Construction and Building Materials 93 (2015) 685–694

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Combined effect of asphalt concrete cross-anisotropy and temperature variation on pavement stress–strain under dynamic loading

M.U. Ahmed *, A. Rahman [1], M.R. Islam [2], R.A. Tarefder [3]

Civil Engineering Department, MSC 01 1070, 1 University of New Mexico, Albuquerque, NM 87131, United States

HIGHLIGHTS

- Combined effect of asphalt concrete (AC) cross-anisotropy and temperature on pavement's response.
- A viscoelastic and cross-anisotropic and temperature dependent AC model is developed in ABAQUS.
- Horizontal tensile strain decreases as horizontal modulus of the AC increases.
- Increase in horizontal modulus of the AC leads to decrease in the vertical strains of pavement layers.
- Tensile strain at bottom of AC and vertical strain in pavement layers are dependent on temperature.

ARTICLE INFO

Article history:
Received 1 November 2014
Received in revised form 27 April 2015
Accepted 13 June 2015
Available online 27 June 2015

Keywords:
Flexible pavement
Stiffness
Asphalt concrete
Cross-anisotropy
Temperature
Viscoelastic
Strain gauge
Dynamic FEM
FWD test

ABSTRACT

This study investigates the combined effects of asphalt concrete (AC) cross-anisotropy and temperature on asphalt pavement's stress–strain under moving wheel loads. To facilitate this study, a dynamic Finite Element Model (FEM) of an instrumented pavement section on Interstate-40 (I-40) near Albuquerque, New Mexico, is developed in ABAQUS incorporating depth-temperature variations in the AC layer under a truck wheel loading. Cross-anisotropy in the model is defined as the ratio of horizontal to vertical modulus (*n*-value) of the AC. Field compacted AC cores were collected from the instrumented pavement section and tested in the laboratory to determine the *n*-value and viscoelastic parameters, which are incorporated in the FEM model using the User Defined Material (UMAT) interface in ABAQUS. Model is validated using field measured deflections and strains values under Falling Weight Deflectometer (FWD) test. The validated model is used for a parametric study by varying *n*-values of AC material under different pavement temperatures. It is observed that the horizontal tensile strain at bottom of the AC layer decreases as the *n*-value approaches 1.0 (isotropy). It indicates that the horizontal tensile strain decreases as the horizontal modulus of the AC increases. It is also observed that the vertical strains on top of pavement layers decreases with an increase in *n*-value. It indicates that increase in horizontal modulus of the AC leads to decrease in the vertical strains of pavement layers. The parametric study based on pavement temperature variation shows that horizontal tensile strain at bottom of the AC layer as well as vertical strains on top of AC, base, subbase, and subgrade are highly sensitive to temperature variation in AC layer.

1. Introduction

Flexible pavements are constructed by compacting hot mix asphalt (HMA) in vertical direction, which results in unequal material stiffness, i.e., defined by the modulus of elasticity, *E*, in horizontal and vertical direction [1]. Asphalt concrete (AC) can be isotropic if its stiffness property (i.e. *E*-value) is same in every direction; otherwise it is anisotropic. If AC's *E*-values are same in two horizontal directions or in horizontal plane, the AC is called cross-anisotropic material. The ratio of stiffness or modulus in horizontal and vertical directions is called degree of cross-anisotropy, *n*-value. Thus AC is isotropic if $n = 1$, otherwise, it is cross-anisotropic.

Before 2000, study of cross-anisotropy was mostly concentrated to the unbound granular aggregate layer [1,2]. The possible presence of cross-anisotropy in asphalt concrete (AC) compacted by

* Corresponding author. Tel.: +1 (505) 489 7183; fax: +1 (505) 277 1988.
E-mail addresses: mahmed@unm.edu (M.U. Ahmed), arahman@unm.edu (A. Rahman), mdislam@unm.edu (M.R. Islam), tarefder@unm.edu (R.A. Tarefder).
[1] Tel.: +1 (505) 948 3766.
[2] Tel.: +1 (505) 363 6902.
[3] Tel.: +1 (505) 277 6083; fax: +1 (505) 277 1988.

http://dx.doi.org/10.1016/j.conbuildmat.2015.06.031
0950-0618/

the Superpave Gyratory Compactor was first studied by Masad et al. [3]. Later, Wang et al. [4] investigated the existence of the cross-anisotropy in the field compacted sample by the triaxial test. This study reported the range of degree of cross-anisotropy of the AC is 20–50%. Motola and Uzan [5] conducted dynamic modulus test on the AC samples to determine the degree of cross-anisotropy. The tests were conducted on the AC samples along both vertical and horizontal directions. The test results indicated that the degree of cross-anisotropy was 40%.

Most of the previous FEM studies considered pavement materials as isotropic under dynamic load [6,7]. Effect of cross-anisotropy was studied for unbound layers only [8–11]. Ignoring AC's cross-anisotropy can cause significant error in prediction of critical strains, which are related to fatigue damage or permanent deformation predictions of a pavement.

The effect of AC cross-anisotropy horizontals strain and vertical stress was investigated by Ahmed et al. [12]. However, effect of AC cross-anisotropy on the vertical strain was not performed by these authors. Nor did they conduct any laboratory testing to determine of the degree of cross-anisotropy (n-value) of the AC. Also, they did not study any temperature dependence of AC modulus or n-value. However, pavement temperature is an important factor that affects AC modulus and performances [13]. Previous study reported that temperature variation through the AC layer is linear [14].

From the above discussions, AC's cross-anisotropy and depth-temperature variation were not studied using dynamic loading in FEM framework yet, which is done here.

2. Objectives

The main objective of this study is to investigate the combined effects of AC cross-anisotropy and depth-temperature variation on pavement response such as vertical strains in all the layers (AC, base, subbase, and subgrade), horizontal strain at the bottom of the AC layer under a truck load. The specific objectives are:

- Develop the temperature and cross-anisotropic viscoelastic model of AC layer and incorporate this to dynamic FEM framework to calculate pavement responses.
- Study pavement responses such as vertical and horizontal strains due to cross-anisotropic variations and depth-temperature variations in AC layer.

3. Dynamic Finite Element Modeling

3.1. Pavement section

The geometry of the FEM is constructed based on an instrumented pavement section at mile post 141 (MP 141) on Interstate 40 (I-40) (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 3.5 in. (88.9 mm). These lifts contain dense graded SuperPave (SP) mix, Type SP-III. The maximum aggregate size is 0.75 in. (19 mm). About 5% of the materials pass through No. 200 sieve (0.075 mm). Performance grade of the asphalt binder is PG 70-22 and the asphalt content is 4.4% (by weight of mixture). The PPC layer is prepared by processing (loosening) existing base and/or subgrade materials and then, compacting it in place. The thickness of the base is 6 in. (152.4 mm) and the subbase is 8 in. (203.2 mm). From Fig. 1, it can be seen that horizontal asphalt strain gauges (HASGs) and vertical asphalt strain gauges (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 cube model is used for a 3D simulation. The depth and horizontal length of a model were selected as such there is no effect of stress near the boundary according to Duncan et al. [15]. In this study, the depth of the model was taken 50 times the loading radius and 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. Dynamic amplification may occur due to this wave reflection that results from the insufficient distance to the boundary [16]. Therefore, the final dimensions, i.e., length, width, and depth, of this entire model were selected to be 300 in. $\times$ 300 in. $\times$ 300 in. (7.62 m $\times$ 7.62 m $\times$ 7.62 m). The number of layers as well as thicknesses of every layer is assigned according to the instrumented section described earlier.

3.3. Mesh generation

The FEM model geometry after meshing is shown in Fig. 2. An 8-noded brick element (C3D8) is used for the mesh generation. It is a common practice to assign fine mesh near the loading region to capture the stress gradient and coarser mesh further from that region. A mesh sensitivity analysis was performed to determine the optimum element size for the fine mesh. The length of the smallest element is 0.6 in. (15 mm) based on the mesh sensitivity analysis. An edge biased structure meshing pattern is used to obtain a smooth transition from fine mesh to coarse mesh.

3.4. Boundary condition

The bottom boundary is restrained to move along the three mutually orthogonal directions (see Fig. 2). Therefore, there will be no deflection in horizontal and vertical directions in this plane. Movements of the vertical boundaries are restrained only in the horizontal directions. The layer interfaces are considered partially-bonded and coulomb friction law is used to model the contact between the interfaces. The friction coefficients required for this contact model are collected from the literature [17]. The friction coefficients along layer interfaces in AC are 0.7 and that along base-subbase as well as subbase-subgrade interfaces is 1.3 [18,19].

3.5. Material properties

Material properties are determined through field and laboratory testing.

3.5.1. AC layer properties

Modulus of the field compacted AC core (E-value) was determined in the laboratory along vertical and horizontal directions to calculate the n-value. Therefore, relaxation modulus tests on AC core with two different loading modes were performed both axially and diametrically, i.e., indirect tensile testing (IDT) mode. It can be noted that all three lifts of AC were constructed using SuperPave (SP) Type-III mix, which uses 0.75 in. (19.0 mm) maximum aggregate size.

The field-compacted AC core with a diameter of 6 in. (152.4 mm) was collected from the pavement section. Next, a 4 in. (101.6 mm) diameter AC cylinder was extracted from the field compacted AC core using a 4 in. (101.6 mm) diameter pressure controlled core drill (see Fig. 3(a)). For a uniaxial test, the recommended height of a test specimen should be 1.5 times the diameter of the specimen [5]. Therefore, the AC core was cut at both of the