Viscoelastic Analysis of Top-Down Crack in Geosynthetic Reinforced Asphalt Pavements Using FEM

Masoud Jalali and Hasan Taherkhani

Abstract The Top-Down crack (TDC) initiates at the pavement surface and propagates downward. One of the major causes of TDC is due to stress resulting from the interaction between truck tires and the pavement surface. Various factors such as tire pressure have a significant effect on the tire-pavement contact area and can lead to the initiation and propagation of TDC. The reinforcement of pavement by geosynthetic can increase the resistance against cracking. However, the geosynthetic performance depends on some parameters such as their elastic modulus. A 3D finite element model utilizes to evaluate the influence of different tire pressures and geosynthetic modulus (that placed at the bottom of the asphalt layer) on TDCs and Bottom-Up cracks (BUCs) in geosynthetic reinforced and unreinforced pavements. In this study, the HMA layer was characterized as a viscoelastic material. The result shows that the variation of geosynthetic modulus has more effect on BUC than TDC. The study also indicates that the timing of the appearance of the cracks be latter as the geosynthetic modulus is increasing. It's also found that the interval of initiate between BUC and TDC is reduced with increasing the geosynthetic modulus. In addition, the effect of variation of tire pressure on BUC is more than TDC.

Keywords Asphalt pavement · Viscoelastic · Top-down crack · Geosynthetic · Finite element

1 Introduction

Top-Down Cracking (TDC) is among the common distresses of asphalt pavements initiating at the pavement surface in the longitudinal direction under wheel path and propagating downward [1, 2]. It has been reported that tire-pavement contact stress is a critical factor for TDC occurrence [3, 4]. Numerous factors, including tire pressure, have been recognized to be effective in the tire-pavement contact area. Generally, increasing tire pressure resulted in a reduction of tire-pavement contact area and

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increased contact stress between the tire and pavement surface. It is suggested that the tire pressure is mainly affecting the asphaltic layer responses while the responses of pavement sub-layers are not significantly affected by the tire pressure [5, 6].

Using geosynthetics for reinforcing could be an effective way for crack mitigation and reduction of critical responses in flexible pavements against detrimental effects of tire inflation pressure. However, the performance of the geosynthetic depends on a variety of factors, such as the elastic modulus of geosynthetic and its position in the pavement structure. The results of previous studies show that placing the geosynthetic beneath the asphaltic layer has the highest effect on reducing tensile strain at the bottom of the asphaltic layer [7]. Some research also showed that the benefits of geosynthetic reinforcement increase with increasing geosynthetic elastic modulus [8].

An exploration of the literature reveals that tensile strain at the top of the asphaltic layer in the vertical direction is related to TDC. This critical strain occurs due to greater horizontal or radial compressive stress at the pavement surface than the vertical or normal compressive stress at this region [4]. However, this vertical tensile strain, as a critical response for TDC, has not been well investigated. Therefore, this research attempted to study the effect of different factors on this strain as a criterion for evaluating the TDC.

It has been proven that asphaltic materials behave as viscoelastic materials. This means that the behavior of asphalt mixtures depends on the loading rate and temperature [7]. Therefore, it is important to use an economical and fairly accurate method for modeling and determining the critical responses of asphalt pavements. This research aimed to make 3D Finite Element (FE) models of a typical asphalt pavement structure and compare the effect of different factors on unreinforced and reinforced pavement with different geosynthetics using the FE method by Abaqus. Hence, three types of geosynthetics, with different elastic modulus, placed at the bottom of the asphaltic layer, and the strains of the maximum horizontal tensile strain at the bottom of the asphaltic layer and the maximum vertical tensile strain at the surface as critical responses for Bottom-Up Cracking (BUC) and TDC, respectively, under various tire pressures of 600, 750 and 900 kPa were investigated.

2 Material Properties and Modeling in Abaqus

For modeling in Abaqus, the viscoelastic properties of the asphaltic layer at a certain temperature (21.1 ºC) were defined by the Prony series using shear modulus. Prony series is a power-law series describing the stress-strain relationship of a linear viscoelastic system. Equations (1) and (2) show the general configuration of the Prony series.

$$g(t) = 1 - \sum_{i=1}^{N} g_i (1 - e^{-t/\tau i}) \quad (1)$$

$$g(t) = G(t)/G(t = 0) \tag{2}$$

Where $g(t)$ is defined as a shear modulus ratio, which is the ration of shear modulus at time t, $G(t)$, to the shear modulus at $t = 0$, $G(t = 0)$. g_i and τ_i are Prony constant depending on the material properties, and N is the number of terms in the Prony series. In this research, a Prony series with $N = 6$ was selected.

Base, sub-base, and subgrade materials were assumed to be homogenous and linear elastic. For elastic materials, the modulus of elasticity and poison's ratio, used in modeling, were selected for the typical materials used in Iranian pavement structures. Also, three types of geosynthetics with different elastic modulus were used for reinforcement in this research. These geosynthetics were modeled as a flexible plane shell with linear elastic behavior. Table 1 shows the properties of subgrade, pavement materials and geosynthetics used in this research.

According to specified properties, 3D FE models of pavement structures were created in Abaqus. The dimensions of the models and the thicknesses of the pavement layers are presented in Fig. 1. Because of symmetry, half of the standard axle with different tire pressures (600, 750, and 900 kPa) was used for the analysis, and its effects on critical responses at section D-D were investigated. The dynamic implicit method with a time step of 0.05 s was used for the analysis of the model. A cyclic load with 0.1 s of loading and 0.9 s of rest time was applied, which was repeated in 25 cycles in each analysis. The interaction between layers was considered so as to be no separation between the layers in the vertical direction under loading and unloading. Moreover, for the interaction between the geosynthetic and pavement

Table 1 Properties of the subgrade, pavement layers, and geosynthetics

Layer	Elastic modulus (MPa)	Poisson's ratio	Instantaneous modulus (MPa)	Prony constant (τ_i)	Prony constant (g_i)
Asphalt surface		0.35	10693	0.000606	0.449043
				0.001514	0.244553
				0.076795	0.123922
				1.334061	0.095569
				36.37552	0.045907
				98.04792	0.006257
Base	276	0.35			
Subbase	104	0.35			
Subgrade	34.5	0.45			
Geogrid I	76000	0.22			
Geogrid II	5516	0.30			
Geogrid III	426	0.25			

materials, it was assumed that the geosynthetic is embedded in the material and the slip was ignored.

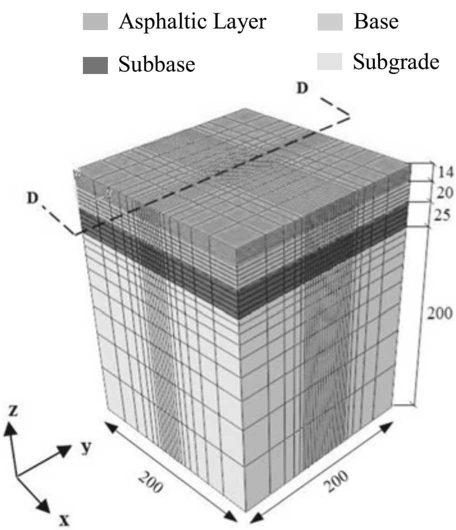
3 Results and Discussion

Figure 2 shows the variation of critical tensile strains at section D-D in the pavement without reinforcement at the 25 loading cycles. As can be seen, both critical tensile strains occurring at the top and bottom of the asphalt layer increase with increasing loading cycles. This stems from the assuming time-dependent viscous behavior for asphaltic materials. Moreover, comparing the maximum vertical and horizontal tensile strain shows that vertical tensile strain occurred at the surface is higher than the longitudinal tensile strain at the bottom of the asphaltic layer. However, the change in the strain rate at the top is the same as those at the bottom.

Figure 3 shows the effect of geosynthetic elastic modulus on the reduction in maximum tensile strains at the surface and bottom of the asphaltic layer with loading time. It is obvious that the use of geosynthetic at the bottom of the asphaltic layer results in a reduction in both maximum tensile strains at the bottom and the top of the asphaltic layer. Also, the effectiveness of geosynthetic increases with increasing its elastic modulus. A comparison of the critical responses of the pavement reveals that placing the geosynthetic beneath the asphaltic layer is more effective in reducing maximum tensile strain in this region which is attributed to the proximity of the geosynthetic to this strain.

The results also show that in the pavement reinforced by geosynthetic I the rate of increase in the normal tensile strain at the surface is higher than horizontal tensile

Fig. 1 Finite element model geometry (unit: cm)



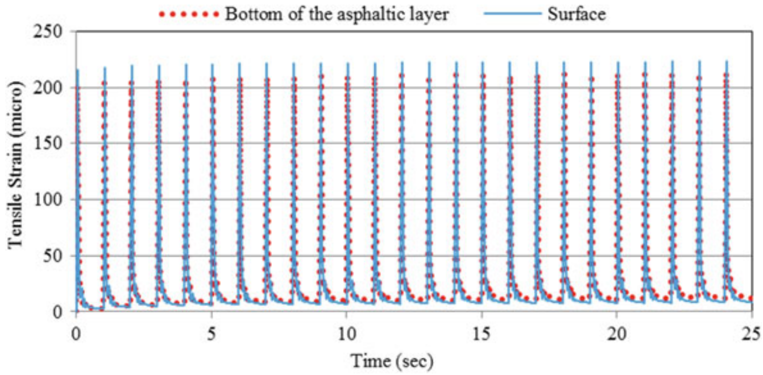


Fig. 2 The variation of tensile strains at the surface and bottom of the asphalt layer with loading time for unreinforced pavement

strain at the bottom. In this case, the maximum horizontal tensile strain is significantly affected by the elastic behavior of the geosynthetic resulted in decreasing the time-dependency of tensile strain at the bottom (Fig. 3a). Furthermore, the rate of increase of the longitudinal tensile strain at the bottom of the asphaltic layer increases, while the rate of increase of the vertical tensile strain at the surface remains unchanged, with decreasing geosynthetic elastic modulus. It can be inferred that the effect of geosynthetic type, placed at the bottom of the asphaltic layer, on BUC is higher than TDC. Also, it can be seen that in all cases the strain value at the top is higher than the strain value at the bottom and this issue affects the crack occurrence time. It worth mentioning that, although the decrease in geosynthetic elastic modulus increases the

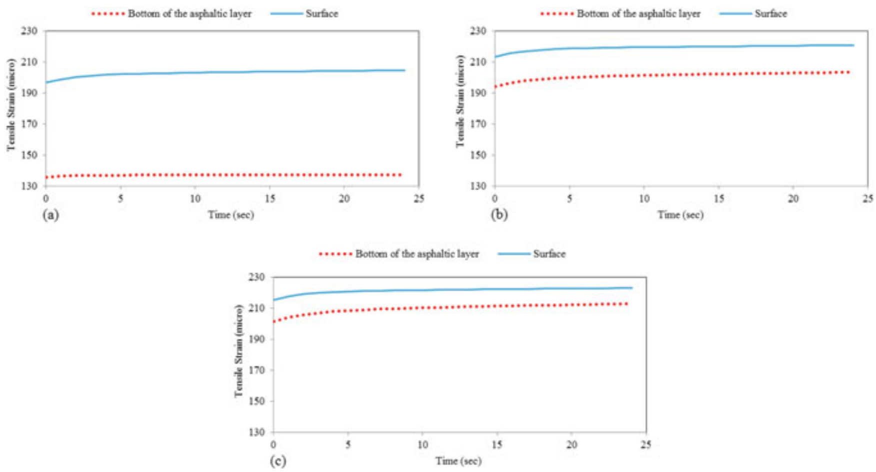


Fig. 3 The variation of maximum tensile strains in the pavement reinforced by geosynthetic: **a** I; **b** II; **c** III

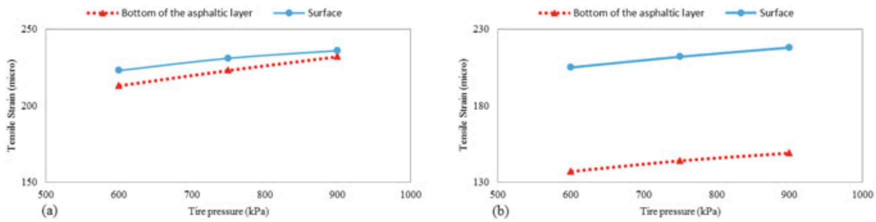


Fig. 4 The effect of tire pressure on the maximum tensile strains: **a** unreinforced pavement; **b** reinforced pavement

strain values and the rate of crack appearance, however, the difference in the strain values at the top and bottom of the asphaltic layer decreases, reducing the difference between TDC and BUC occurrence time.

Figure 4 shows the maximum tensile strain value at the top and bottom of the asphaltic layer of the reinforced (with geosynthetic I) and unreinforced pavement under the tire pressure of 600, 750, and 900 kPa. As was expected, for both reinforced and unreinforced pavement, the strain values increase with increasing tire pressure.

It is also clearly seen in Fig. 4a that, in the unreinforced pavement under the tire pressure of 600 kPa the tensile strain at the pavement surface is higher than those at the bottom, while this difference between the vertical tensile strain and horizontal tensile strain decreases with increasing tire pressure. In other words, the rate of increase in tensile strain at the bottom of the asphaltic layer with increasing tire pressure is higher than that at the surface. In addition, it can be stated that although placing geosynthetic at the bottom of the asphaltic layer results in decreasing strain values the rate of increase in critical strains is not significantly affected by reinforcement (Fig. 4b).

4 Conclusion

In brief, the following conclusions can be drawn from this study:

- Comparing the critical strains in the reinforced pavements shows that the variation in elastic modulus of geosynthetic placed at the bottom of the asphaltic layer is more effective on BUC than TDC.
- In spite of increasing the probability of cracking with decreasing elastic modulus of the geosynthetic placed at the bottom of the asphaltic layer, the difference between TDC and BUC occurrence time decreases.
- The rate of increase in critical strains varies with tire pressure, such that, the effectiveness of variation in tire pressure on the rate of increase in tensile strain at the bottom is more noticeable than tensile strain at the top.

- Using geosynthetic I at the bottom of the asphaltic layer results in reduction of strain values, while it is not really effective on the variation in the rate of increase in critical strains with tire pressure.

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