Spring 4-21-2017

Effects of tire inclination (turning traffic) and dynamic loading on the pavement stress-strain responses using 3-D finite element modeling

Xiaodi Hu

Abu N.M. Faruk

Jun Zhang

Mena I. Souliman
University of Texas at Tyler, msouliman@uttyler.edu

Lubinda F. Walubita

Available online at www.sciencedirect.com

ScienceDirect

International Journal of Pavement Research and Technology 10 (2017) 304–314

www.elsevier.com/locate/IJPRT

Effects of tire inclination (turning traffic) and dynamic loading on the pavement stress–strain responses using 3-D finite element modeling

Xiaodi Hu [a], Abu N.M. Faruk [b], Jun Zhang [c], Mena I. Souliman [d,*], Lubinda F. Walubita [b]

[a] Transportation Research Center, Wuhan Institute of Technology, Wuhan 430074, Hubei Province, China
[b] Texas A&M Transportation Institute (TTI) – The Texas A&M University System, College Station, TX 77843, USA
[c] Department of Civil Engineering, Texas A&M University, College Station, TX 77843, USA
[d] The University of Texas at Tyler, Departments of Civil Engineering and Construction Management, 3900 University Blvd, RBS 1008, Tyler, TX 75701, USA

Received 18 August 2016; received in revised form 16 March 2017; accepted 11 April 2017
Available online 21 April 2017

Abstract

In this study, ABAQUS finite element (FE) modeling in three-dimensional (3-D) loading mode was utilized to analytically investigate and quantify the effects of tire inclination and dynamic loading on the stress–strain responses of a pavement structure under varying loading and environmental conditions. The input variables for modeling consisted of actual laboratory and field data obtained from an in-service highway US 59 and included the in-situ pavement structure, material properties (i.e., modulus and shear strength), traffic, and climatic (i.e., temperature) data. Computational modeling and sensitivity analyses were conducted through variation of the following two input variables with a focus on the top surfacing hot-mix asphalt (HMA) layer: a) tire inclination angle to simulate turning traffic, and, b) dynamic loading to simulate accelerating, steady rolling, and decelerating (braking) traffic. The generated maximum shear stress and vertical strain responses were then analyzed and correlated to the HMA material strength and the actual measured/observed field rutting performance data. The corresponding results indicated that inclined tires (simulating turning traffic) and decelerating (braking) vehicles induced the most severe shear stresses and vertical strains on the pavement structure in terms of magnitude (i.e., increased); exceeding the HMA material strength in some cases. Thus, for pavement design and structural analysis purposes, the following critical highway areas that may be subjected to extreme stresses and strains due to turning and stopping (braking) traffic, particularly in high temperature environments, should be given more attention with respect to material strength characterization to mitigate potential shear/rutting failures: intersections, junctions; urban stop–go sections, and curves.

Keywords: 3-D FE stress–strain modeling; Rutting; Shear deformation; Shear stress; Vertical strains

1. Introduction

Rutting is one of the undesirable structural distresses occurring in hot-mix asphalt (HMA) pavements [1,2]. It is characterized by longitudinal depressions (or permanent deformation) on the pavement surface. These longitudinal distortions/depressions on the pavement surface result in poor ride quality and also rain water pooling in the rutted areas ultimately causes hydroplaning with a high potential for traffic accidents, which is a safety concern. Additionally, rutting can exacerbate the manifestation of HMA cracking and disintegration, which leads to a reduced pavement service life with an undesirable increase in the cost of pavement maintenance and/or rehabilitation [1,2].

* Corresponding author.
E-mail addresses: huxiaodi625@hotmail.com (X. Hu), a-faruk@tti.tamu.edu (A.N.M. Faruk), jzhang@civil.tamu.edu (J. Zhang), msouliman@uttyler.edu (M.I. Souliman), lfwalubita@tamu.edu (L.F. Walubita).
Peer review under responsibility of Chinese Society of Pavement Engineering.

http://dx.doi.org/10.1016/j.ijprt.2017.04.005
1996-6814/© 2017 Chinese Society of Pavement Engineering. Production and hosting by Elsevier B.V.

Total rutting in pavement structures is a complex phenomenon resulting from numerous factors (i.e., materials, traffic loading, environment, temperature, etc.) and occurs continuously over the service life of the pavement. In terms of material effects, it can either be due to the HMA mix, base, subbase, subgrade, or a combination of all these layers [3]. However, with the recorded high summer temperatures of the recent years, the State of Texas has, for instance, experienced several premature shear and rutting failures with some surfacing HMA mixes. These failures occurred mostly in high shear stress locations, in particular with slow moving or turning traffic at controlled intersections, in areas of elevated temperatures, high traffic loading, and where lower performance grade (PG) of asphalt binders have been used. On this basis, the focus of this study was on rutting issues related with the surfacing HMA mixes rather than the underlying pavement layers.

For the most part, the primary mechanism of rutting or permanent deformation (PD) in the HMA mix is shear deformation caused by large stresses in the upper portions of the HMA layers under traffic loading, particularly at elevated temperatures [4–7]. Therefore, understanding the HMA material behavior and stress–strain distribution profile within a pavement structure when subjected to variable traffic loading and environmental conditions is a critical step toward designing satisfactory performing mixes and pavement structures [8–11].

2. Study objectives

With the aforementioned background, this computational modeling study was undertaken to investigate the effects on the pavement stress–strain responses, in particular the surfacing HMA mix/layer, of the following two variables: a) tire inclination angle (effects of turning traffic), and b) dynamic traffic loading including accelerating, steady rolling, and decelerating (braking) traffic. Additionally, a sensitivity analysis and stress–strain distribution profiling was performed in order to determine the critical factors/thresholds that influence shear deformation and rutting when the pavement structure is subjected to the worst case scenario in terms of traffic loading, intersections/turning traffic, traffic stop–go sections (i.e., at traffic lights), etc. To accomplish these objectives, viscoelastic finite-element (FE) modeling in three-dimensional (3-D) loading mode was conducted with the ABAQUS software. In the subsequent sections, the ABAQUS software and the input variables are discussed. Results are then presented and synthesized followed by a summary of key findings and recommendations to conclude the paper.

3. The ABAQUS software and FE modeling

The specific FE program and module used in this study was ABAQUS/CAE that has an intuitive and consistent user interface throughout the system [8,12]. ABAQUS was selected for FE modeling in this study because of its versatility and capabilities to realistically simulate material behavior, traffic loading, and environmental conditions – including the potential to model the HMA viscoelastic behavior and can also simulate both static and dynamic traffic loading in a 3-D configuration, which were very critical aspects to this study [8]. Additionally, driving maneuvering scenarios such as stopping wheels including the tractive or breaking frictional forces caused by heavy trucks accelerating/decelerating can easily be modeled in ABAQUS as was needed in this study. Also, the interactive user-defined programing in ABAQUS/CAE provides flexibility with the consideration of viscoelastic and viscoplastic damage models for material characterization, thereby adding merit to the accuracy of the FE simulations and numerical results.

However, one challenge experienced in this study was modeling the pavement contact stresses: uniform versus non-uniform models and explicit versus implicit. Simulation of the rolling tire interaction with the pavement explicitly is generally computationally expensive and complex due to the high computational time, high non-linearity nature, and inertial effects of the tire-pavement interaction. A simple and computationally effective way to model the tire-pavement interaction is to consider the tire imprint forces, i.e., consider the tires implicitly. In most literature [13,14], the tire-pavement interaction is considered statically or tire rolling for very limited number of passes. The goal of this study was to model the stress–strain responses with respect to shear and rutting distresses. So considering the tire-pavement interaction implicitly was viably considered the most practical and realistic way to model these phenomena for the study. Thus, the tire footprint was modeled implicitly under non-uniform pavement contact stresses without physically modeling the tire or the stress profiles within the tire ribs. Implicit modeling in this context, as utilized in this study, means that the contact stress and pressure induced from the tire to the pavement surface was modeled through discretization of tire footprint as illustrated in Fig. 1 [14,16–18]

4. ABAQUS FE (3-D) modeling and input variables

The FE input variables used for modeling are discussed in the subsequent text and include some of the fundamental factors influencing pavement response/performance; namely the pavement structure, material properties, traffic loading, and environmental conditions.

4.1. Pavement structure of highway US 59

For FE modeling, the in-service section of highway US-59 in the Atlanta District of Texas, with a known pavement layer profile, material properties, traffic, and climatic data, was utilized as the reference pavement structure. The corresponding pavement structure and an illustrative 3-D FE model assembly are shown in Figs. 2 and 3.

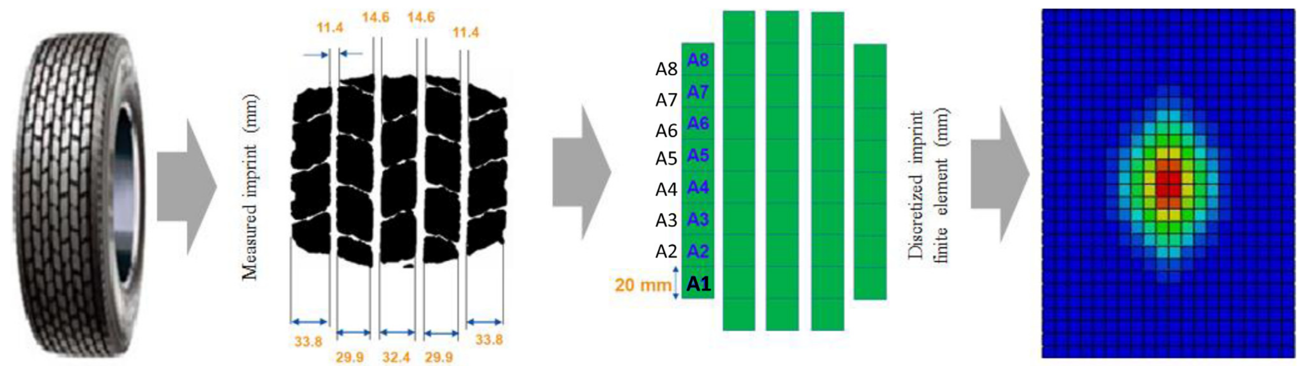

Fig. 1. Implicit tire modeling – discretization of the tire footprint [14,16–18].

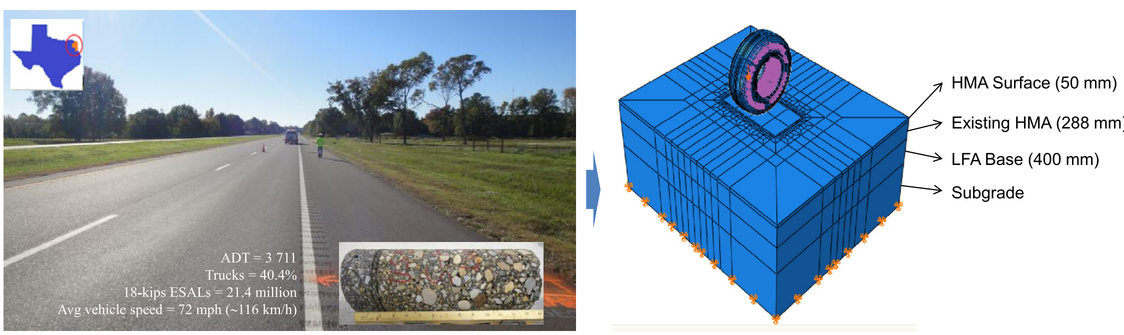

Fig. 2. Pavement structure and ABAQUS model assembly for highway US 59 [18].

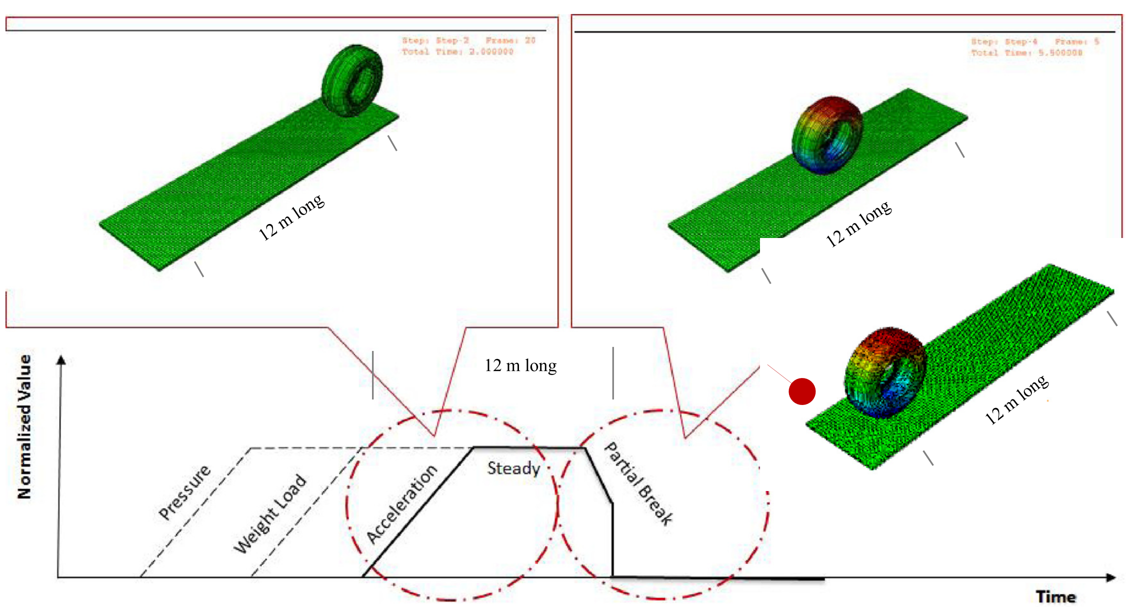

Fig. 3. Loading phase illustration and 3-D FE modeling of a moving tire.

Table 1 illustrates the pavement structure, geometry, and material properties for the 3-D FE model assembly shown in Fig. 2. The loading phases (acceleration, steady rolling, and decelerating [braking]) and 3-D FE modeling of a moving tire is schematically illustrated in Fig. 3 [19–21]. As illustrated in the figure, dynamic loading was simulated by moving the tire over a 12 m long stretch of the pavement. In terms of the mesh configuration, all parts of the model, for all the scenarios evaluated in this study, were meshed with 8-node brick elements (C3D8-continuum, 3-D, 8-node) [19–23].

The three temperatures shown in Table 1 represent actual average in-situ pavement temperatures measured in the field during the Spring and Summer seasons, respec-

Table 1
Pavement structure, geometry, and material properties.

Layer	Thickness (mm)	Modulus, E (MPa)			Shear Strength, τ_s (kPa)	Poisson's Ratio (ν)
HMA surfacing – Overlay (Dense-graded Type D mix)	50	1 018 (44 °C)	1 767 (33 °C)	2 919 (25 °C)	2 896 (60 °C)	0.35
Old existing HMA	288	3 299			–	0.35
LFA base (Lime fly-ash treated)	400	895			–	0.30
Subgrade	–	303			–	0.40
Mesh configuration	8-node brick elements (C3D8- continuum, 3-D, 8-node) for case scenarios					

tively, over a 3-year period. All the moduli values in Table 1 represent real field values measured with the falling weight reflectometer (FWD), also averaged over a 3-year period [2,15]. The HMA shear strength represent is also an average value that was measured in the laboratory via shear testing performed on both field cores and lab-molded HMA specimens from the plant-mix materials collected from the US 59 construction site [18].

The HMA surfacing (overlay) layer, which was the primary focus of the study, was modeled as an isotropic viscoelastic medium, and the other underlying layers (i.e., the old existing HMA, the base, and the subgrade) were simplistically modeled as elastic media [18]. For simulating traffic loading on the pavement surface, the tire was modeled inclusive of the rubber and steel wires, assuming a smooth tire without any discrete consideration of the tire treads or ribs [18,23–26].

4.2. HMA material property characterization

HMA exhibits time- and temperature-dependent viscoelastic behavior, which is modeled in the ABAQUS software through employing the viscoelastic models. The generalized Maxwell model available in ABAQUS was used for modeling the viscoelastic properties of the surfacing HMA layer (overlay), namely Type D mix, and is represented by the following equations [18,25]:

$$s = \int_{-\infty}^{t} 2G(t-\tau)\frac{de}{d\tau}d\tau \quad (1)$$

$$p = \int_{-\infty}^{t} K(t-\tau)\frac{d(tr[\varepsilon])}{d\tau}d\tau \quad (2)$$

where, s and e are the deviatoric stress and strain, respectively; p and $tr[\varepsilon]$ are the volumetric stress and trace of volumetric strain, respectively; and t is the relaxation time. K and G are the bulk and shear moduli of HMA in the time domain, respectively, and were obtained from laboratory dynamic modulus (DM) tests that were performed on the HMA surfacing (overlay) mix, namely the Type D mix [18]. For ABAQUS modeling and to satisfy the needs of the time functionalized Eqs. (1) and (2), the frequency-dependent DM data were converted to moduli values in the time domain using the Prony series shown in Eqs. (3) and (4) [18]:

$$G(t) = G_o\left[1 - \sum_{i=1}^{n} G_i(1 - e^{-t/\tau_i})\right] \quad (3)$$

$$K(t) = K_o\left[1 - \sum_{i=1}^{n} K_i(1 - e^{-t/\tau_i})\right] \quad (4)$$

where G_o and K_o are the instantaneous shear and elastic moduli, respectively. G_i, K_i, and τ_i are Prony series parameters [18]. Note that, viscoelastic characterization through Eqs. (1)–(4) was only applied to the surfacing HMA layer (overlay), which was the primary focus of the study. For

Table 2
Input variables for FE modeling.

Input variable	Parametric values	Remark
Surfacing HAM layer (overlay) thickness	50 mm	
Tire pressure	690 kPa	Close simulation of a typical standard truck tire pressure
Tire load	40 kN	Close simulation of a typical standard truck single-tire load
Pavement temperature	25, 33, and 44 °C	Actual field temperature conditions
Tire inclination angle	0, 5, and 10°	Arbitrarily selected to simulate effects of turning traffic
Tire configuration	Single tire	
Traffic movement condition	Accelerating (6.7 m/s^2), steady rolling (96.6 km/h), and decelerating or braking (6.7 m/s^2) traffic	Stop-go traffic such as intersections
Vehicle (truck) speed	96.6 km/h (88 fps)	Represent field average truck speed
Layer interface condition	No slip	

simplicity of analysis, linear elastic behavior was assumed for all the other underlying layers including the existing HMA, stabilized base, and subgrade [18,19,27,28].

4.3. FE modeling input variables and sensitivity evaluation

For the sensitivity analysis, critical input variables affecting the stress–strain responses were identified as listed in Table 2. The sensitivity analysis was predominantly focused on the following two input variables: tire inclination angle (to simulate effects of turning traffic), and dynamic traffic movement condition (i.e., accelerating, decelerating, etc.) [23,24,26]. In Table 2, the tire pressure (690 kPa) and load (40 kN) were selected to closely simulate typical standard values for truck tires. For simplicity and to optimize on the complexity of FE modeling, particularly under rolling or dynamic loading conditions, the pavement-tire contact stresses were simplistically equated to the tire inflation pressure throughout the study – note however, that better accuracy would definitely be achieved if the actual pavement-tire contact stresses are used. The tire inclination angles (0, 5, and 10°), on the other hand, were arbitrarily selected to conservatively cover the theoretical range of the worst case scenario for the tire tilting angles of turning traffic. The computed stress–strain responses with variation of these input variables are presented and discussed in the subsequent section.

Note that although the overall average vehicles speed as indicated in Fig. 2 is 116 km/h on highway US 59, the measured average "truck" speed was about 96.6 km/h [18]. Therefore, 96.6 km/h was utilized in the ABAQUS dynamic modeling in this study as shown in Table 2.

5. FE numerical simulation results and analysis

The FE modeling results are presented and discussed in this section and are predominantly focused on the HMA overlay (surfacing layer) that has been reported (in Texas) to be more susceptible to premature shear and surface rut failures due to direct exposure to traffic loading and extreme summer temperature environments, among other influencing factors [18]. However, it should be noted that these numerical results pertain only to the pavement structure, materials, traffic loading, environmental, and FE boundary conditions defined in this study. Therefore, the overall findings and conclusions may not be exhaustive.

5.1. Tire inclination angle and effects of turning traffic

Highway sections where turning traffic volumes are relatively high (e.g., at intersections) are often more susceptible to shear and surface rutting failures, which may be partly due to slow turning traffic. It is theoretically assumed that a turning vehicle generally has its tires inclined at an angle with the pavement surface that could cause a difference in the shear stress and vertical strain distribution within the pavement structure as compared to straight sections of the highway or from the case where the tires do not have to tilt with no inclination angle. To investigate and verify this assumption, the tire tilt angle was varied at 0°, 5°, and 10°, respectively. The other input variables including the 50-mm thick HMA surfacing (overlay), material moduli values at 25 °C, standard 690 kPa tire pressure, and 40 kN static single-tire load were all maintained as constant [28]. The corresponding results are presented in Fig. 4.

For the FE modeling conditions considered, it is noticed in Fig. 4 that the top HMA overlay (surfacing) experience the maximum shear stress and vertical strains. For the vertical strains in the existing HMA layer, there is minimal variation across the pavement depth. However, the shear stress profiles for the three inclination angles in the existing HMA layer appear to vary significantly. For tire inclination angles of 0° and 10°, the maximum shear stress occurs on the top of the existing HMA surface, while the 5° inclination has a maximum shear stress at the bottom. It is clear that the maximum shear stress increases with an increase in the tire inclination angle from 0° to 10°, which provide evidence to support the theoretical assumption that turning traffic can cause higher shear stresses on the pavement sur-

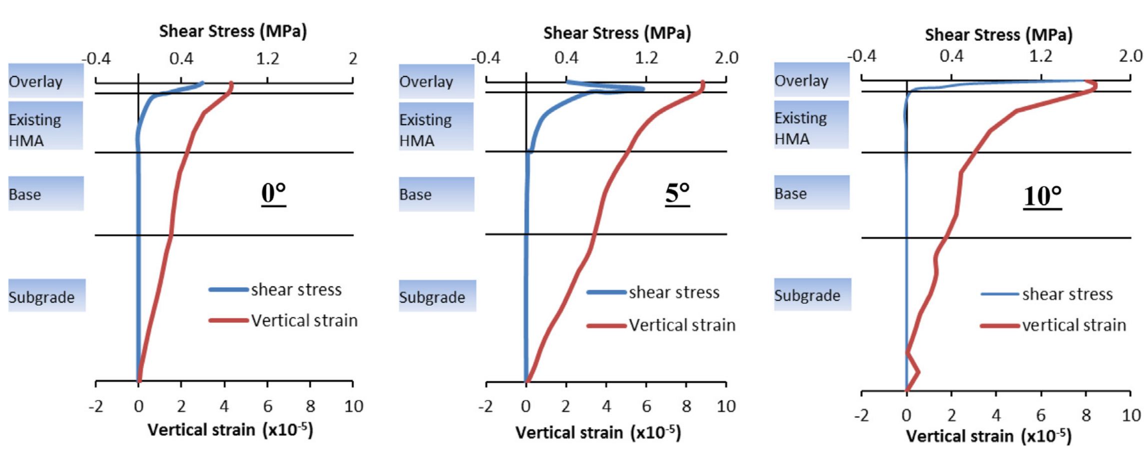

Fig. 4a. Tire inclination angle: stress–strain profiles in entire pavement structure.

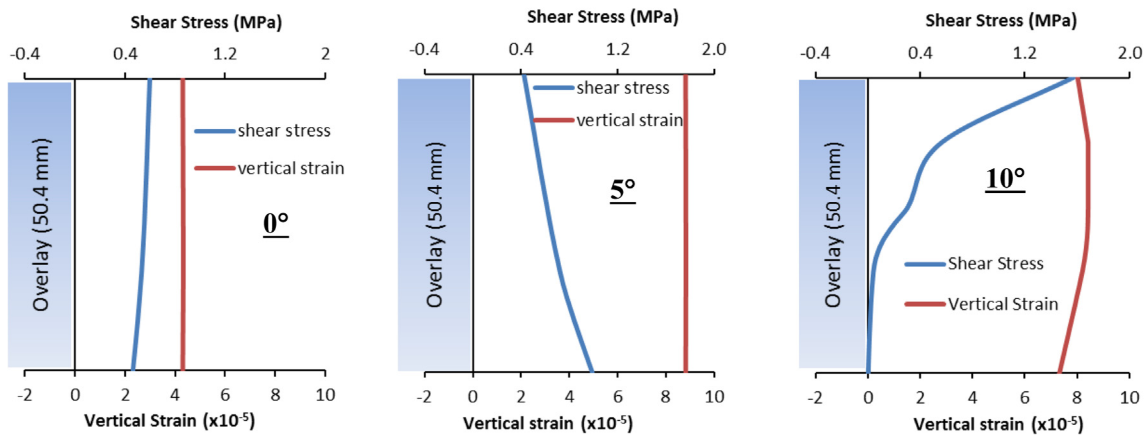

Fig. 4b. Tire inclination angle: stress–strain profiles in the surfacing HMA overlay.

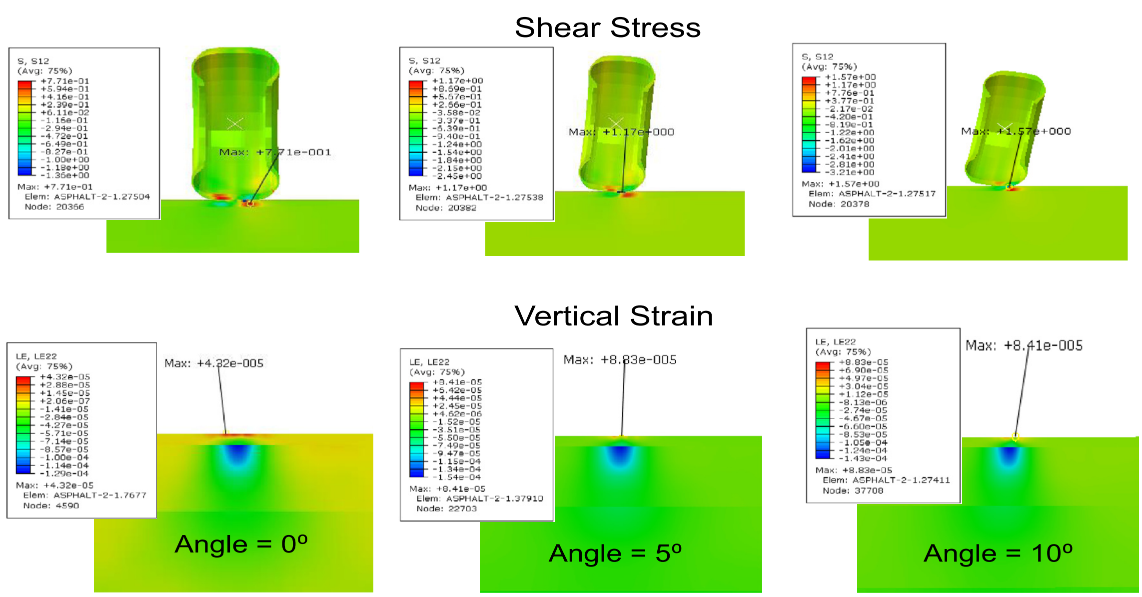

Fig. 4c. Tire inclination angle: stress–strain color maps.

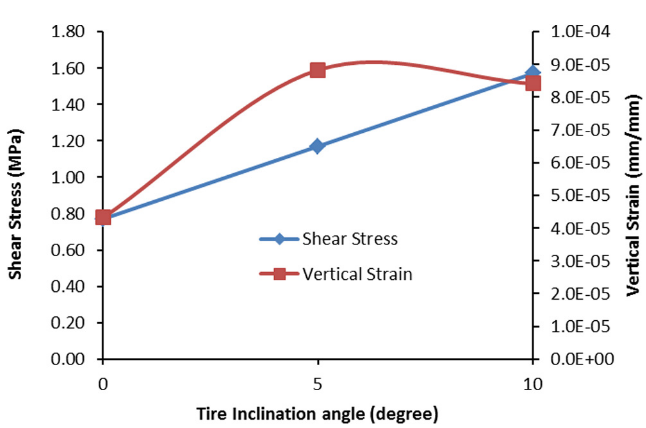

Fig. 4d. Tire inclination angle: maximum stress–strain in the surfacing HMA overlay.

face than normal driving (no tire inclination angle) – needless to say that only three case studies (0°, 5°, and 10°) with only three data points were evaluated. As one of the causes of rutting is shear deformation, the sections of the highway with turning traffic (e.g., intersections) may thus be more susceptible to surface rutting failures, which is consistent with some recent field observations, particularly under elevated summer temperatures [18].

Fig. 4a and Fig. 4b also shows that at a tilting angle of 5°, the existing old HMA experiences more shear stresses as compared to the other two tire tilting angles (0 and 10°, respectively). This, in part, might contribute to the higher vertical strains observed in the case of the 5° tire tilting angle. Also worth noting is that the impact of the shear stresses and vertical strains are not only confined to the top HMA overlay, but also penetrates deep enough to affect the underlying HMA materials that may also be vul-

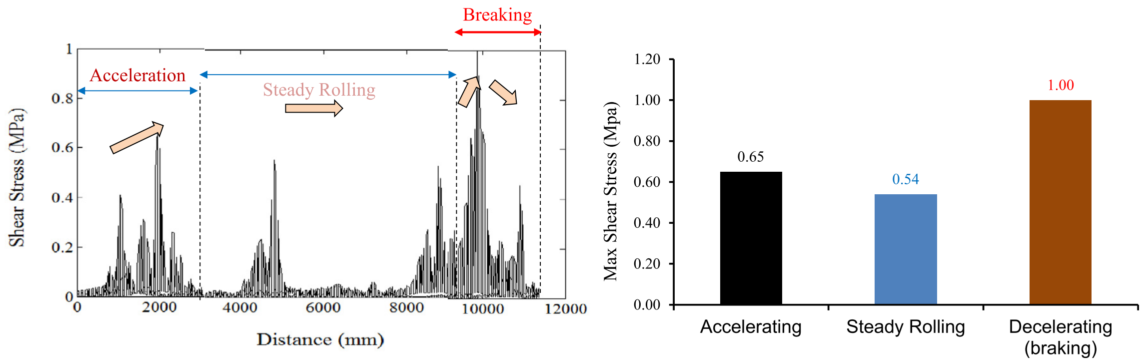

Fig. 5. Maximum shear stresses for accelerating, steady rolling, and decelerating.

nerable to rutting/shear failures, particularly under the combination of extreme traffic loading (volume/weight) and environmental conditions (i.e., elevated temperatures). From Fig. 4c and Fig. 4d, the vertical strain seems to have a peak value at 5° tilting angle for this particular pavement structure. Although limited to only three case studies (0°, 5°, and 10°) with only three data points, it can be theoretically inferred that the geometric redesign of this particular highway section would have to be carefully done so as to ensure that tire inclination angles are below 5°. Similarly, the HMA shear strength design should also be based on the maximum possible inclination angle that generates the most critical strains, which for this case would be 5°. Nonetheless, more case studies with varying tire inclination angles and multiple data points are warranted to statistically substantiate these findings.

5.2. Effects of dynamic loading – Accelerating, steady rolling, and decelerating traffic

For dynamic wheel loading simulations, stress–strain analyses were conducted for three case scenarios, namely accelerating, steady rolling, and decelerating (braking) traffic [23,26]. This dynamic modeling was accomplished by simulating a single tire moving over a 12 m long (Figs. 3 and 5) stretch of the pavement. The moving speeds of the tire for accelerating, steady rolling, and decelerating were 6.7 m/s^2, 96.6 km/h (60-mph), and 6.7 m/s^2, respectively. The other input variables included material properties and layer moduli at a pavement temperature of 25 °C, tire inflation pressure of 690 kPa, tire inclination angle of 0°, and a single tire configuration [29]. The model assembly and the corresponding shear stress results are presented in Fig. 5.

From Fig. 5, it is evident that the maximum shear stress occurs at the onset of tire braking, suggesting that intersections and stop–go sections with slowing and/or stopping vehicles may be more susceptible to shear deformation and surface rutting. It can be observed in Fig. 5 that the maximum shear stress (1 000 kPa) is induced for braking and the least shear stress (540 kPa) is for steady rolling. Thus, for pavement design and structural analysis purposes, the following critical highway areas should be given more attention with respect to the HMA shear strength characterization and mitigation of shear failure and surface rutting: intersections, junctions, urban stop–go sections, and speed hump areas.

5.3. Correlations with field rutting performance data

As observed in Fig. 5, the computed maximum shear stress for vehicle braking is 1 000 kPa, which is much lower than the HMA shear strength (2 896 kPa) of the Type D HMA overlay (surfacing) mix used on highway US 59.

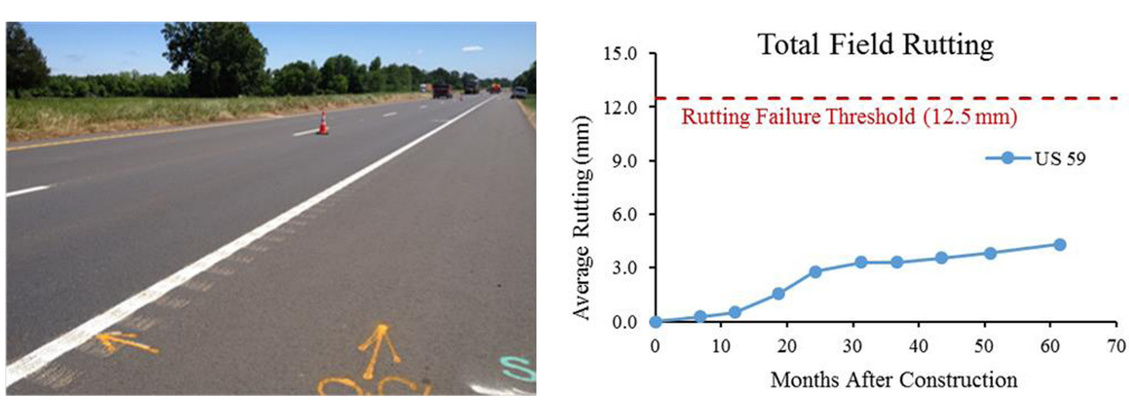

Fig. 6. Field performance (visual and graphical) of highway US 59 as of Spring 2016

Similarly, the most severe shear stress induced with respect to the investigated tire inclination angles (i.e., effects of turning traffic) was about 1 600 kPa (Fig. 4) at a tire tilting angle of 10°; but still lower than the 2 896 kPa shear strength of the HMA surfacing (overlay) mix. Assuming that all the other influencing variables remain equal or constant, this comparison suggests that no shear failure or surface rutting failure would theoretically be expected on highway US 59, which is consistent with the field observations made as of Spring 2016 (see Fig. 6).

Evidently Fig. 6 shows satisfactory field performance for highway US 59 as of Spring 2016, which somewhat correlates with the FE computational simulations and the numerical results predicted by ABAQUS. Highway US 59 was resurfaced in 2011, i.e., overlaid with the dense-graded Type D mix. After over 3 years of service, the total field surface rutting is still very marginal at only about 4.5 mm, which is significantly lower than the terminal rut depth threshold of 12.5 mm [2,18]. Although field conditions are complex and the inputs used for FE modeling may not include all the critical factors from the field, these simulation results give an insight into which factors are more detrimental to pavement stress–strain response and shear/rutting performance. For example, based on the simulated shear stress responses, the pavement may be more susceptible to shear/rutting failure under decelerating (braking) than accelerating and steady rolling vehicles, and that highway intersections may be more prone to shear failure and surface rutting than the straight sections of the highway.

However, these study findings were limited to only one field in-service highway section, one pavement structure, and one HMA mix type. As such, evaluation of multiple case studies and highways is strongly recommended in the future. This will inevitably supplement the results reported herein and lend more credence to this study's findings.

6. Synthesis and discussion of the results

The preceding results in Figs. 4 and 5 indicated that an inclined tire (i.e., at a tilting angle of 10°) and decelerating (braking) traffic induced the most severe shear stresses and vertical strains on the HMA surfacing layer (overlay) when compared to say steady rolling and 0° tire tilting angle. For highway US 59, however, the HMA surfacing material (Type D mix) was of sufficient shear strength (2 896 kPa) as measured in the laboratory to sustain the maximum shear stresses induced by tire inclination (1 600 kPa) and braking tire (1000 kPa), respectively (Figs. 4 and 5). The measured field FWD modulus value (2919 MPa) at 25 °C (Table 1) of the HMA surfacing layer (overlay) was also within the typical Texas range (2758–4137 MPa) and considered to be structurally sufficient to mitigate surface rutting failures [18]. As is pictorially and graphically demonstrated in Fig. 6, field performance was still satisfactory on highway US 59 as of Spring 2016 with no serious surfacing rutting or shear failure problems after over 3 years of service [18]. Considering that HMA is generally more susceptible to rutting in its early life after construction, among others due to traffic densification, these correlation results (laboratory versus FE modeling versus field data) are promising and indicates the predictive potential of FE modeling with ABAQUS [18,30]. However, the study was based only on one highway section and pavement structure with statistically limited data points. Therefore, the results and findings are not exhaustive. More cases

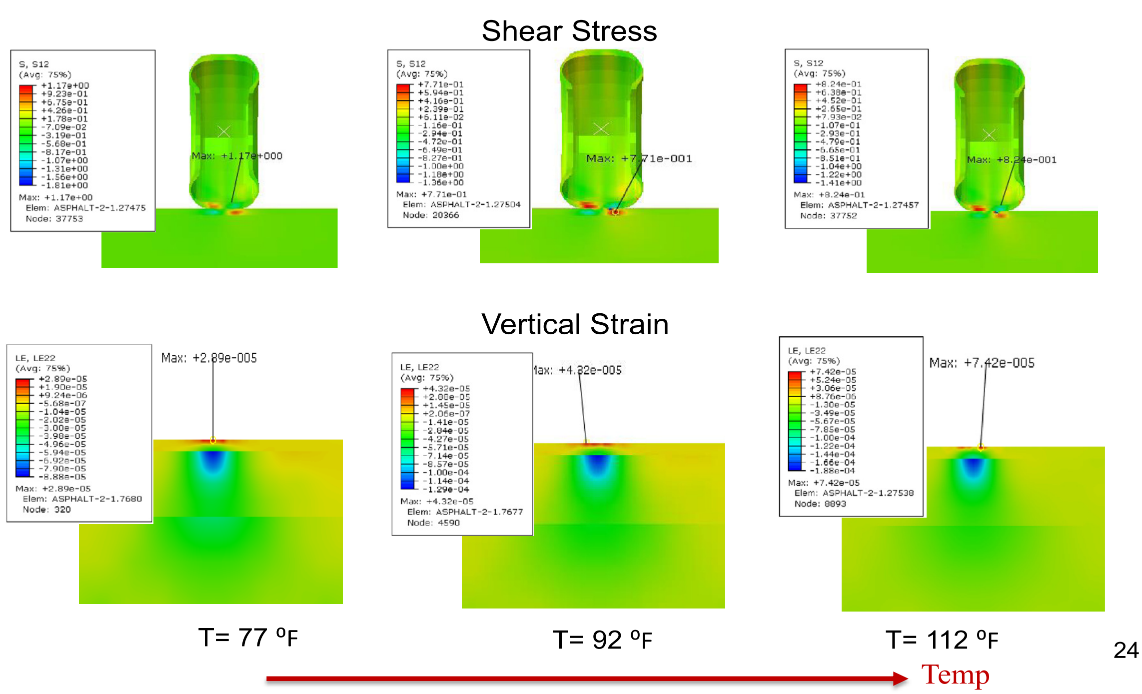

Fig. 7a. Stress–strain profiles (color maps) and pavement temperature.

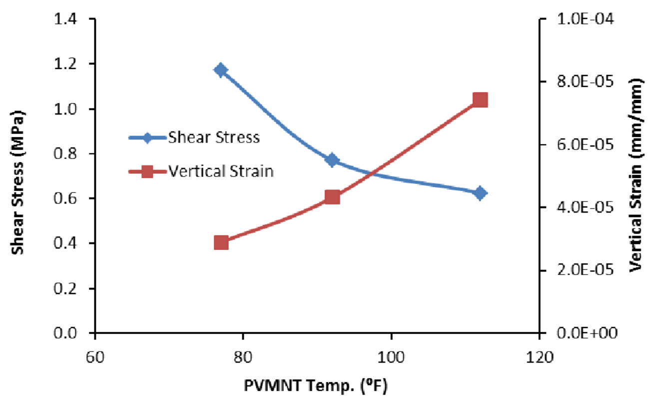

Fig. 7b. Maximum stress–strain responses and pavement temperature.

studies with numerous highway sections and data points need to be evaluated to statistically supplement and substantiate the study findings.

Note that while the maximum shear stresses computed under an inclined and braking tire, respectively, did not exceed the surfacing HMA (overlay) shear strength, in reality, this may not be so if the combined effects of all the other elevated shear situations such as tire inclination, deceleration, high temperature, etc., are interactively considered. That is, in order to effectively compare the modeling results with field performance, combinations of all the critical parameters producing maximum shear damage need to be evaluated interactively. For instance, the currently prevailing high summer temperatures that often result in high pavement temperatures have detrimental effects on the stress–strain responses under turning and braking traffic; which is attributed to the decay in HMA strength with increasing temperature. In this study, all the FE modeling was based on a reference temperature of 25 °C without interactively considering the temperature variation effects. Fig. 7 exemplifies the effects of temperature variation on the stress–strain responses.

In Fig. 7, the maximum shear stress decreases with an increase in the pavement temperature. This might seem counter-intuitive since from field experience, it is known that HMA rutting and shear failures are most critical at high pavement temperatures and occurs over the entire in-service domain. However, due to HMA's viscoelastic nature, the HMA's shear strength is also reduced drastically with increasing temperature [2,14,18]. Due to this decrease in the HMA modulus/strength with increasing temperature, the maximum shear stress that the HMA mix can endure prior to shear failure also decreases; making it more susceptible to surface rutting as indicated by the higher vertical strain magnitude in Fig. 7b. Quite often, the shear stress exerted on the pavement (due to traffic loading or at intersections, stop–go sections, etc.) exceeds the shear strength of the HMA, thus leading to more shear failures and surface rutting. This is particularly prevalent at elevated temperatures where the HMA shear strength deteriorates even further.

Clearly, Fig. 7 shows the impacts of temperature variations on the pavement stress–strain responses and the importance of interactively considering all the influencing factors in FE modeling. However, this aspect was beyond the scope of this study, due partly, to the complexity and computational intensive nature of the 3-D dynamic FE modeling with ABAQUS. Thus, future studies warrant the holistic consideration of all the combined and interactive effects of these severe shear conditions, i.e., high temperature, inclined tire, braking tire, etc.

7. Conclusions and recommendations

In this study, ABAQUS FE modeling for stress–strain analyses in 3-D mode with varying traffic loading and environmental conditions was conducted using an in-service highway pavement structure on highway US 59. The input variables for computational modeling consisted of actual laboratory and field data, including material properties (i.e., modulus and shear strength), traffic, climate (i.e., temperature), and in-service pavement structure. The maximum shear stress and vertical strains were then analyzed and correlated to the HMA material shear strength and the actual measured/observed field performance. Based on the simulation results, the key findings, conclusions, and recommendations drawn from this paper are summarized as follows:

- The maximum shear stress increases with an increase of the tire inclination angle from 0° to 10°, which provide analytical evidence to support the theoretical assumptions that turning traffic on highways (e.g., at intersections) can cause higher shear stress in the pavement than through moving traffic (no turning/tire inclination angle). This suggests that sections of a highway with a large volume of turning traffic maybe more susceptible to shear and surfacing rutting failure.
- For the three tilting angles (0, 5, and 10°) investigated, the maximum vertical strains in the HMA surfacing layer (overlay) occurred at 5°. These modeling results theoretically allude to the existence of a critical tire inclination angle corresponding to the maximum critical vertical strains, an aspect worth considering both during material, geometrical, and pavement structural design phases for turning traffic, say at highway intersections. However, more case studies with varying tire inclination angles and multiple data points are strongly recommended to statistically substantiate these findings.
- For dynamic loading simulation, decelerating (braking) induced much larger maximum shear stresses than accelerating and steady rolling, indicating, as would be theoretically expected, that intersections and stop–go sections with braking and stopping vehicles may be more susceptible to shear deformation and surfacing rutting. Thus, for pavement design and structural analysis purposes, the following critical highway areas should be given more attention with respect to the

HMA shear strength property and mitigation of shear/rutting failures: intersections and junctions; urban stop–go sections, and speed hump areas.
- Due to the viscoelastic nature of HMA and the decrease in modulus/strength with increasing temperature, the maximum shear stresses sustained by the surfacing HMA (overlay) layer decreased significantly with increase in the pavement temperature. Similarly, the shear strength of the HMA also decreases greatly when the temperature increases. This indicates that the HMA and the entire pavement structure would be more susceptible to rutting failure at elevated temperatures as was evidenced by the observed high vertical strains.

Overall, it should be noted that although the numerical simulations in this study considered and incorporated most of the key influencing variables of the stress–strain responses such as the pavement structure, material properties, traffic loading, and climate (i.e., pavement temperature), the overall findings should not be considered exhaustive. The true conditions for pavements in the field are interactively very complex and thus, it's quite a challenge to fully incorporate all the influencing variables and make accurate performance predictions. Additionally, only one field in-service highway section and pavement structure, with a relatively thin surfacing HMA layer (50 mm thick) and limited data points, was considered. Thus, there is need to consider more case studies and highways, with varying pavement materials, layer thicknesses, loading conditions, tire tilting angles, and numerous data points to lend further credence and statistically substantiate the findings from this study.

However, for better simulation and more accuracy in the modeling results, visco-elastic–plastic and damage models for the HMA should be considered. Additionally, the non-linear anisotropic behavior of the base and subgrade layers needs to be properly modeled including varying the pavement layer thicknesses. In this study, only the surfacing HMA layer (overlay) was modeled as a viscoelastic material, whereas the rest of the underlying layers, were simplistically modeled as elastic media. Furthermore, the pavement-tire contact stresses were simplistically assumed to be equal to the tire inflation, which might have had an impact on the accuracy of the results. Nonetheless, the FE modeling and simulations with simplified material properties and loading conditions (and limited data points), as conducted in this study, gives an insight into the stress–strain responses of a pavement structure when subjected to dynamic traffic loading and varying environmental conditions, particularly the effects of tire inclination angle. Thus, future studies should particularly focus on this aspect, namely tire inclination angle and further investigation of the critical angle.

Acknowledgements

The authors thank the Texas Department of Transportation (TxDOT) and the Federal Highway Administration (FHWA) for their financial support and all those who helped during the course of this research work and documentation of this paper. The first author (Dr. Xiaodi Hu) also acknowledges the support provided by the National Natural Science Foundation of China [51278389] and the Science and Technology Foundation of Department of Transportation of Hubei Province [2013-731-1-3] toward the technical contributions and documentation of this paper.

The contents of this paper reflect the views of the authors who are responsible for the facts and accuracy of the data presented herein and do not necessarily reflect the official views or policies of any agency or institute. This paper does not constitute a standard, specification, nor is it intended for design, construction, bidding, contracting, tendering, certification, or permit purposes. Trade names were used solely for information purposes and not for product endorsement, advertisement, or certification.

References

[1] R.C. Meininger, Effects of Aggregates and Mineral Fillers on Asphalt Mixture Performance, (1992), Issue 1147, pp. 69.
[2] J. Zhang, A.E. Alvarez, S.I. Lee, A. Torres, L.F. Walubita, Comparison of flow number, dynamic modulus, and repeated load tests for evaluation of HMA permanent deformation, J. Constr. Build. Mater. 44 (2013) 391–398.
[3] R.A. Tarefder, M. Zaman, K. Hobson, A laboratory and statistical evaluation of factors affecting rutting, Int. J. Pavement Eng. 4 (1) (2003) 59–68.
[4] F.L. Roberts, P.S. Kandhal, E.R. Brown, D.Y. Lee, T.W. Kennedy, Hot Mix Asphalt Materials, Mixture Design, and Construction, 2nd Ed., NAPA Education Foundation, Lanham, MD, 1996.
[5] A. Simpson, Characterization of Transverse Profile. Transportation Research Record 1655, National Research Council, Washington D. C., 1999, pp. 185–191.
[6] J.E. Haddock, A.J.T. Hand, H. Fang, T.D. White, Determining layer contributions to rutting by surface profile analysis, J. Transp. Eng. 131 (2) (2005) 131–139.
[7] X. Shu, B. Huang, X. Chen, L. Robison, Effect of coarse aggregate angularity on rutting performance of HMA, Pavement Mech. Perform. (2006) 126–133
[8] E.J. Yoder, M.W. Witczak, Principles of Pavement Design, John Wiley & Sons Inc, New York, N.Y., 1975.
[9] Y.H. Huang, Pavement Analysis and Design, Prentice-Hall, Englewood Cliffs, N.J., 1993.
[10] R. Siddharthan, J. Yao, P. Sebaaly, Pavement Strain from Moving Dynamic 3D Load Distribution, J. Transp. Eng. 124 (6) (1998) 557–566.
[11] R. Blab, J. Harvey, Modeling Measured 3D Tire Contact Stresses in a Viscoelastic FE Pavement Model, Int. J. Geomech. 2 (3) (2002) 271–290.
[12] D.S. Simulia, Abaqus/CAE User's Manual. Providence, RI, 2007.
[13] R. Siddharthan, J. Yao, P. Sebbaly, Pavement Strain from Moving Dynamic 3D Load Distribution, J. Transp. Eng. 124 (6) (1998) 557–566.
[14] K.T. Danielson, A.K. Noor, J.S. Green, Computational Strategies for Tire Modeling and Analysis, Comput. Struct. 61 (4) (1996) 673–693.
[15] J. Pousa, J. Deacon, S. Weissman, J. Harvey, C.L. Monismith, F.N. Finn, R.G. Hicks, G. Paulsen, J. Coplantz, Permanent Deformation Response of Asphalt Aggregate Mixes. Report SHRP-A-415, Strategic Highway Research Program, TRB, National Research Council, Washington, D.C., 1994.

[16] S.L. Weissman, Influence of Tire-Pavement Contact Stress Distribution on Development of Distress Mechanisms in Pavements, Transp. Res. Rec. 1655 (1999) 161–167.
[17] M. de Beer, C. Fisher, F.J. Jooste, Evaluation of Non-Uniform Type Contact Stresses on Thin Asphalt Pavements. Proc., In: 9th International Conference on Asphalt Pavements, Copenhagen, Denmark, 2002, Aug. 17–22.
[18] L.F. Walubita, A. Faruk, S. Lee, D. Nguyen, R. Hassan, T. Scullion, HMA Shear Resistance, Permanent Deformation, and Rutting Tests for Texas Mixes: Final Year-2-Report. Report No. FHWA/TX-15/0-6744-2, Texas A&M Transportation Institute, College Station, Texas, 2014.
[19] B. Sukumaran, M. Willis, N. Chamala, Three dimensional finite element modeling of flexible pavements, Adv. Pavement Eng. (2005) 1–12
[20] M. Kim, E. Tutumluer, J. Kwon, Nonlinear pavement foundation modeling for three-dimensional finite-element analysis of flexible pavements, Int. J. Geomech. 9 (5) (2009) 195–208.
[21] P. Reynaud, S.B. Nasr, F. Allou, T. Chaise, D. Nelias, C. Petit, 3D modelling of tyre-pavement contact pressure, Eur. J. Environ. Civil Eng. (2016) 1–18
[22] J.A. Hernandez, A. Gamez, I.L. Al-Qadi, Effect of wide-base tires on nationwide flexible pavement systems: numerical modeling, Transp. Res. Rec. 2590 (2016) 104–112.
[23] K. Xia, Y. Yang, Three-dimensional finite element modeling of tire/ground interaction, Int. J. Numer. Anal. Meth. Geomech. 36 (4) (2012) 498–516.
[24] Y. Liu, Z. You, Y. Zhao, Three-dimensional discrete element modeling of asphalt concrete: size effects of elements, Constr. Build. Mater. 37 (2012) 775–782.
[25] M.T. Rahman, K. Mahmud, S. Ahsan, Stress-strain characteristics of flexible pavement using finite element analysis, Int. J. Civil Struct. Eng. 2 (1) (2011) 233.
[26] H. Wang, I.L. Al-Qadi, I. Stanciulescu, Simulation of tyre-pavement interaction for predicting contact stresses at static and various rolling conditions, Int. J. Pavement Eng. 13 (4) (2012) 310–321.
[27] P. Khavassefat, D. Jelagin, B. Birgisson, A computational framework for viscoelastic analysis of flexible pavements under moving loads, Mater. Struct. 45 (11) (2012) 1655–1671.
[28] M. De Beer, J.W. Maina, Y. Van Rensburg, Modelling Tyre-Road Contact Stresses in Pavement Design and Analysis. SATC 2013, 2013.
[29] N. Chawla, V.V. Ganesh, B. Wunsch, Three-dimensional (3D) microstructure visualization and finite element modeling of the mechanical behavior of sic particle reinforced aluminum composites, Scripta Mater. 51 (2) (2004) 161–165.
[30] E.G. Fernando, D. Musani, D. Park, W. Liu, Evaluation of Effects of Tire Size and Inflation Pressure on Tire Contact Stresses and Pavement Response. Report FHWA/TX-06/0-4361-1, Texas A&M Transportation Institute, College Station, Texas, 2006.