Civil Engineering Infrastructures Journal, 53(1): 33 – 51, June 2020
Print ISSN: 2322-2093; Online ISSN: 2423-6691
DOI: 10.22059/ceij.2020.267723.1521

Investigating the Performance of Cracked Asphalt Pavement Using Finite Elements Analysis

Taherkhani, H.[1] and Tajdini, M.[2*]

[1] Associate Professor, Civil Engineering Department, University of Zanjan, Zanjan, Iran.
[2] Ph.D., Civil Engineering Department, University of Tabriz, Tabriz, Iran.

Received: 17 Oct. 2018; Revised: 29 Dec. 2019; Accepted: 04 Jan. 2020

ABSTRACT: Occurrence of top down and bottom up fatigue cracking in asphaltic pavements is common. Conventional pavement analysis methods ignore the existence of cracks in asphaltic layers. However, it seems that the responses of cracked pavement would not be the same as a pavement without crack. This paper describes effects of crack type, position and length, and vehicles tire inflation pressure and axle load on the performance of cracked asphalt pavement. Tensile strain at the bottom of asphaltic layer, the vertical strain on subgrade, maximum deflection on the surface, rut depth and the stress intensity factors of cracked pavement, with top down and bottom up crack have been computed using 3D Finite Elements method in ABAQUS. Moving load of standard single axle with different loads and tire pressures have been used in the analysis. Standard 8.2 ton single axle load at different tire pressures of 552(80), 690(100), 828(120) and 1035(150) kPa(psi) and single axle at different loads of 5, 8.2 and 15 ton, all at the same tire pressure of 690 kPa, have been used. Results show that the pavement responses increase with increasing tire pressure and axle load with higher values and rate of increase with increasing tire pressure and axle load for the cracked pavement compared with the pavement without crack. For the pavement structure investigated in this study, it was found that, in general, top down crack results in higher responses than bottom up crack.

Keywords: Axle Load, Cracked Asphalt Pavement, Fatigue Cracking, Rutting, Tire Pressure.

INTRODUCTION

Asphalt pavements are the most common type of structures which are used in highway construction worldwide. In order to preserve the huge asset used in these structures, and protect the environment, utilization of a reliable pavement design method is necessary (Khavandi Khiavi et al., 2019). One of the requirements of a reliable pavement design method is the capability of accurate prediction of pavement performance during its service life. In mechanistic-empirical design methods, the pavement performance is related to the pavement responses using empirical transform functions. Many agencies have used the horizontal tensile strain at the bottom of the asphalt concrete layer and the vertical compressive strain at the top of the sub-grade for prediction of pavement long term performance. The horizontal tensile strain at the bottom of

* Corresponding author E-mail: m.tajdini@tabrizu.ac.ir

asphalt layer is related to the fatigue cracking, initiating from the bottom and propagates to the surface. However, due to excessive tensile strains, the pavement cracks may also start at the pavement surface and propagate downward (Wu et al., 2019; Alae et al., 2019).

The vertical compressive strain at the top of the sub-grade is related to the pavement rutting due to densification and/or consolidation of the sub-grade soil (Huang, 2004). The accurate prediction of pavement long-term performance relies on the accuracy of determining the responses. Responses of pavement can be determined using mechanistic methods. Multilayer linear or non-linear elastic or viscoelastic and finite elements method are the common methods used for flexible pavement analysis (Taherkhani and Jalali, 2018; Rahman et al., 2019; Alae et al., 2019).

Multilayer analysis methods have many limitations, due to their simplifications in dealing with the load, materials and sub-grade mechanical behavior, geometry of pavement structure and heterogeneity of pavement materials, which are far from the reality. Considering all of the realistic conditions requires extensive computation and development of accurate constitutive models for simulation of the pavement materials behavior.

Finite Elements (FE) method is a useful tool for doing the computation. FE method can model complex structures with complex behavior of constituting materials. Using three dimensional FE methods makes it possible to consider the complexity of the pavement materials behavior, the geometry of layers, inclusion of cracks and geo-synthetics, and the complex nature of loads in the analysis and more accurately determination of pavement responses. Many general purpose FE analysis packages have been developed, among which ABAQUS is used more frequently than the others for pavement analysis (Alae et al., 2019).

Due to the replacement of the bias-ply tires by radial-ply tires, the truck tire pressures have increased steadily since the AASHTO road test (Hutchinson and Mallett, 1990). Although in AASHTO road tests, the tire pressures of 75 to 80 psi were used, the tire pressures of 95 to 105 psi are more common nowadays, and in some cases 120 to 130 psi have also been used. The most evident result of increasing tire pressure is the reduction of the area of tire imprint. The studies conducted in Texas University have shown that 50% of increase in tire pressure has resulted in 8 to 25% reduction of the imprint surface area (Marshek et al., 1985).

Similarly, studies in Ireland have shown that the increase of tire pressure from 50 to 110 psi, have resulted in 35% and 22.4% reduction of tire contact surface area of the front and rear wheels, respectively (Owende at al., 2001). The same results have been reported by Good Year Co. (Ford and Yap, 1990). The reduction of tire imprint surface area results in the increase of surface pressure and pavement damage.

Several studies can be found in literature, which has investigated the effects of tire pressure on the pavement responses. Some have conducted the studies by using instrumented pavement sections (Mahoney et al., 1995; Chatti et al., 1996). The others have utilized the analytical methods, including multilayer (Prozzi et al., 2005, Abdel-Motaleb, 2007) and FE methods (Hernandez et al., 2014; Kim et al., 2018). In both methods, it has been found that the tire pressure has significant influence on the pavement responses, especially on the horizontal tensile strain at the bottom of asphalt layer.

Asphalt pavements are prone to the occurrence of different cracks. The cracks occur due to a combined effect of loads and environmental conditions. They are classified according to the cause of occurrence, such as thermal or fatigue cracking, and the shape and position of cracks, such as longitudinal, transverse, diagonal, block, alligator, top down and bottom up cracks. Fatigue cracking occurs as a result of repeated tensile and/or shear strain in asphaltic layers. For a long time the assumption was that fatigue cracks occurs at the bottom of asphaltic layers and propagate upward to the pavement surface, known as bottom up fatigue cracking. However, studies in recent years have indicated that top-down fatigue cracking is a major mode of distress in asphaltic pavements, which initiate at the top and propagate downward (Sun et al. 2005; Zhao et al. 2018). Top down fatigue cracks are longitudinal and their location is in wheel path. Various factors such as the contact stress between tire and pavement, pavement structure, stiffness of base layer and the modulus gradient in asphalt layer due to ageing and temperature gradient, may cause the occurrence of top down cracking (Ling et al. 2017; Alae et al., 2019).

Accurate analysis of pavement needs to consider the existence of crack in asphaltic layers. The responses of cracked asphaltic materials are different from those without cracks. You et al. (2018) investigated the effects of pavement distresses on the deflection basin measured by FWD evaluation. They found that crack type and position relative to the loading point affect the pavement responses. In cracked pavement, in addition to the traditional responses of horizontal tensile strain in asphaltic layer and the vertical strain on the top of subgrade, fracture parameters, which are related to the rate of crack propagation, are also important. Stress Intensity Factors (SIF) are the most common fracture parameters used for evaluating fracture resistance of asphaltic pavements (Jacobs et al., 2006; Modarres and Shabani, 2015).

For viscoelastic materials J-integral and fracture energy are more suitable to be used for evaluation of crack propagation (Alae et al., 2019). SIF is a measure of stress state at crack tip. In fracture mechanics, three SIF, namely K_I, K_{II} and K_{III} are used, which are related to the modes of crack opening, sliding and tearing, respectively (Ameri et al., 2011). Aliha and Sarbijan (2016) investigated the effects of length and number of cracks and position of vehicles relative to crack on the fracture parameters of bottom up and top down cracks. They found that the position of vehicle load is significantly effective on the fracture parameters. It was also found that the top down cracks are more vulnerable to propagation than the bottom up cracks. The thinner and stiffer overlay has more pronounced fracture parameters.

Exploring literature shows that investigating the pavement performance has commonly been done using intact asphaltic layers. However, the reality is that pavement is cracked and their effect on the structural analysis and performance needs to be considered. Therefore, this research aimed to investigate the effects of tire pressure and axle load on the responses of cracked asphalt pavement using Finite Elements method by the application of commercially available FE program of ABAQUS.

RESEARCH METHODOLOGY

As mentioned earlier, the main objective of this study is to investigate the critical responses of cracked asphaltic pavement sections under different tire inflation pressures and axle loads and their comparison with those of a pavement section without cracks as control section. Therefore, a typical flexible pavement structure, including asphalt concrete surface layer, unbound aggregate base and sub-base layers on sub-grade soil, all with linear elastic behavior, have been modeled in ABAQUS.

Table 1 shows the properties of the sub-grade and pavement layers. Although it is expected that the responses of different pavement structures can be different, in this study, only a fixed structure has been selected, which is close to the typical structures used for flexible pavements for highways. Also, more realistic results can be obtained by considering the realistic behaviors for pavement layers and sub-grade. However, in this research, for simplicity, all layers were considered to behave elastically.

Different types of cracks may occur in asphaltic layers of flexible pavements. However, the most common type of cracks observed in wheel path is the fatigue cracking, which occurs due to the fatigue of asphaltic materials as a result of repeated tensile strain induced by traffic loads. They may occur as top down or bottom up cracks, which are normally developed longitudinally at their initial stage. In this research, longitudinal top down and bottom up cracks with the same length of 0.5 m and depth of 7.5 cm (half of the surface layer thickness) have been used in modeling. The critical position of crack relative to the dual tires imprint will be used for evaluation of tire pressure and axle load effects on the pavement responses.

Three dimensional models of the pavement structure were made using cubical elements which is the most common type used in previous studies (Sun and Duan, 2013). The dimensions of 6×6×6 m for the model were selected after trying different dimensions. Figure 1 shows the model used in this research. As can be seen, the dimensions of the meshes around the load were chosen to be smaller than the rest of elements. In order to have more convergence and accuracy, 8 node elements (3D8R) have been used (Rahman et al., 2011).

The boundary conditions were defined to simulate the free movement of sides in vertical direction and the constrained horizontal movement of the bottom of the model (Fakhri and Farokhi, 2010). To prevent the horizontal movement of the model, the circumferential nodes were constrained against horizontal movements, while were free to move vertically. The nodes at the bottom of the model were tied to prevent moving in any direction.

Table 1. Properties of pavement layers used in modeling (Huang, 2004)

Layers	Thickness (cm)	Elastic modulus (MPa)	Poisson's ratio	Unit weight (gr/cm^3)
Surface	15	4000	0.4	2.4
Base	25	400	0.3	2.1
Sub-base	25	200	0.3	2
Sub-grade	535	50	0.25	1.8

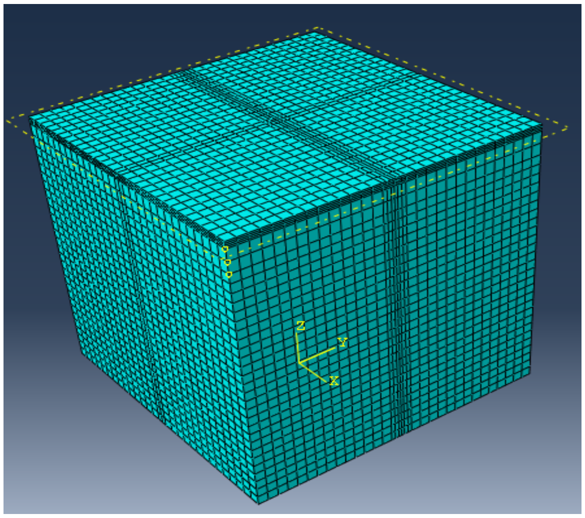

Fig. 1. Cubical element used in modeling

The analysis of the models have been undertaken using 8.2ton single axle load with dual tires assembly at different tire pressures of 552(80), 690(100), 828(120) and 1035(150) kPa(psi). In addition, in order to evaluate the effects of axle load on the pavement responses, single axle load with single tire and different weights of 5, 8.2 and 15 ton, all with the same tire pressure of 690 kPa (100 psi) have been used. All of the loads were considered to move at a speed of 80 km/h.

Different contact areas of tire and pavement have been used by researchers, including oval, rectangular, circular etc. Rectangular contact area has been used in this study, as previous studies have shown that acceptable results can be obtained (Fakhri et al., 2009; Chen et al., 1990; Zheng and Xie, 2003). The area of the contact surface was obtained by dividing the tire load to the tire pressure. The length and width of the rectangles were considered to be 0.8721L and 0.6L, respectively, (Huang, 2004). Eq. (1) was used for determination of L.

$$L = \sqrt{\frac{A_C}{0.5227}} \qquad (1)$$

where; A_C: is the area of contact surface. Moving loads were applied, all at the same speed of 80 km/h (22.22 m/s). The total loading time *T*, calculated by Eqs. (2) and (3), was used for calculating the amount of pressure at different moments over the period of loading (Sun and Duan, 2013).

$$T = 12\frac{a}{V} \qquad (2)$$

$$p = p_0 \sin(\frac{\pi t}{T}) \qquad (3)$$

where; *a*: is the length of contact area in cm, *V*: is the speed in cm/sec, *p*: is the amount of pressure at time *t* and p_0: is the maximum contact pressure. Table 2 shows the length of contact surface rectangle and loading time for different tire pressures and axle loads investigated in this study.

For verification, the cracked pavement section, with the similar layer thicknesses and material properties as used by Sun and Duan (2013), were analyzed under moving load with the tire contact area as shown in Figure 2 and contact pressure of 690 kPa (100 psi). Table 3 shows the results of analysis for the maximum surface deflection, the maximum tensile strain in asphalt layer and the stress intensity factor K_I at different speeds, and those obtained by Sun and Duan (2013). As can be seen, the differences are not significant, which verify the modeling used in this research.

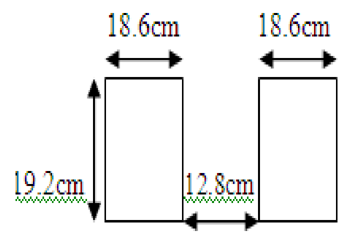

Fig. 2. Tire contact area

Table 2. Length of contact area and loading time for different tire pressures and axle loads

Axle load (kN)	Tire pressure (kPa (psi))	L (cm)	T (sec)
82	552 (80)	23.2	0.125
82	690 (100)	20.78	0.112
82	828 (120)	18.96	0.103
82	1035 (150)	17.2	0.093
50	690 (100)	22.95	0.124
82	690 (100)	29.38	0.159
150	690 (100)	39.74	0.21

Table 3. Results of analysis for verification

Speed (km/h)	Maximum tensile strain (× 10^{-5})		Surface deflection (× 10^{-5} m)		Stress intensity factor K_I (kPa × $m^{0.5}$)	
	This research	Sun and Duan	This research	Sun and Duan	This research	Sun and Duan
60	4.7	4.97	3.44	3.33	102	100
80	4.75	5.07	3.3	3.2	102	100
100	4.8	5.08	3.1	3.11	104	100

RESULTS AND DISCUSSIONS

Critical Position of Crack

The responses of the pavement were evaluated by positioning the 1.5 m long full depth crack at different lateral distances from the geometric center of dual tire imprints, as shown in Figure 3. 8.2 ton single axle with dual tires and tire pressure of 552 kPa (80 psi) was used, for which the width of rectangle was 16 cm and the width of the gap between dual tires was 8 cm. The results of analyses are presented in Table 4. As was expected, results show that the responses under cracked pavement are higher than those in the pavement without crack. The results also show that the most critical position of crack is when the center of crack is placed at the geometric center of dual tires, for which the highest responses are resulted. In addition, it can be seen that the responses resulted from placing the center of each tire on the crack is much lower than those resulted from placing the inner or outer edge of tire on crack. Also, it is seen that, the responses decreases with increasing the distance between crack position and tire load. Based on these results, it was decided to use the critical position of crack for further investigation in this research.

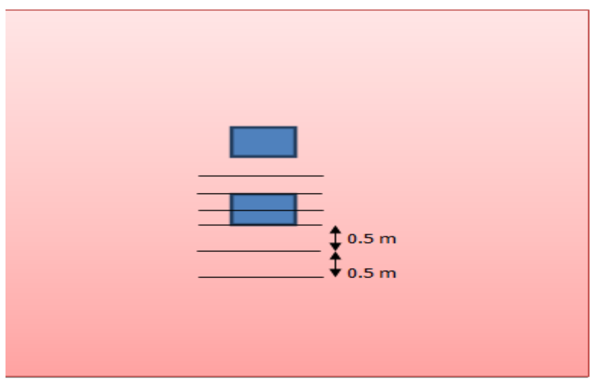

Fig. 3. Lateral positions for the longitudinal crack

Table 4. Variation of pavement responses with position of crack

Position of crack	The maximum tensile strain in asphaltic layer (× 10^{-5})	The maximum vertical strain on subgrade (× 10^{-5})	The maximum surface deflection (mm)	Stress intensity factor K_I (kPa × $m^{0.5}$)	Stress intensity factor K_{II} (kPa × $m^{0.5}$)
Along the axis of symmetry of dual tires	9.9	2.25	0.384	324	16
Along the inner edge of tires	9.84	2.21	0.382	318	48
Along the center of tires	6.11	1.11	0.215	60	38
Along the outer edge of tires	9.49		0.38	261	247
0.5 m from the outer edge	9.2	2.19	0.37	43	13
1 m from the outer edge	9.09	2.17	0.368	32	6
1.5 m from the outer edge	8.91	2.13	0.367	18	4
2 m from the outer edge	8.73	2.12	0.367	7	2
Uncracked pavement	8.59	2.1	3.62	-	-

Effects of Crack Length

The responses of the pavement including the maximum tensile strain in asphaltic layer, the maximum vertical strain on the subgrade, the maximum vertical deflection on surface and the stress intensity factors in mode I and II were determined by analysis of model under single axle load of 8.2 ton and tire pressure of 552 kPa (80 psi) in pavement sections with and without crack. In these analyses the top down and bottom up cracks with 7.5 cm in depth were considered to be along the center of dual tires. Results are shown in Table 5. As can be seen, in general, the responses under top down cracks are higher than those under bottom up cracks. In addition, the responses increase with increasing crack length. Among the responses the stress intensity factors are more sensitive to crack length than the other responses, and the vertical compressive strain in sub-grade is the least influenced response.

The Results for the Effects of Tire Inflation Pressure

As mentioned earlier, in order to investigate the effects of tire pressure on the responses of cracked pavement sections and its comparison with the section without crack, 8.2 ton single axle with dual tires assembly and different tire pressures of 552(80), 690(100), 828(120) and 1035(150) kPa was used in all analyses. The load was applied at a constant speed of 80 km/h. Longitudinal top down and bottom up cracks, denoted by TD and BU, respectively, both with the same length of 0.5 m and different depths, located at the middle of the gap between the dual tires imprints, were used for analysis. The responses of interest were the maximum tensile strain in asphalt layer, the maximum vertical compressive strain on the sub-grade, the surface maximum rut depth, and the stress intensity factors of K_I and K_{II}. As an example, Figure 4 shows the deformation counters of the model with top down crack under tire pressure of 1035 kPa (150 psi). The total loading time was considered as the time required for crossing the length of rectangular contact area at the speed of 80 km/h (22.22 m/s). The load amplitude increases from 0 at the beginning of the length of rectangle to its maximum value at the middle of rectangle for which *t/T* is 0.5. Figure 5, as an example, shows the variation of the maximum tensile strain in asphalt layer with the ratio of *t/T*. The maximum values of pavement responses, corresponding to the *t/T* of 0.5 have been selected for more analysis.

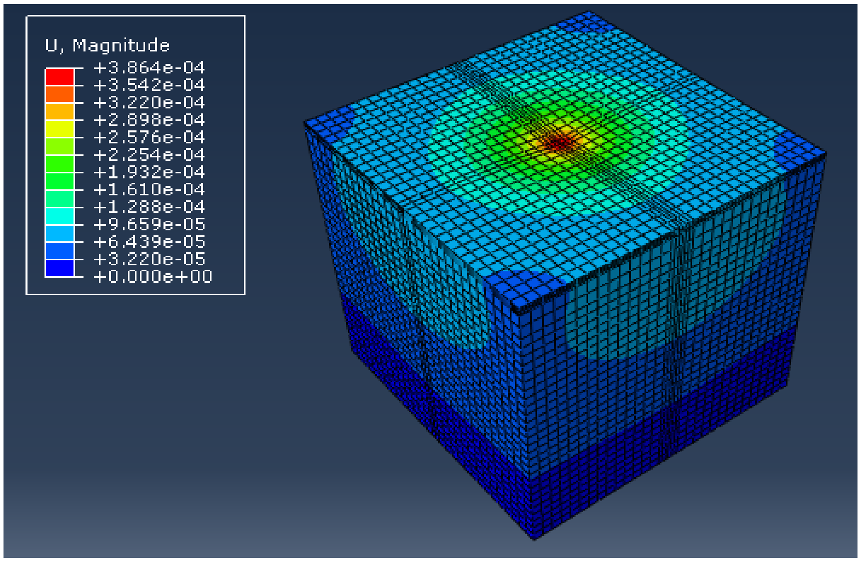

Fig. 4. Deformation counters of the element with top down crack under tire pressure of 1035 kPa

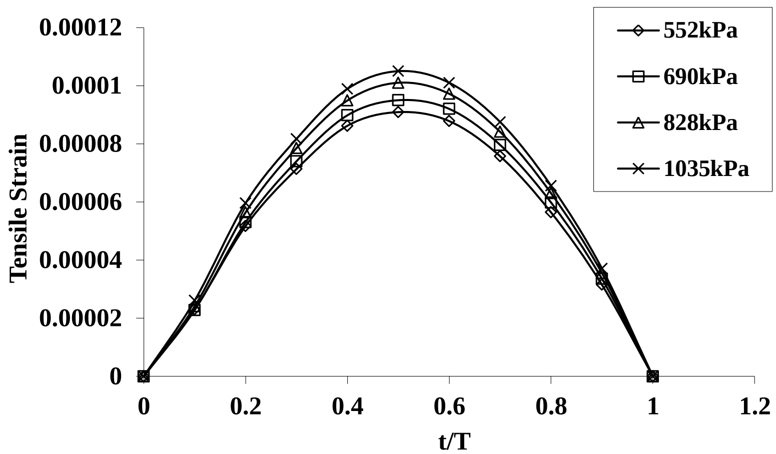

Fig. 5. Variation of tensile strain with the time of loading

Table 5. Variation of pavement responses with crack length

Crack length (cm)	Horizontal tensile strain in asphalt (× 10^{-5})		The maximum vertical strain on subgrade (× 10^{-4})		The maximum surface deflection (mm)		Stress intensity factor K_I (kPa × $m^{0.5}$)		Stress intensity factor K_{II} (kPa × $m^{0.5}$)	
	TD*	BU**	TD	BU	TD	BU	TD	BU	TD	BU
0	8.59	8.59	2.1	2.1	0.362	0.362	-	-	-	-
5	8.68	8.6	2.25	2.24	0.372	0.37	84	21	13	7
15	8.83	8.68	2.26	2.26	0.375	0.373	201	47	27	21
25	9.29	8.71	2.29	2.27	0.376	0.374	232	56	15	11
50	9.91	9.09	2.35	2.28	0.384	0.385	324	91	16	48
75	10.8	9.18	2.38	2.31	0.391	0.391	468	151	23	92

*Top down crack, **Bottom up crack

One of the critical responses of flexible pavements is the maximum tensile strain in the asphaltic layers, which is related to the critical distress of fatigue cracking. The fatigue life decreases exponentially with increasing the tensile strain in asphalt layer. Several equations can be found in literature that relate the tensile strain to the fatigue life.

Figure 6 shows the variation of the maximum tensile strain of asphalt layer with tire pressure for the pavement sections with different depths of top down and bottom up crack and the control section without crack (UC). In this figure the notations of TD and BU, have been used for top down and bottom up crack, after which the numbers show the depth of crack in cm. The TD-15 and BU-15 are corresponding to models in which a crack depth of 14.9 cm has been used.

As can be seen in Figure 6, for all sections, the maximum tensile strain in asphalt layer increases with increasing tire pressure, which is consistent with the findings in previous studies (Machemehl et al., 2005; Prozzi and Luo, 2005). However, the rate of increase grows with increasing crack depth, with higher rate of increase for the sections with top down crack than that for bottom up crack. For example, by the increase of the tire pressure from 552 to 1035 kPa, the maximum horizontal tensile strain of asphalt layer in the pavement section without crack, with 7.5 cm deep top down and bottom up crack increases 13, 33 and 15%, respectively. At the tire pressure of 1035 kPa, the maximum tensile strain of the section with 7.5 cm deep top down crack is, approximately, 33 and 24%, respectively, higher than that of the section without crack and the section with bottom up crack. However, at 552 kPa, those values are 12.7 and 7.4%, respectively.

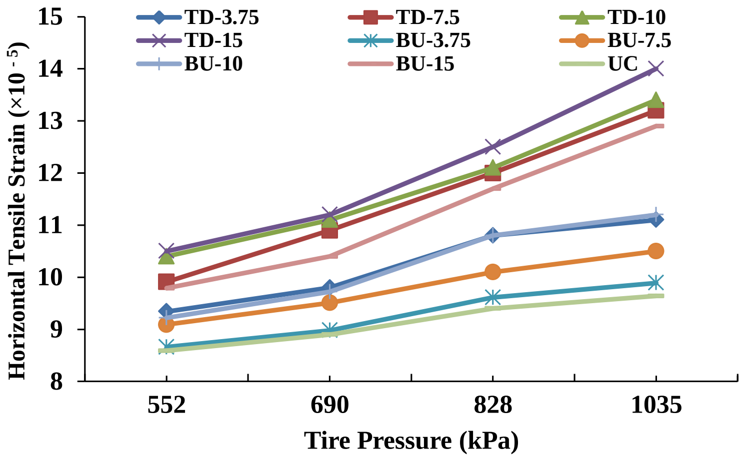

Fig. 6. Variation of the maximum tensile strain in asphalt layer with tire pressure

Another critical response of flexible pavements is the vertical compressive strain at the top of the sub-grade. Mechanistic-empirical design methods use this response for prediction of pavement rutting. The higher the compressive strain on the sub-grade, the lower the rutting life, which is defined as the number of loads applied before the occurrence of the critical rut depth. Figure 7 shows the variation of the maximum compressive strain on the sub-grade with tire pressure for the pavement sections with different depths of top down and bottom up crack, and the control pavement without crack.

As can be seen, the strain increases with increasing tire pressure and crack depth. Also, the results reveal that for the crack depths of 3.75 and 7.5 cm, the strain of the sections with bottom up crack is higher than that of those with top down crack. However, for higher depths, the trend reverses and the strain for the sections with top down cracking is higher than that for the sections with bottom up cracks. Comparing the results in Figure 7 with those in Figure 8 reveals that the increase of the compressive strain at the top of sub-grade with increasing tire pressure is not as much as the increase of the horizontal tensile strain of asphalt layer, indicating that the compressive strain on sub-grade, is not sensitive to the tire inflation pressure as much as the tensile strain in asphalt layer. Increase of the tire pressure is more influencing on the fatigue cracking of asphalt layer than the permanent deformation in sub-grade.

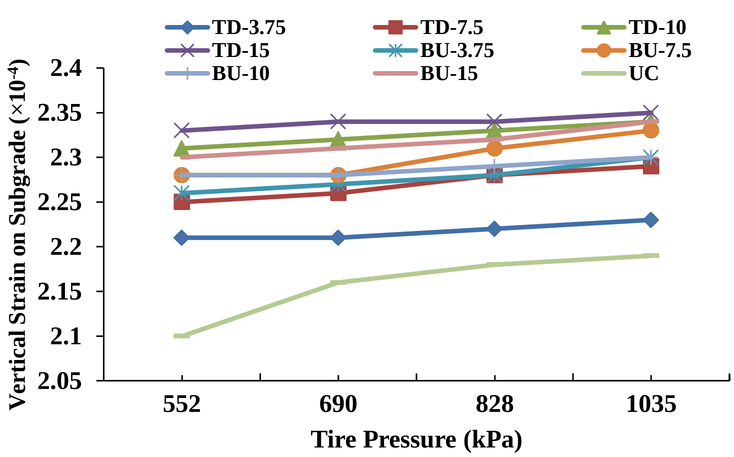

Fig. 7. Variation of the maximum compressive strain on sub-grade with tire pressure

Stress intensity factor shows the intensity of stress at a crack tip. The magnitude of the crack intensity factor is an indication of the potential of crack propagation. Three modes of failure are defined for relating the stress and displacement in cracks, which are opening mode (mode I), shear mode (mode II), and torsion mode (mode III), as shown in Figure 8. In mode I, II and III, the crack propagates due to pure tension, shear and torsion, respectively. The crack will propagate in a mode with a higher corresponding stress intensity. Previous studies show that mode I and II are dominant in pavement (Sun and Duan, 2013). Therefore, the stress intensity factors of mode I and mode II, K_I and K_{II}, have been investigated in this research, and mode III has been disregarded.

Figures 9 and 10 show, the variation of the stress intensity factor in mode I and mode II, respectively, with tire pressure and crack depth for the pavement sections. As can be seen, the stress intensity factors increase with increasing tire pressure, indicating that the potential of crack propagation increases with increasing tire pressure. Consistent with previous studies (Sun and Duan, 2013; Fakhri et al., 2010), it is observed that the mode I is more critical than mode II, indicating that the opening mode in crack propagation is dominant. It can also be seen that the stress intensity factors of K_I and K_{II} of the pavement increase with increasing crack depth, with higher values for top down crack than bottom up crack, indicating that the rate of crack propagation increases with increasing crack depth with higher rate for pavement with top down crack than that with bottom up crack. Comparing Figure 9 and 10 reveals that the stress intensity factor of K_I is more sensitive to the crack depth than the factor K_{II}. However, the factor K_{II} is more sensitive to tire pressure than K_I.

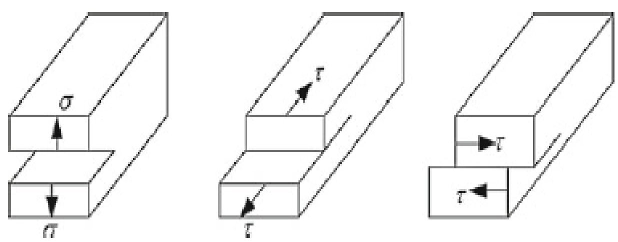

Fig. 8. Crack propagation in different modes (Sun and Duan, 2013)

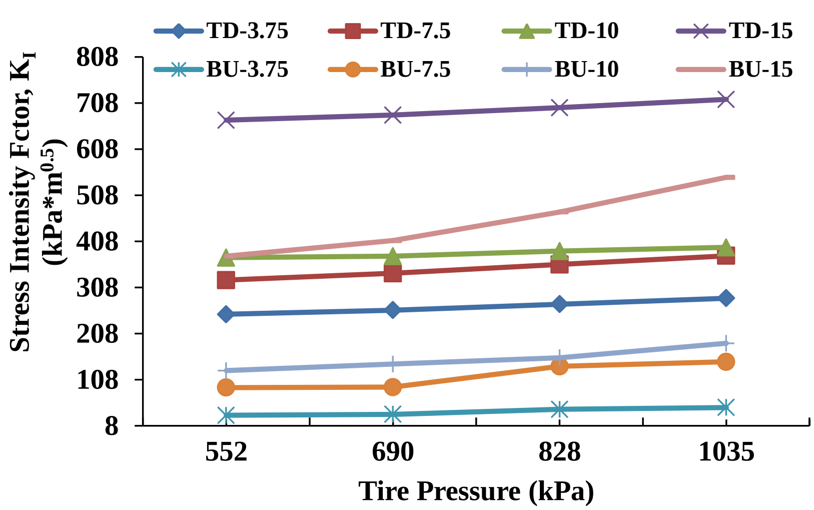

Fig. 9. Variation of the stress intensity factor K_I with tire pressure

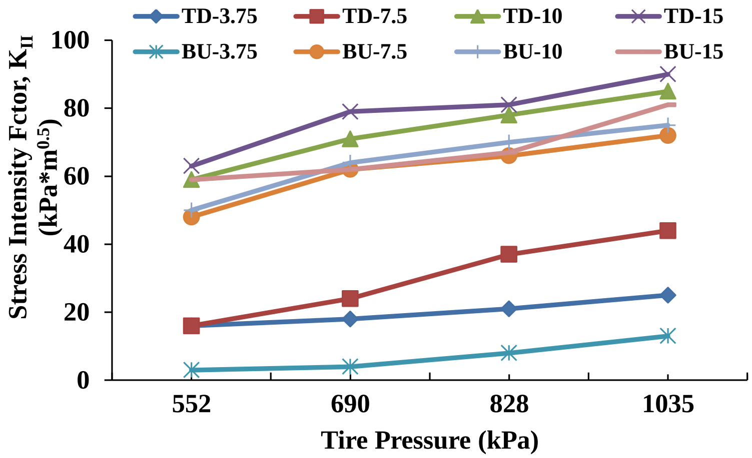

Fig. 10. Variation of the stress intensity factor K_{II} with tire pressure

Rutting is one of the major structural failure modes in flexible pavements, which occurs as a result of accumulation of the plastic deformation in all layers and subgrade (Taherkhani and Arshadi, 2018). Rutting is defined by its depth, and the appropriate measures for maintenance is usually chosen based on the rut depth. The rut depth of pavement sections in this study was calculated using Eq. (4).

$$RD = \sum_{i=1}^{n} \varepsilon_p^i h^i \quad (4)$$

where, *RD*: is the total rut depth on the surface in mm, ε_p^i: is the plastic strain in i^{th} sub-layer, h^i: is the thickness of i^{th} sub-layer in mm and n: is the number of sub-layers.

To this end, the pavement in each model was divided into n sub-layer and the plastic strain in the mid-depth of each sub-layer was calculated using Eq. (5) for asphaltic layer and Eq. (6) for the unbound layers and subgrade (Wang and Machemehl, 2006).

$$\frac{\varepsilon_p}{\varepsilon_r} = k_1 10^{-3.4488} T^{1.5606} N^{0.479244} \quad (5)$$

$$\frac{\varepsilon_p}{\varepsilon_r} = \beta_1 \left(\frac{\varepsilon_0}{\varepsilon_a}\right) e^{-\left(\frac{\rho}{N}\right)^{\beta}} \quad (6)$$

where, ε_p: is plastic strain, ε_r: is resilient strain, k_1: is asphalt layer thickness correction factor, T: is pavement temperature in °F, N: is the number of axle load repetitions, ε_a: is resilient strain imposed in laboratory tests, β_1: is regression coefficient and β, ε_0 and ρ: are pavement materials properties.

The resilient strain in sub-layers was determined by finite element analysis and the values for other parameters were obtained from previous studies (Wang and Machemehl, 2006). The rut depth at different lateral distances from the center of dual tires was calculated and it was found that the maximum rut depth occurs at 14 cm from the center of dual tires. For example, Figure 11 shows the rut depth on the pavement with 7.5 cm top down crack after 1000 loading cycles. The maximum rut depth of cracked and intact pavement sections was determined after 1000, 10000, 100000 and 1000000 loading cycles.

Figure 12 shows the maximum rut depth of the pavements after different loading cycles. As can be seen, the rutting of cracked pavements is higher than that of the pavement without crack. Also, the results show that the rutting depth increases with increasing crack depth, with higher rut depth for the pavements with top down crack than that for bottom up crack. Furthermore, it can be seen that the rate of increase of rut depth with loading repetition increases with increasing crack depth with higher rate for the pavement with top down cracks.

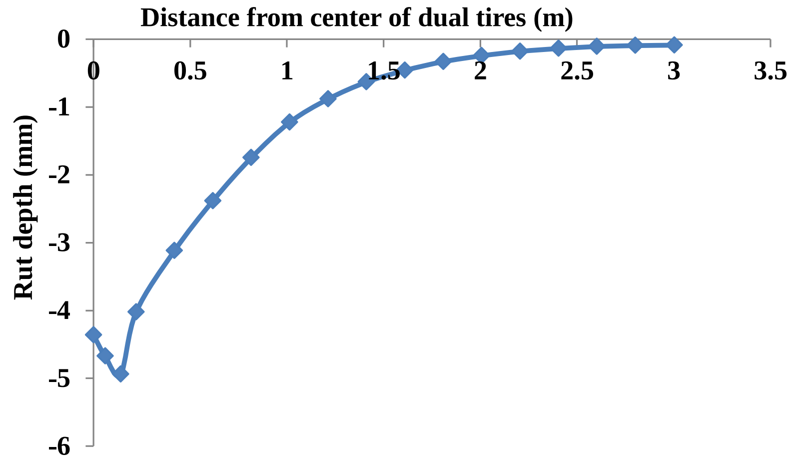

Fig. 11. Rut depth after 1000 loading repetitions in pavement with 7.5 cm top down crack

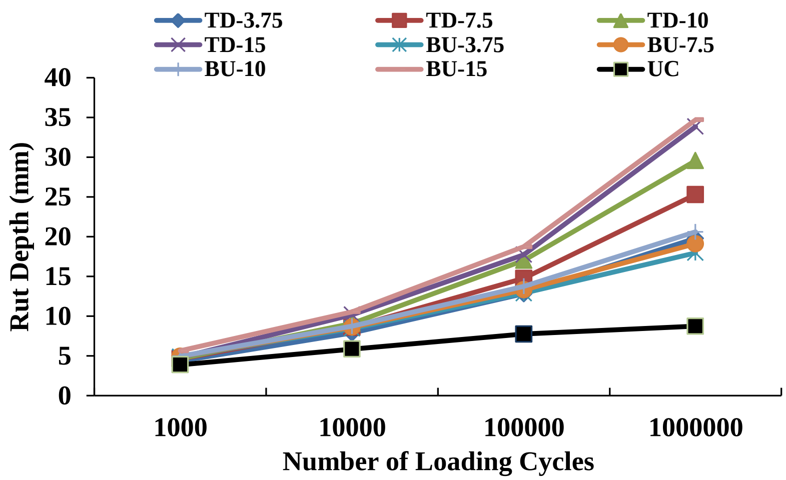

Fig. 12. Variation of rut depth with number of loading repetitions

Figure 13 shows the variation of the maximum rut depth with number of loading repetition under different tire pressures for a pavement with 7.5 cm deep top down crack. These results have been obtained by using 8.2 ton single axle with dual tires. As can be seen, the rut depth increases with increasing tire pressure. Also, these results reveal that the rate of increase of rut depth with loading repetition increases with increasing tire pressure, indicating that the high pressure tires results in fast propagation of rut depth in cracked pavements, such that, the rut depth occurred after 1000000 repetition of 8.2 ton axle load with a tire pressure of 1035 Kpa (150 psi) is approximately 3 times higher than that with a tire pressure of 552 kPa (80 psi).

The Results for the Effects of Axle Load

One of the major properties of vehicles influencing the pavement performance is the load transmitted by the axles to the pavement. The maximum load of different types of axles is limited to specified legal values. In order to investigate the effect of axle load on the immediate responses of cracked pavement and its comparison with the pavement without crack, single axle with single tire and different axle loads of 5, 8.2 and 15 ton were used in modeling. These values were used according to the maximum legal value of 8ton for this type of axle in Iran, to evaluate the damage caused by the axle loads higher and lower than the legal value. Using the same structure as described earlier, three dimensional models of cracked pavements, in which longitudinal top down and bottom up cracks with a length of 0.5 m and depth of 7.5 cm located at the geometric center of rectangular tire contact surface were made in addition to the pavement section without crack.

In all cases, the tire pressure of 690 kPa (100 psi), which is normally used for truck tires nowadays, and speed of 80 km/h was used. After analysis, the responses of the maximum tensile strain in asphalt layer, the maximum compressive strain on the sub-grade, the maximum vertical deflection of surface and the stress intensity factors of K_I and K_{II} were used for evaluation.

Figure 14 shows the variation of the maximum tensile strain in asphalt layer for the cracked and intact pavement sections. As can be seen, the maximum tensile strain in asphalt layer increases with increasing axle load, with different rate of increase for different pavement sections. As can be seen, the section with bottom up crack has the highest rate of increase. It can also be seen that the maximum tensile strain of the section with top down crack is higher than that of the section with bottom up crack and the intact section. The maximum tensile strain of the section with top down and bottom up crack is approximately, 35 and 25%, respectively, higher than that of the control section, indicating that the pavement sections with top down cracks are more vulnerable to fatigue cracking.

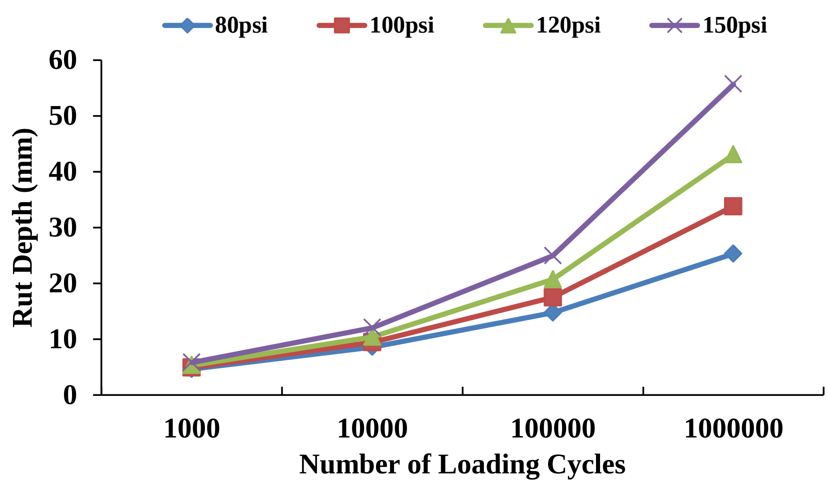

Fig. 13. Variation of rutting depth with tire pressure and load repetitions

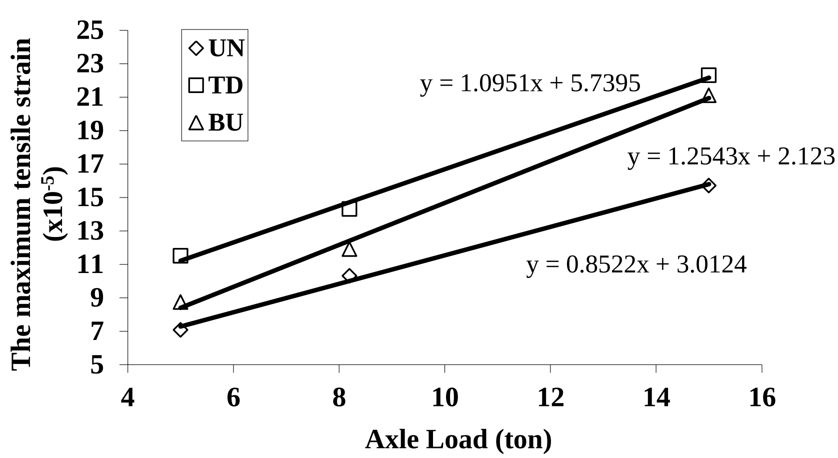

Fig. 14. Variation of the maximum tensile strain in asphalt layer with axle load

Figure 15 shows the variation of the maximum vertical compressive strain on the sub-grade with the axle load in three different pavement sections. As can be seen, the maximum compressive strain on the sub-grade increases with increasing axle load in all sections, with a higher values and rate of increase for the cracked sections. The values for the cracked sections are approximately 17% higher than those for intact section. It can also be seen that the difference between the maximum compressive strain on sub-grade for the section with top down and bottom up crack is not significant, although for the section with top down crack is slightly higher. Comparing the results with those for tire pressure, it can be inferred that the compressive strain on sub-grade, which is normally related to rutting, is more sensitive to the axle load rather than the tire pressure.

The surface deflection under applying a single load is an indication of the structural capacity of a pavement, and a pavement with a higher deflection has a lower remained life. Figure 16 shows the variation of the maximum surface vertical deflection of the pavement sections with axle load. As can be seen, the surface deflection increases with increasing axle load, with the higher values for the section with top down crack, and the lowest values for the intact pavement. The maximum surface deflection of the pavement with top down crack is, approximately, 18% higher than that of the section with bottom up crack, and 50% higher than that of the section without crack. These results imply that the cracked sections will have much lower life than the sections without crack. It can also be seen that the rate of increase with increasing axle load is higher for the cracked sections than the intact pavement, indicating that allowing the trucks with axle loads higher than the legal values, leads different consequences in the sections with crack, especially with top down cracks, and those without crack.

Figures 17 and 18 show, respectively, the variation of the stress intensity factor K_I and K_{II}, with the axle load for the pavement sections with top down and bottom up crack. As can be seen in Figures 17 and 18, over the range of axle loads used in this research, in both modes, the values of stress intensity factors in the pavement section with top down crack are higher than those of the pavement section with bottom up crack, indicating that the top down cracks have more potential to propagate in opening and shear mode than the bottom up crack. In addition, the rate of increase of the stress intensity factor K_I with axle load for the pavement section with top down crack is 4 times higher than that for the pavement section with bottom up crack, indicating that the increase of vehicles axle load causes more propagation of top down cracks than the bottom up cracks. However, in mode II, the rate of increase of stress intensity factor for the pavement section with bottom up crack is higher than that for the section with top down crack, indicating that at higher axle load levels, the stress intensity factor of K_{II} for the bottom up cracked section may become dominant.

In order to investigate the effects of axle load on rutting, following the method as described earlier, the rut depth of a pavement section with 7.5 cm top down crack was calculated at different lateral distances from the center of dual tires under different axle loads. In these analyses, a tire pressure of 690 kPa (100 psi) has been used. Figure 19 shows the rutted shapes of the pavement. As can be seen, the rut depth increases with increasing axle load. Also, it can be seen that the rate of increase in rut depth increases with increasing axle load. Comparing the rutted shape of the pavement with top down and bottom up crack under axle load of 8.2 ton reveals that the top down cracked sections results in higher rut depth than the sections with bottom up crack.

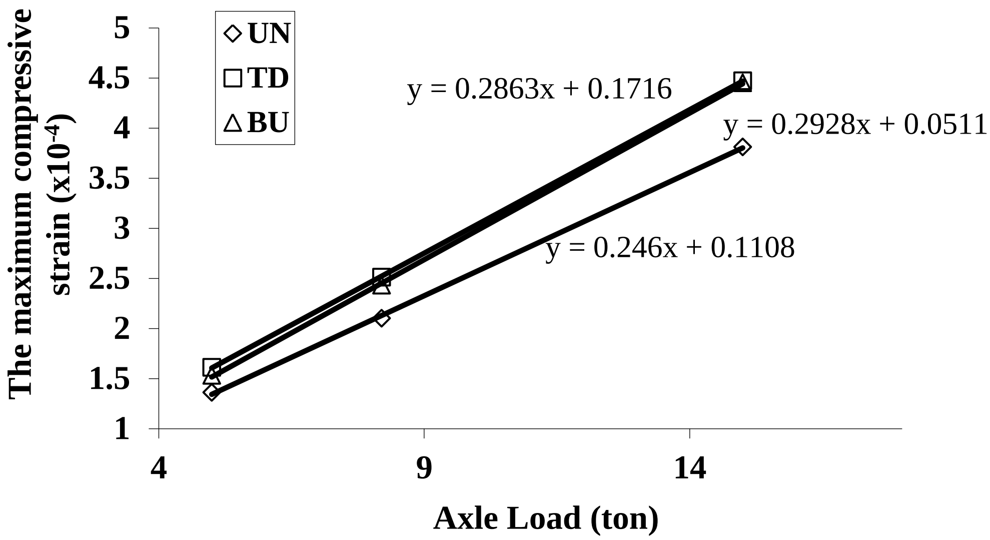

Fig. 15. Variation of the maximum compressive strain on sub-grade with axle load

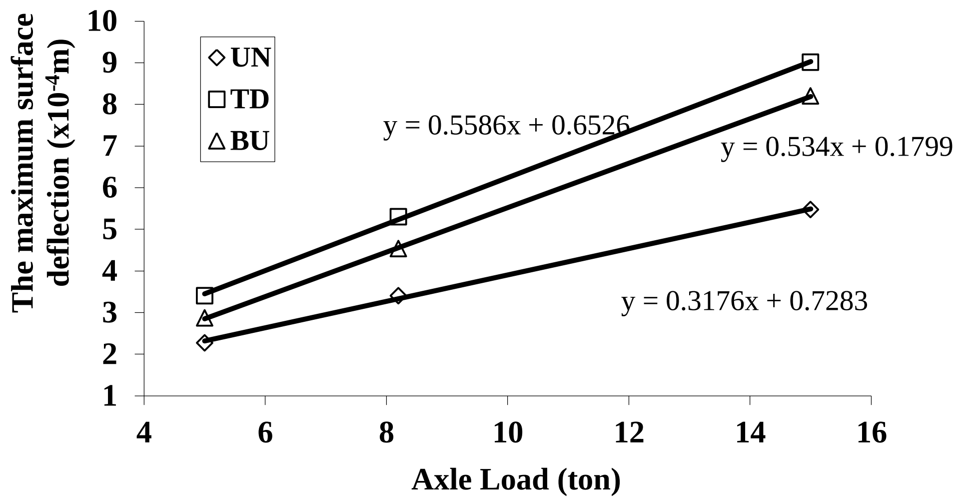

Fig. 16. Variation of the maximum surface deflection with axle load

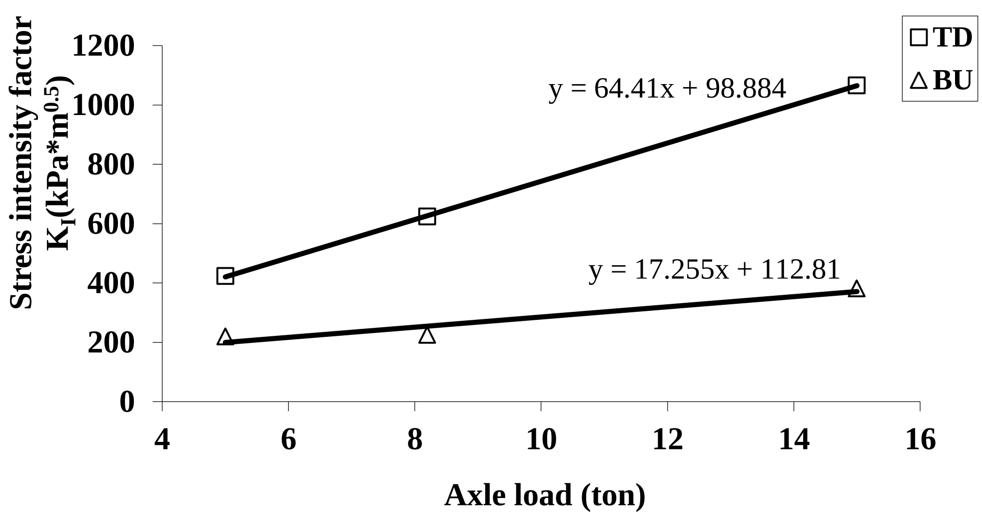

Fig. 17. Variation of the stress intensity factor K_I with axle load

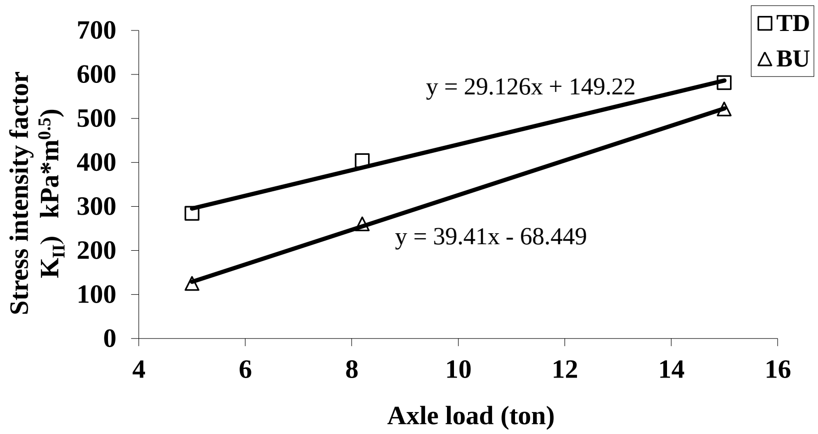

Fig. 18. Variation of the stress intensity factor K_{II} with axle load

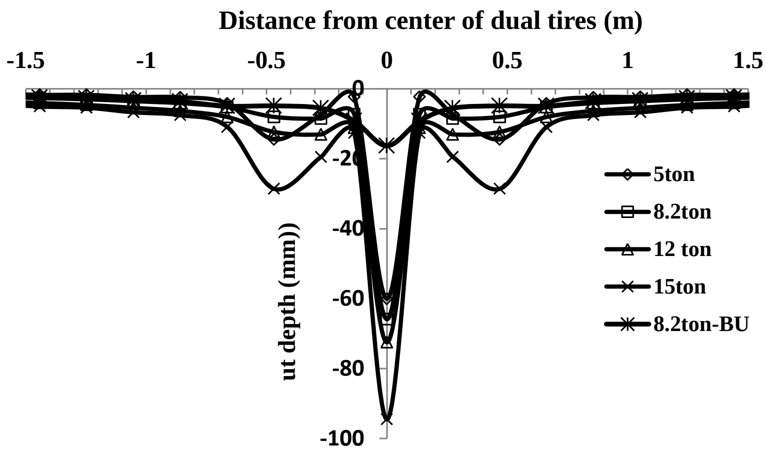

Fig. 19. Rutting of the pavement section with 7.5cm top down crack under different axle loads

In order to compare the effect of using dual tires with single tire, the responses of the cracked and intact pavement sections, corresponding to 8.2 ton single axle with dual and single tires, both at the same tire pressure of 690 kPa (100 psi) have been presented in Table 6. As can be seen, the single tire results in higher responses than the dual tires, with the highest difference for the stress intensity factor K_I, for which the stress intensity factor under single tire is approximately, 244 and 184% higher than that of dual tire for the sections with bottom up and top down crack, respectively, indicating that the sections with bottom up crack are more vulnerable to crack propagation under single axles with single wheel.

The results in Table 6 also show that the maximum tensile strain in asphalt layer is also significantly affected by using single tire instead of dual tires. The maximum tensile strain of asphalt layer under single tire is approximately, 8.5, 31 and 24% higher than that under dual tires for the pavement section without crack, with top down crack and bottom up crack, respectively; indicating that, under the same axle load, the axles with single tire has more deteriorating effect on the fatigue cracking of sections with top down crack. The results also show that, although the axles with single tire result in the same compressive strain at the top of sub-grade and lower surface deflection than the axles with dual tires, for the cracked sections, the deflection of pavement and the compressive strain at the top of sub-grade are higher under single tire than those under dual tire, with higher responses for the section with top down crack.

Table 6. Comparison between the responses of single axle with single and dual tires

Section type	Tensile strain in asphalt layer (× 10^{-5})		Compressive strain on sub-grade (×10^{-5})		Surface deflection (× 10^{-4}m)		Stress intensity factor K_I (kPa × $m^{0.5}$)	
	Single tire	Dual tires	Single tire	Dual tires	Single tire	Dual tires	Single tire	Dual tires
UN	10.3	9.5	2.1	2.1	3.4	3.82	-	-
TD	14.3	10.9	2.51	2.26	5.3	3.85	624	339
BU	11.9	9.6	2.43	2.28	4.53	3.87	225	92

CONCLUSIONS

The effects of varying tire pressure and axle load on some responses of cracked flexible asphalt pavement have been evaluated and compared with the pavement without crack. For the pavement section used for modeling in this research, the following are the brief results.

- The maximum tensile strain of asphalt layer increases with increasing tire pressure and axle load, with a higher values and rate of increases for the pavement section with top down crack.
- The maximum compressive strain on sub-grade of cracked and intact pavement sections increases with increasing tire pressure and axle load, with more sensitivity to the axle load and higher rate of increase for the section with bottom up crack.
- The maximum compressive strain on sub-grade of the pavement with bottom up crack is higher than those of the section with top down crack and intact pavement section.
- The maximum surface deflection of cracked pavement is higher than that of intact pavement with a higher deflection for the pavement with bottom up crack under the axle with dual wheels, while under the axles with single wheel, the maximum deflection of the pavement with top down crack is higher than the others.
- The rut depth increases with increasing tire pressure, axle load and crack depth, with higher rut depth for the sections with top down crack than those with bottom up crack. The rate of increase in rut depth with loading repetition increases with increasing tire pressure and crack depth.
- The results of stress intensity factors show that the opening mode is dominant, with the highest potential of crack propagation for the top down crack.
- The stress intensity factor in opening mode increases with increasing tire pressure and axle load, with a higher rate of increase with tire pressure for the section with bottom up crack, and a higher rate of increase with axle load for the pavement with top down crack.
- The results of this research shows that the top down cracks are more critical than the bottom up cracks and need more care for having an acceptable pavement performance. It is worthy to note that the top down cracks are visible and can be filled; while the bottom up cracks cannot be seen until propagate to the surface.

REFERENCES

Abdel-Motaleb, M.E. (2007). "Impact of high pressure truck tires on pavement design in Egypt", *Emirates Journal for Engineering Research*, 12(2), 65-73.

Alae, M., Haghshenas, H.F. and Zhao, Y. (2019). “Evaluation of top-down crack propagation in asphalt pavement under dual tires loading”, *Canadian Journal of Civil Engineering*, 5, 185-193.

Aliha, M.R.M. and Sarbijan, M.J. (2016). “Effects of loading, geometry and material properties on fracture parameters of a pavement containing top-down and bottom-up cracks”, *Engineering Fracture Mechanics*, 166, 182-197.

Ameri, M., Mansourian, A., Khavas, M.H., Aliha, M.R.M. and Ayatollahi, M.R. (2011). “Cracked asphalt pavement under traffic loading, A 3D Finite Element analysis”, *Engineering Fracture Mechanics*, 78(8), 1817-1826.

Chatti, K., Kim, H.B., Yun, K.K., Mahoney, J.P. and Monismith, C.L. (1996). “Field investigation into effects of vehicle speed and tire pressure on asphalt concrete pavement strains", *Transportation Research Record*, No. 1539, Transportation Research Board, Washington D.C., 66-71.

Chen, H.H., Marshek, K.M. and Saraf, C.L. (1990). "*Effects of truck tire contact pressure distribution on the design of flexible pavements: A three dimensional Finite Element approach"*, *Transportation Research Record*, No. 1095, 72-78.

Fakhri, M., Farokhi, M. and Kheiry, P.T. (2009). "Modeling of Top-Down Cracking (TDC) propagation in asphalt concrete pavements using fracture mechanics theory", *Advanced Testing and Characterisation of Bituminous Materials*, II, 681-692.

Ford, T.L. and Yap, P. (1990). "The truck tire/pavement interface", *The Promise of New Technology in the Automotive Industry*, Torino, Italy, 330-340.

Huang, Y.H. (1993). *Pavement analysis and design*, Prentice-Hall, Inc., Englewood Cliffs, New Jersey.

Hutchinson, B.G. and Mallett, J.J.L. (1990). "Line haul transportation cost and pavement damage characteristics of some Ontario trucks", *Canadian Journal of Civil Engineering*, 17(1), 28-35.

Hernandez, J., Gamez, A., Al-Qadi, I. and De Beer, M. (2014). "Analytical approach for predicting three-dimensional tire-pavement contact load", *Journal of the Transportation Research Board*, 2456, (1), 75-84.

Jacobs, M.M.J., Hopman, P.C. and Molenaar, A.A.A. (1996). "Application of fracture mechanics principles to analyze cracking in asphalt concrete (with discussion)", *Journal of the Association of Asphalt Paving Technology*, 65, 1-35.

Khavandi Khiavi, A., Naghiloo, M. and Rasouli, R. (2019). "Considering a new sample unit definition for Pavement condition index", *Civil Engineering Infrastructure Journal*, 52(1), 101-114.

Kim, S.M., Darabi, M.K., Little, D.N. and Al-Rub, R.K.A. (2018). "Effect of the realistic tire contact pressure on the rutting performance of asphaltic concrete pavements", *KSCE Journal of Civil Engineering*, 22(6), 2138-2146.

Ling, M., Luo, X., Gu, F. and Lytton, R.L. (2017). "An inverse approach to determine complex modulus gradient of field-aged asphalt mixtures", *Materials and Structures*, 50(2), 138.

Machemehl, R.B., Wang, F. and Prozzi, J.A. (2005). "Analytical study of effects of truck tire pressure on pavements using measured tire-pavement contact stress data", *Proceedings for the 84th TRB Annual Meeting*, Transportation Research Board, Washington DC, January 9-13.

Mahoney, J.P., Winters, B.C., Chatti, K., Moran, T.J., Monismith, C.L. and Kramer, S.L. (1995). *Vehicle/pavement interaction at the PACCAR test site*, Final Report No. WA-RD 384.1, Washington State Department of Transportation, Olympia, Washington, November.

Marshek, K.M., Hudson, W.R., Connell, R.B., Chen, H.H. and Saraf, C.L. (1985). *Experimental investigation of truck tire inflation pressure on pavement-tire contact area and pressure distribution*, Research Report 386-1, Center for Transportation Research, the University of Texas at Austin.

Modarres, A. and Shabani, H. (2015). "Investigating the effect of aircraft impact loading on the longitudinal top-down crack propagation parameters in asphalt runway pavement using fracture mechanics", *Engineering Fracture Mechanics*, 150, 28-46.

NCHRP. (2004). *Guide for mechanistic-empirical design of new and rehabilitated pavements structures*, Final Report, Part 3: Design Analysis. National Cooperative Highway Research Program, Washington, D.C.

Owende, P.M.O., Hartman, A.M., Ward, S.M., Gilchrist, M.D. and O'Mahony, M.J. (2001). "Minimizing distress on flexible pavements using variable tire pressure", *ASCE Journal of Transportation Engineering*, 127, 254-262

Prozzi, J.A. and Luo, R. (2005). *Quantification of the Joint Effect of Wheel Load and Tire Inflation Pressure on Pavement Response*, TRB Annual Meeting, Transportation Research Board, Washington D.C., January.

Rahman M.T., Mahmud K. and Ahsan, S. (2011). "Stress strain characteristics of flexible pavement using Finite Element analysis", *International Journal of Civil and Structural Engineering*, 2(1), 352-364.

Rahman, M.M., Saha, S., Hamdi, A.S.A. and Alam, M.J.B. (2019). "Development of 3-D Finite Element models for geo-jute reinforced flexible pavement", *Civil Engineering Journal*, 5, 437-446.

Sun, L. and Duan, Y. (2013). "Dynamic response of top-down cracked asphalt concrete pavement under a half-sinusoidal impact load", *Acta Mechanica*, 224(8), 1865-1877.

Sun, L. and Hudson, W.R. (2005). "Probabilistic approaches for pavement fatigue cracking prediction based on cumulative damage using Miner's law", *Journal of Engineering Mechanics*, 131(5), 546-549.

Taherkhani, H. and Arshadi, M.R. (2018). "Investigating the creep properties of PET-modified asphalt concrete", *Civil Engineering Infrastructure Journal*, 51(2), 277-292.

Taherkhani, H. and Jalali, M. (2018). "Viscoelastic analysis of geogrid-reinforced asphaltic pavement under different tire configurations", *International Journal of Geomechanics*, 18(7), 04018060.

Wang, F. and Machemehl, R.B. (2006). "Mechanistic-empirical study of effects of truck tire pressure on pavement using measured tire-pavement contact stress data", 85th TRB Annual Meeting, Transportation Research Board, Washington D.C., January.

Wu, S., Wen, H., Zhang, W., Shen, S., Mohammad, L. N., Faheem, A. and Muhunthan, B. (2019). "Field performance of top-down fatigue cracking for warm mix asphalt pavements", *International Journal of Pavement Engineering*, 20(1), 33-43.

Zheng, C. and Xie, S. (2003). "Effects of the tire-pavement contact pressure on asphalt pavement", *Proceedings of the Eastern Asia Society for Transportation Studies*, 4, 401-407.

Zhao, Y., Alae, M. and Fu, G. (2018). "Investigation of mechanisms of top-down fatigue cracking of asphalt pavement", *Road Materials and Pavement Design*, 19(6), 1436-1447.