investigate the effects of cross-anisotropy and stress-dependency of pavement layers on pavement response such as horizontal tensile strain at the bottom of the AC layer and vertical strains in all the layers (AC, base, subbase, and subgrade) under dynamic truck loading. The specific objectives are described as follows:

(1) Develop the temperature-dependent and cross-anisotropic viscoelastic model for the AC as well as stress-dependent nonlinear elastic and cross-anisotropic model for unbound layers, such as base and subbase, and to incorporate these to the dynamic FEM.

(2) Perform the parametric study of pavement response, such as vertical and horizontal strains due to cross-anisotropic variations in pavement layers, incorporating both linear and stress-dependent nonlinear elastic unbound layers under the truck load.

The dynamic FEM of the instrumented pavement section is developed in the commercial FEM software, ABAQUS.

3. Development of dynamic finite element model

3.1. Instrumented pavement section

The FEM is developed based on an instrumented pavement section at mile post 141 (MP 141) on Interstate 40 (I-40), Rio Puerco, New Mexico (see Fig. 1). It consists of four major layers: AC at the surface, aggregate layer at the base, process-place and compacted (PPC) layer at the subbase, and a subgrade soil layer. The AC layer consists of three lifts each with a thickness of 88.9 mm (3.5 in.). The PPC layer was prepared by processing (loosening) existing base and/or subgrade materials and then compacting it in place. The thickness of the base is 152.4 mm (6 in.) and the subbase is 203.2 mm (8 in.). From Fig. 1, it can be seen that horizontal asphalt strain gages (HASGs) and vertical asphalt strain gages (VASGs) were installed at the bottom and inside of the AC layer, respectively. Earth pressure cells were installed at different depths to measure the vertical stress.

3.2. Model geometry

A quarter of cube model was used for a three-dimensional (3D) simulation. The depth and horizontal length of a model were selected, as there is no effect of stress near the boundary according to Duncan et al. (1968). In this study, the depth of the model was taken 50 times the loading radius, and the horizontal length was taken more than 12 times the loading radius. Wave reflection by the boundary is one of the major concerns in a dynamic analysis.