Analysis of Interface Stress in Asphalt Pavement Under Dynamic Loading

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Abstract. Pavement interfaces play a critical role in the structural integrity of flexible pavements, serving as contact areas that bear significant stress due to traffic and environmental conditions. Despite their importance, interface behavior under varying conditions is not fully understood, particularly in terms of shear stress. This study addresses this gap by assessing stress conditions at asphalt layer interfaces in flexible pavements, focusing on the effects of dynamic loading. To accomplish this objective, the pavement structure was modeled as a multilayer system composed of overlapping horizontal layers, with multiple simulations conducted using Abaqus. The applied load was analyzed as either static or dynamic, incorporating vertical, horizontal, or a combination of both loading conditions. Furthermore, the asphalt concrete layers were modeled as either elastic or viscoelastic. Five combinations of road materials elastic modulus, with different ratios of asphalt concrete and foundation layer, were calculated and analyzed. For the distribution of vertical stress and shear stress in the pavement, impacts of temperature and speed were revealed. The findings reveal that shear stress is highest when the asphalt concrete layer's elastic modulus significantly exceeds that of the foundation, whereas reduced modulus ratios result in lower stresses. For dynamic conditions, vehicle speed significantly influences stress behavior: higher speeds amplify shear stress, while lower speeds increase vertical stress. Additionally, elevated temperatures lead to higher vertical stresses but lower shear stresses, highlighting the critical role of temperature and speed management in mitigating pavement damage during hot weather. These results provide practical insights for optimizing pavement design and preventing interface failure in flexible pavements.

Keywords: Asphalt pavement; Finite elements; Numerical simulation; Stress; Abaqus

1 Introduction

Pavement deterioration is the process through which distress develop in the pavement as a result of the combined effects of traffic loading and environmental conditions, leading to a loss of structural integrity [1]. Therefore, understanding the actual me-

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chanical behavior within the pavement structure is crucial, particularly at the interfaces, which are the contact areas between pavement layers. Numerous research studies have focused on the factors influencing pavement performance, including pavement structures, traffic conditions, climatic conditions, and construction materials [2,3,4]. Since the performance of asphalt concrete is affected by variables such as time, stress, and temperature, it is essential to predict its behavior using appropriate models. Asphalt concrete is a complicated mixture. As the main material in flexible pavements, exhibits stress-dependent, temperature-sensitive, and time-dependent behavior [5,6]. These characteristics necessitate advanced modeling techniques to predict pavement performance under real-world conditions. Numerical simulations using finite element (FE) methods, such as those conducted with Abaqus, provide a robust framework for analyzing complex pavement systems. Such models enable researchers to incorporate critical material behaviors, including elasticity, viscoelasticity, and plasticity, to simulate pavement responses under various scenarios [7,8].

The primary objective of this study is to analyze the stress state at asphalt pavement layer interfaces, with a particular focus on shear stress under dynamic loading conditions. To achieve the objective, this study employs FE modeling to investigate the stress states at pavement layer interfaces under various loading scenarios. The pavement structure is modeled as a multilayer system with both elastic and viscoelastic material properties. Five combinations of asphalt concrete and foundation elastic moduli are considered to capture the variations in stress behavior. The study incorporates both static and dynamic loading scenarios, simulating the effects of different vehicle speeds and temperature on stress distribution. The analysis focuses on shear stress and vertical stress at the interfaces, providing insights into how these factors influence pavement performance. The relevance of this study lies in its potential to inform the design and maintenance of durable pavements, particularly in managing the negative effects of high temperatures and extreme vehicle speeds. These findings can assist engineers in developing strategies to mitigate interface failures and optimize pavement's service life.

2 Finite Element Parameters in Abaqus

2.1 Methodology

This study employed finite element (FE) modeling using Abaqus due to its ability to accurately simulate complex material behaviors, such as the viscoelastic and temperature-dependent properties of asphalt concrete. Appropriate material properties such as elastic moduli and Poisson's ratio were selected to reflect typical pavement structures. This choice was made by consulting the pavement catalogue, prepared by Ministry of Transport of the People's Republic of China (MOT), in which it suggests to the designer a range of solutions of road structure of various types for the traffic and environmental conditions typical of China.

2.2 Material Elastic Properties

Regarding Young's modulus, five different examples (ex) were selected, each with the same Poisson's ratio (ν) but varying elastic moduli (E), in order to capture the different responses of the pavement. These cases are summarized in Table 1.

Table 1. Adopted Calculation Parameters

	Parameter	ex.1	ex.2	ex.3	ex.4	ex.5
Asphalt concrete	E (MPa)	3000	500	10000	3000	3000
	ν	0.35	0.35	0.35	0.35	0.35
	E (MPa)	3000	500	10000	3000	3000
	ν	0.35	0.35	0.35	0.35	0.35
Foundation	E (MPa)	300	300	300	30	1000
	ν	0.35	0.35	0.35	0.35	0.35
Subgrade	E (MPa)	30	30	30	30	30
	ν	0.4	0.4	0.4	0.4	0.4

The material properties for the model are described in Table 2.

Table 2. Material Elastic Properties in Abaqus

Layer	Thickness (m)	Young's modulus (MPa)	Poisson's ratio	Bulk Density (kg/m^3)
Layer 1	0.042	3000/500/10000	0.35	2400
Layer 2	0.126	3000/500/10000	0.35	2400
Layer 3	0.36	300/30/1000	0.35	1800
Layer 4	∞	30	0.40	1800

2.3 Material Viscoelastic Properties

Abaqus software analyzes the behavior of viscoelastic materials in two main domains: time and frequency. This study utilized the time domain, where the Prony Series function was applied to fit the variation of the relaxation modulus over time. The variations of the bulk modulus K(t) and shear modulus G(t) over time were estimated using the following equations, under the assumption that the Poisson's ratio (ν) remains constant over time:

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

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

This mathematical law is the expression of the standard linear mechanic model represented by a spring in parallel with a Maxwell element. The relaxation function in the temporal domain of the generalized Maxwell model can be obtained directly. It can be expressed as follows:

$$E(t) = E_\infty + \sum_{i=1}^{n} E_i * exp\,(-t/\tau_i)\;\; for\; t \geq 0 \quad (3)$$

The procedure that is followed in this work about the Prony's Series is:
Find the model parameters E_i (MPa) and τ_i(s);
Solve the equation 3;
Assume that the Poisson's ratio doesn't change with time: $G(t) = \frac{E(t)}{2(1+\nu)}$;
Find the equation: $g_R(t) = 1 - \sum_i^n g_i\,[1 - e^{-t/\tau i}]$;
Find the parameters to input in Abaqus: g_i and k_i;
Use the shift factor for change the reference temperature:

$$log\alpha(T, Tref) = \frac{-C1+(T-Tref)}{C2+(T-Tref)} \quad (4)$$

Prony's Series parameters are shown in Table 3.

Table 3. Prony's Series Parameters utilized in Abaqus

No.	39 °C		27 °C	
	g_i	t_i	g_i	t_i
1	0.03921	2.9E-10	0.03921	8.83E-09
2	0.04506	1.89E-09	0.04506	5.75E-08
3	0.06569	1.48E-08	0.06569	4.51E-07
4	0.08048	1.26E-07	0.08048	3.82E-06
5	0.09493	9.89E-07	0.09493	3.01E-05
6	0.11831	7.98E-06	0.11831	0.000243
7	0.12347	5.85E-05	0.12347	0.00178
8	0.13138	0.000398	0.13138	0.012108
9	0.12898	0.002691	0.12898	0.081873
10	0.10146	0.018558	0.10146	0.564725
11	0.05297	0.132095	0.05297	4.01966

After emphasizing the significance of dynamic analysis and its ability to simulate a more realistic scenario compared to an elastic case, it is crucial to consider the impact of vehicle speed on the pavement. The pavement was subjected to four different speed conditions: 10 km/h, 30 km/h, 60 km/h, and 120 km/h. Corresponding application times for the moving load were 0.54432 s at 10 km/h, 0.18144 s at 30 km/h, 0.09072 s at 60 km/h, and 0.04536 s at 120 km/h.

2.4 Loading Parameters

The traffic loading data adopted are summarized as following: Axle configuration: single axle with one wheel; Load: 1 kN; Tire pressure: 20 kPa; Radius of contact area: the contact radius was 0.126 m. To simulate moving traffic, a load with variable intensity over time was assumed, following the haversine function, as illustrated in Equation 5.

$$F(t) = q \times sin^2(\frac{\pi \times t}{\tau}) \tag{5}$$

where q is the load, t is the time loading and τ is expressed by the following equation:

$$\tau = \frac{12 \times a}{v} \tag{6}$$

where a is the radius of the loading area and v is the speed in m/s of the moving load.

3 Finite Element Idealization

A domain size of 6 meters was chosen for the width, length, and vertical direction of the model. The pavement thickness is 0.52 m, while the subgrade thickness is 4.68 m. A load of 1 kN was applied to the pavement, distributed over a circular area with a radius of 0.126 m. The mesh consisted of rectangular elements, including 8-node linear brick elements (C3D8R), 6-node linear triangular prism elements (C3D6), and 4-node elements. For the calculation points, the y coordinate is always the same for the ten points and equal to 0, the selected points from the center of the load area along the x-axis were: x=0 m, 0.042 m, 0.084 m, 0.126 m, 0.168 m, 0.21 m, 0.252 m, 0.378 m, 0.50.4 m, 0.756 m. The z-coordinate was kept constant for each system analyzed, with nine different calculation depths considered: z=0 m, 0.21 m, 0.42 m, 0.63 m, 0.84 m, 0.105 m, 0.126 m, 0.147 m, 0.168 m.

4 Results and Discussion

4.1 Static Case with vertical Unit Load Applied

A comparison was conducted by analyzing the pavement response at a fixed depth (z=0.042 m), focusing on the variations in the elastic moduli of the asphalt concrete layers and the unbonded foundation layer. Fig. 1 shows how the maximum values of the shear stress are obtained at the edge of the loading area for all the cases examined.

Comparing different modulus, the shear stress of example 4 (elastic modulus of AC layer is 3000 MPa, elastic modulus of foundation is 30 MPa) is the biggest. The shear stress of example 2 (elastic modulus of AC layer is 500 MPa, elastic modulus of foundation is 300 MPa) is the lowest.

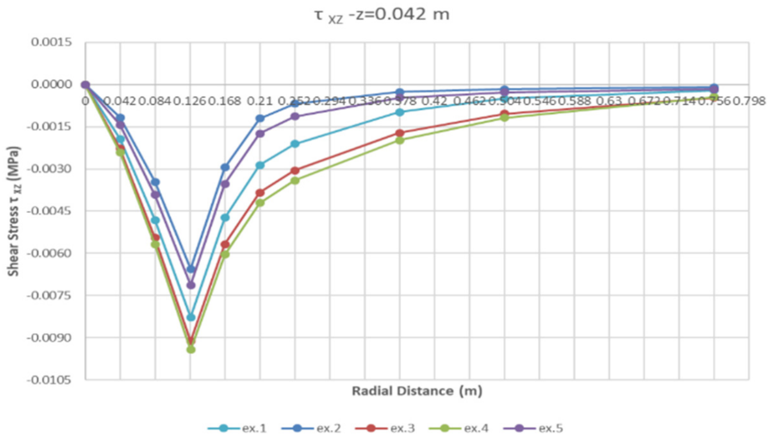

Fig. 1. Trend of the shear stress with different Young's modules

4.2 Dynamic Case with Vertical and Horizontal Unit Loads Applied

Comparison of the Same Load at Different Speeds. Four different speeds (10, 30, 60 and 120 km/h) were selected to evaluate the response of the asphalt concrete layers in the viscoelastic field subjected to the application of a dynamic load. The chosen speeds, 10,30,60 and 120 km/h, are representative of the real stress conditions to which the road pavements are subjected every day. The comparison was made at a depth of z = 0.084 m.

Fig. 2 illustrates the variation in vertical stress at 27 °C, while Fig. 3 shows the variation in vertical stress at 39 °C. Fig. 4 presents the variation in shear stress at 27 °C and Fig. 5 depicts the variation in shear stress at 39 °C.

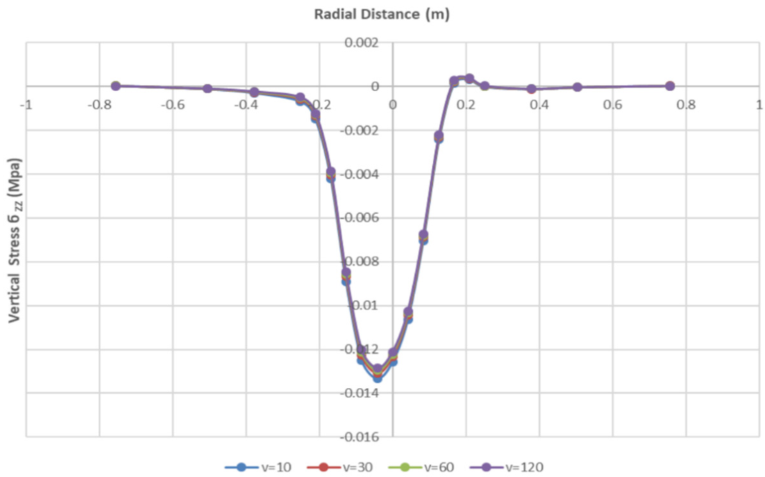

Fig. 2. Trend of σ_{ZZ} for different speeds at 27 °C

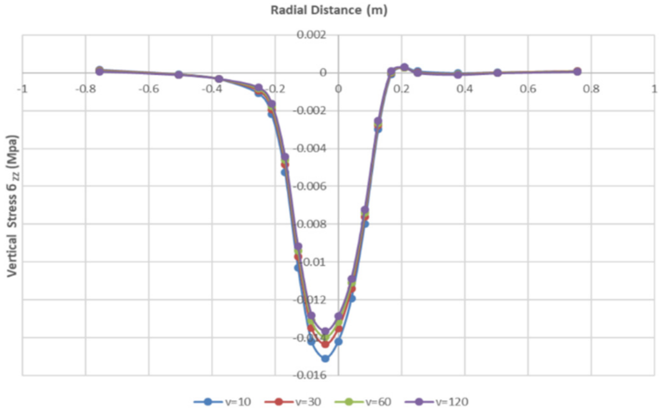

Fig. 3. Trend of σ_{ZZ} for different speeds at 39 °C

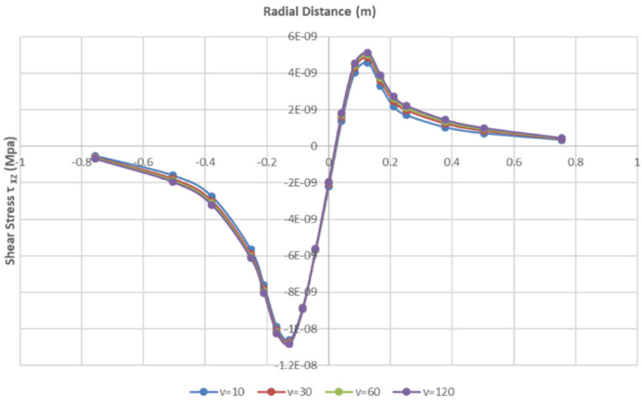

Fig. 4. Trend of the τ_{XZ} for different speeds at 27 °C

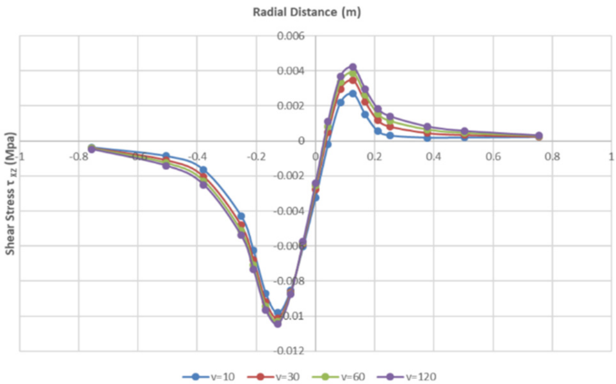

Fig. 5. Trend of the τ_{XZ} for different speeds at 39 °C

For vertical stress, it increases when the speed is reduced. Compared with the case at 27 °C, more differences are visible even if the difference between the two temperature are not high. The speed of 10 km/h causes the largest vertical stress; the vertical stress is decreased by 10.5% when the speed is increased from 10 km/h to 120 km/h. The maximum vertical stress value is reached at x = -0.042 m for all the different speeds investigated and it decreases almost symmetrically until the minimum value is reached at position x = ±0.756 m.

For shear stress, the maximum value is obtained at the higher speed (120 km/h) and decreasing with decreasing speeds. Compared with the case at 27°C, the impact of speed becomes significant and the shear stress at 120 km/h is 1.56 times of the shear stress at 10 km/h. The maximum value is reached at the edge of the loading area.

Comparison of the Same Speed at Different Temperatures. For the comparison a speed of 60 km/h was chosen, and the results obtained at two different temperatures (T = 27 °C and T = 39 °C) were compared. The comparison was made at a depth of z = 0.084 m. The results are shown in Fig. 6 and Fig. 7.

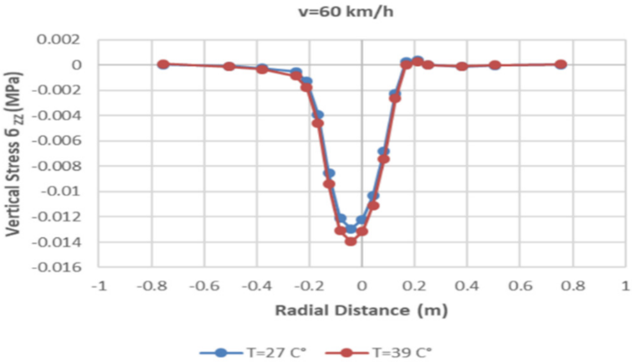

Fig. 6. Trend of vertical stress for different temperatures at the same speed

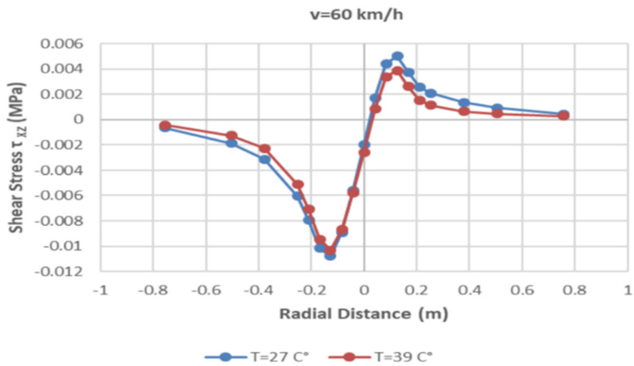

Fig. 7. Trend of shear stress for different temperatures at the same speed

It can be observed that as the temperature increases, the pavement becomes softer. Under lower elastic modulus conditions, the pavement experiences higher vertical stress. However, for shear stress, the maximum value occurs at lower temperatures, indicating that the pavement is subjected to greater shear stress when the elastic modulus is higher.

5 Combination of the Negative Conditions

The viscoelastic properties of asphalt significantly influence pavement response and performance. Both high temperatures and extreme vehicle speeds, whether very low or very high, negatively impact the pavement. In this context, two scenarios were analyzed: 10 km/h at 39 °C and 120 km/h at 39 °C. The comparison was conducted at a depth of z=0.084m. The results are shown in Fig. 8 and Fig. 9. The results demonstrate that at high temperatures, both high and low vehicle speeds negatively affect the pavement. Therefore, to prevent the pavement from suffering damage, vehicle speed should be carefully considered, especially during the hot summer.

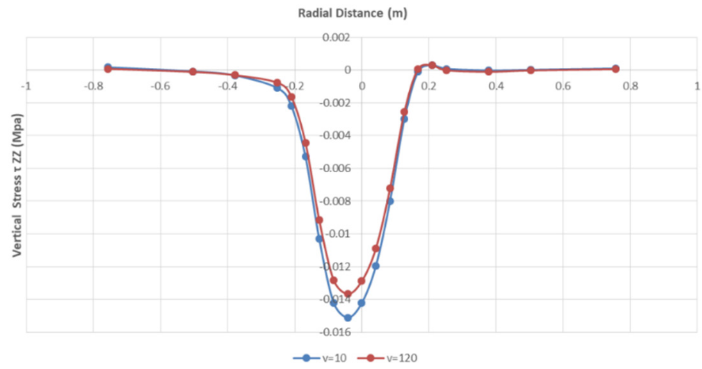

Fig. 8. Trend of vertical stress at 39℃ at different speeds

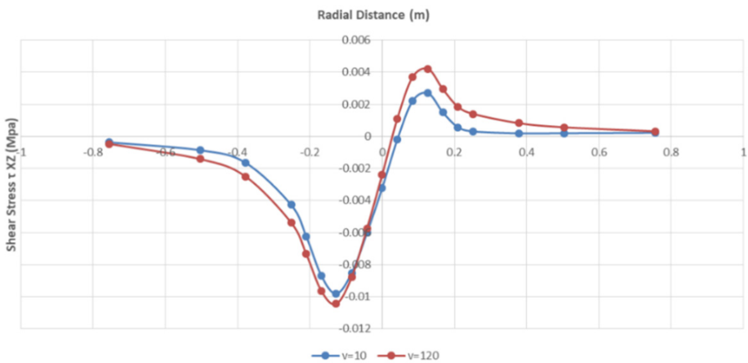

Fig. 9. Trend of shear stress at 39 °C at different speeds

6 Conclusions

This study aimed to evaluate the stress state at the interfaces of flexible pavements, with a particular focus on shear stress, using Abaqus. Various simulations were performed, considering different types of loads and material properties. The main conclusions of this study are as follows:

1. Material properties: Shear stress at the interface is highest when the elastic modulus of the asphalt concrete layer significantly exceeds that of the foundation layer. Lower stiffness ratios result in reduced stress levels, emphasizing the importance of optimizing material combinations in pavement design.

2. Vehicle speed: Higher vehicle speeds amplify shear stress, while lower speeds increase vertical stress. These effects are critical in determining the pavement's resistance to deformation and shear failure.

3. Temperature effects: Elevated temperatures increase vertical stress due to asphalt softening but reduce shear stress. This highlights the vulnerability of pavements in hot climates and the need for proper temperature management strategies.

4. This study has some limitations, including the use of idealized material properties and the exclusion of critical factors such as traffic-induced fatigue, thermal gradients, and construction-induced imperfections. The dynamic loading simulation in this study is a simplified representation of vehicle loading, which assumed uniform load intensity and idealized tire-pavement contact conditions. This approach did not account for more complex factors such as uneven load distributions and varying tire pressures.

5. Future studies could address these limitations by incorporating more realistic parameters to enhance the accuracy of pavement stress analysis, as well as investigate more complex pavement structures, including the effects of multilayer variations and different traffic conditions.

6. In site experimental validation of the simulation results would help strengthen the findings and improve pavement design guidelines.

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