Dynamic Response of Asphalt Pavement in Tunnel Entrance and Exit Area Based on Mixture Viscoelasticity

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Abstract. To further investigate the variation of stress under moving traffic loads in tunnel entrance and exit area, in this paper, a 3-D finite model(FE) of the pavement structure in entrance and exit section was established. The pavement of the tunnel consists of asphalt concrete and cement concrete. The viscoelastic property of asphalt mixture and the damping effect of the structure were considered. Dynamic traffic loads was applied during simulation. It is shown that the maximum interlayer shear stress between AC and PCC in the entrance and exit area of the tunnel was 28.37% larger than that of the regular pavement in the tunnel, which may be caused by the low cohesion between AC and PCC layers in the entrance and exit area of the tunnel.

1 Introduction

Great achievements have been made on highway construction in China, but pavement distress e.g. rutting, fatigue cracking, water damage, etc. appear in some sections within the design life, especially in special sections, such as polishing and traffic accidents in the entrance and exit section of freeway tunnel. Taking Niuwangshan tunnel in Jincheng-Yangcheng freeway[3] as a typical example, only 18 months after opening, the pavement texture depth decreased from 0.72mm to less than 0.2mm, and accordingly the number of traffic accidents in this section rose dramatically, accounting for about 50% of the total accidents in the whole line.

Taking into account this situation, researchers have already made great efforts. Fang Jing et al, established operating speed models for trucks at freeway tunnel sections and analyze the characteristics of driving behaviors through car following tests[2]. Li Yingtao analyzed working conditions of tunnel pavement, compared the performance between cement concrete pavement and asphalt concrete pavement in the tunnel and found that asphalt concrete pavement was preferred in tunnel pavement selection[3]; Gao Jing also analyzed working conditions of tunnel pavement and suggested that composite pavement should be taken precedence in the entrance and exit section for its comfort, anti-slide and convenient to repair[1].

In previous, there are not many studies on the stress response under moving loads in entrance and exit section. In this paper, based on Jinan-Dongying freeway, three critical stress indexes(shear stress between AC and PCC in pavement of the tunnel τ_{AC-PCC}, interlayer shear stress between SMA-13 and AC-16 τ_{SMA-AC}, AC-16 and AC-20C τ_{AC-AC} in main line pavement) are chosen, calculated and analyzed under moving loads, considering of viscoelastic property of asphalt mixture and the damping effect of the structure through ANSYS FE program.

2 Dynamics Basic Theory

According to Hamilton's Principle, pavement dynamics finite element equation is as follows:

$$M\ddot{u} + C\dot{u} + Ku = F(t) \qquad (1)$$

Where: M is the pavement mass matrix; C is the pavement damping matrix; K is the pavement stiffness matrix; F(t) is the loading function; u,u ,u are node displacement, velocity and acceleration respectively.

Rayleigh damping assumptions was used to calculate damping matrix:

$$C = \alpha M + \beta K \qquad (2)$$

Where: α and β are damping coefficient, and in this analysis, their simplified forms were used:

$$\alpha=2\lambda 1\omega 1,\ \beta=2\lambda 1/\omega 1 \qquad (3)$$

where: ω1 is the natural circular frequency; λ1 is modal damping ratios.

3 Viscoelastic parameters of asphalt mixture

To characterize the mechanical property of asphalt mixture, the Burgers model has been used in this paper, which is illustrated in Figure 1 and given in Equation 4.

$$\sigma + p_1\dot{\sigma} + p_2\ddot{\sigma} = q_1\dot{\varepsilon} + q_2\ddot{\varepsilon} \qquad (4)$$

Where: $p_1 = \frac{\eta_1}{E_1} + \frac{\eta_2}{E_2} + \frac{\eta_1}{E_2}, q_1 = \eta_1$

$$p_2 = \frac{\eta_1\eta_2}{E_1E_2}, \qquad q_2 = \frac{\eta_1\eta_2}{E_2}$$

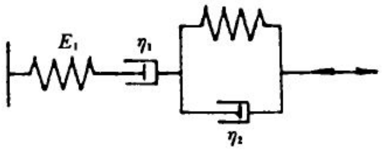

Figure 1. Burgers Model

Through Laplace transform method, shear relaxation modulus G(t) could be solved as:

$$G(t) = \frac{1}{q_0}\left[(\eta_1 - \beta E_1 p_2)e^{-\beta t} - (\eta_1 - \alpha E_1 p_2)e^{-\alpha t}\right] \qquad (5)$$

Whereq_0 , α and β are parameters related to E_1, E_2, η_1 and η_2 and thus shear relaxation modulus were transformed to Prony series as shown in equation 7. The material constants E_1, E_2, η_1 and η_2 were obtained from Reference[8].

$$G(t) = G_\infty + G_0(g_1 e^{-\frac{t}{t_1}} + g_2 e^{-\frac{t}{t_2}}) \qquad (6)$$

Where $G_\infty = 0$; G_0, g_1, g_2, t_1, t_2 are constants related to E_1, E_2, η_1 and η_2.

4 Pavement Structure and FE Model

4.1. Pavement Structure

Based on the structure of main line of Jinan-Dongying Freeway and other studies[1,5], the proposed pavement structure of entrance and exit section and geomaterial are shown in Table 1and Table 2.

Table 1. Drafted pavement structure of main mine section

Course	Depth h(cm)	Dynamic Modulus E*(MPa)	Poisson's ratio μ
SMA-13	4	7000	0.35
AC-16	5	9500	0.3
AC-20C	6	9000	0.3
LSPM-30	12	7000	0.3
cement stabilized macadam	36	1600	0.2
lime and fly ash stabilized soil	18	800	0.2
subgrade	---	35	0.35

Table 2. Drafted pavement structure of tunnel

Course	Depth h(cm)	Dynamic Modulus E*(MPa)	Elastic Modulus E(MPa)	Poisson's ratio μ
SMA-13	4	7000	---	0.35
AC-16	5	9500	---	0.3
C40 cement concrete board	24	---	40000	0.15
C15 invert cement concrete	---	---	15000	0.15
bedrock	---	---	60000	0.15

4.2 The FE model

Loads were applied at three different positions respectively: (a) pavement in entrance and exit area of the main line; (b) junction pavement in entrance and exit area; (c) pavement in entrance and exit area in the tunnel to simulate the process of entering and leaving a tunnel. Three corresponding finite element models were established respectively and shown in Figure 2, Figure 3 and Figure 4.

The size(x,y,z) was 4m×5m×10m. The x-axis was on the pavement transverse direction and the z-axis was on the advancing direction. To simplify the grounding shape of tires, it was assumed that the grounding shape was rectangle (18cm×20cm) and the distance between the center of two tires was 30cm[4].

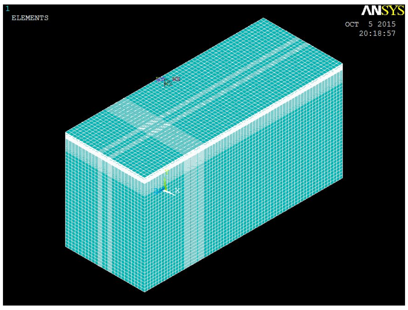

Figure 2. pavement in entrance and exit area of the main line

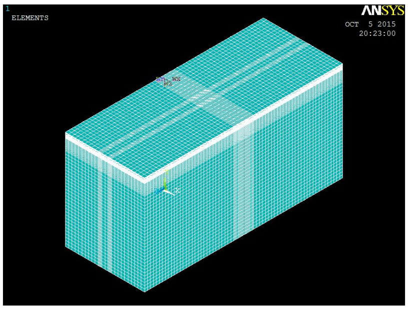

Figure 3. junction pavement in entrance and exit area

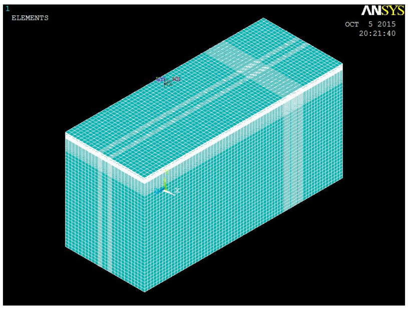

Figure 4. pavement in entrance and exit area in the tunnel

It was supposed that surface course materials were linear viscoelastic and other materials were homogeneous, isotropic and linear elastic[7]. The natural circular frequency of subgrade was 8.2 rad/s, and other materials' were 18.6 rad/s[6].

In this section, the speed varies. Vehicles accelerate when entering tunnels and decelerate when leaving tunnels. Thus in this paper, both vertical and horizontal loads were applied. Traffic loads would move 0.1m in every load step and there were 9 load steps in each position.

Speed, acceleration[2] and physico-mechanical calculation parameters of traffic loads were given in Table 3 and Table 4:

Table 3. Speed and acceleration of entrance and exit section

Into tunnel		Out of tunnel	
Speed	Acceleration	Speed	Acceleration
70km/h	-0.16m/s^{-2}	72km/h	0.2m/s^{-2}

Table 4. physico-mechanical Calculation parameters of traffic loads

Standard axle load P(KN)	100	Grounding shape	Rectangle 18cm*20cm
tire pressure p(MPa)	0.7	Distance between centers of two tires (cm)	30
Friction coefficient	0.3		

5 Simulation Results and Analysis

5.1 Critical stress chosen for entrance and exit section

(1) Critical stress for tunnel pavement
Due to the large difference of dynamic modulus between asphalt mixtures and cement concrete, it was easy to fail in the interlayer. Thus, the maximum interlayer shear stress between asphalt concrete layer and cement concrete layer(τ_{AC-PCC})was chosen for the pavement of tunnel.

(2) Critical stress for main line pavement
Due to the variation of speed and the consequent horizontal braking force, interlayer shear stress between SMA-13 and AC-16(τ_{SMA-AC}), AC-16 and AC-20C(τ_{AC-AC}) in main line pavement were chosen.

5.2 Results and analysis of τ_{AC-PCC}

To make a comparison between the pavement in entrance and exit area of the tunnel and regular one in the tunnel, the simulation results of τ_{AC-PCC} are shown in Table 5.

Table 5. τ_{AC-PCC} in entrance and exit area of the tunnel and regular pavement in the tunnel

Load step	Into tunnel	Regular pavement in the tunnel(MPa)	Out of tunnel
	pavement in entrance and exit area of the tunnel(MPa)		pavement in entrance and exit area of the tunnel(MPa)
1	0.2474	0.1810	0.2476
2	0.2491	0.1959	0.2493
3	0.2479	0.1941	0.2480
4	0.2474	0.1940	0.2476
5	0.2472	0.1941	0.2475
6	0.2472	0.1941	0.2474
7	0.2472	0.1942	0.2474
8	0.2472	0.1942	0.2474
9	0.2465	0.1937	0.2467
Average value	0.2475	0.1928	0.2477

From Table 5, it is shown that τ_{AC-PCC} in entrance and exit area of the tunnel is 28.37% larger than that of regular pavement in the tunnel, in both processes of entering and leaving tunnel.

It was probably because in the entrance and exit section the pavement geomaterials changed suddenly, therefore low cohesion between AC and PCC and inconsistent deformation of AC and PCC were caused. Besides, frequent acceleration and deceleration of moving loads may further deepen the difference. Thus τ_{AC-PCC} in entrance and exit area of tunnel increased.

When loads were applied on pavement in entrance and exit area of the main line and pavement in junction parts, the corresponding τ_{AC-PCC} in entrance and exit area of the tunnel was shown in Table 6.

Table 6. τ_{AC-PCC} in entrance and exit area of tunnel when loads applied on pavement in entrance and exit area of the main line and pavement in junction parts

Load step	Into tunnel		Out of tunnel	
	Pavement in entrance and exit area of the main line(MPa)	Pavement in entrance and exit area of the junction part(MPa)	pavement in entrance and exit area of the main line(MPa)	Pavement in entrance and exit area of the junction part(MPa)
1	0.0076	0.0708	0.0261	0.2461
2	0.0208	0.1022	0.0259	0.2484
3	0.0340	0.1513	0.0255	0.2519
4	0.0456	0.2641	0.0250	0.2505
5	0.0556	0.2968	0.0243	0.2687
6	0.0640	0.2495	0.0231	0.2995
7	0.0708	0.2387	0.0208	0.2185
8	0.0760	0.2424	0.0160	0.1549
9	0.0796	0.2444	0.0079	0.1163

It is found that in the process of entering tunnel, τ_{AC-PCC} increases with loads moving forward and peaks when loads arrive just at the junction position of two pavement structures. After that it decreases to the value of the pavement in entrance and exit area of the tunnel (shown in Figure 5), and vice versa in the process of going out of tunnel(shown in Figure 6). But the maximum of τ_{AC-PCC} during the processes of going into and out of tunnel are 19.92% and 20.91% larger than the average value of τ_{AC-PCC} in entrance and exit area of the tunnel respectively, which may be also caused by the suddenly changing geomaterials.

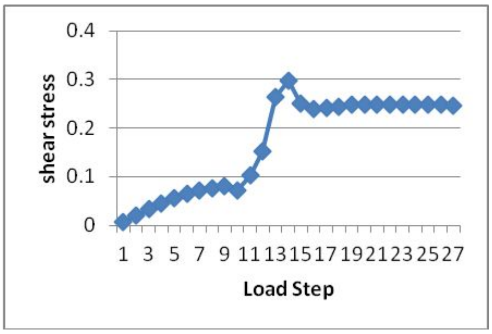

Figure 5. The variation of τ_{AC-PCC} in the process of entering tunnel

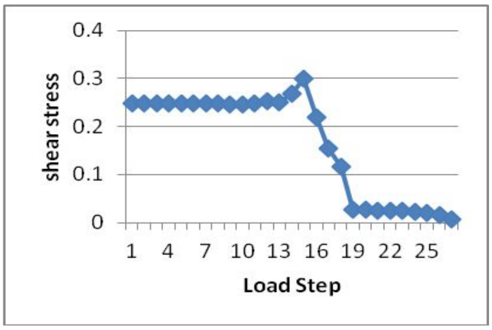

Figure 6. The variation of τ_{AC-PCC} in the process of leaving tunnel

5.3 Results and analysis of τ_{SMA-AC}

The simulation results of τ_{SMA-AC} in the entrance and exit area of the main line and regular main line pavement are listed in Table 7.

Table 7. τ_{SMA-AC} in the entrance and exit area of the main line and regular main line pavement

Load step	Into tunnel	Regular main line pavement (MPa)	Out of tunnel
	pavement in entrance and exit area of the main line(MPa)		pavement in entrance and exit area of the main line(MPa)
1	0.1420	0.1419	0.1395
2	0.1862	0.1863	0.1837
3	0.1792	0.1798	0.1763
4	0.1775	0.1787	0.1748
5	0.1769	0.1785	0.1744
6	0.1767	0.1786	0.1743
7	0.1768	0.1788	0.1742
8	0.1771	0.1789	0.1740
9	0.1773	0.1786	0.1737
Average value	0.1744	0.1756	0.1717

From Table 7, it is shown that there is minor difference between τ_{SMA-AC} of regular main line pavement and that in entrance and exit area of main line in both processes. The average τ_{SMA-AC} value of regular main line pavement are the biggest in the three, which is 0.69% higher than that in the process of going into tunnel and 2.27% higher than that in the process of going out of tunnel.

τ_{SMA-AC} in entrance and exit area of main line is quite small when loads were applied on pavement in entrance and exit area in the tunnel and decreases with the increase of distance away from the pavement in entrance and exit area of main line in both process(shown in Table 8). It should also be taken notice that in this situation τ_{SMA-AC} in the process of going out of tunnel is almost 4~5 times of that in the other process. When loads were applied on junction parts, τ_{SMA-AC} increases and peaks at the junction position both in the processes of going into and leaving tunnel, but their maxima are quite different, with the former 32.24% higher than the latter.

Table 8. τ_{SMA-AC} in entrance and exit area of main line when loads applied on pavement in entrance and exit area of the tunnel and pavement in junction parts

Load step	Into tunnel		Out of tunnel	
	Pavement in entrance and exit area of the junction part(MPa)	Pavement in entrance and exit area of the tunnel(MPa)	Pavement in entrance and exit area of the tunnel(MPa)	Pavement in entrance and exit area of the junction part(MPa)
1	0.1529	0.000070	0.000210	0.0040
2	0.2132	0.000055	0.000223	0.0073
3	0.2220	0.000050	0.000232	0.0159
4	0.2748	0.000055	0.000241	0.0859
5	0.3060	0.000055	0.000251	0.1620
6	0.1558	0.000052	0.000263	0.2314
7	0.0638	0.000047	0.000276	0.2184
8	0.0244	0.000040	0.000291	0.2087
9	0.0120	0.000033	0.000308	0.2003

5.4 Results and analysis of τ_{AC-AC}

τ_{AC-AC} in the entrance and exit area of the main line and regular main line pavement are shown in Table 9.

Table 9. τ_{AC-AC} in the entrance and exit area of the main line and regular main line pavement

Load step	Into tunnel	Regular main line pavement (MPa)	Out of tunnel
	pavement in entrance and exit area of the main line(MPa)		pavement in entrance and exit area of the main line(MPa)
1	0.1129	0.1128	0.1109
2	0.1457	0.1457	0.1435
3	0.1437	0.1441	0.1415
4	0.1423	0.1432	0.1404
5	0.1417	0.1430	0.1400
6	0.1415	0.1430	0.1399
7	0.1416	0.1431	0.1398
8	0.1417	0.1431	0.1397
9	0.1417	0.1428	0.1392
Average value	0.1392	0.1401	0.1372

From Table 9, it could be found that τ_{AC-AC} of regular main line pavement is slightly different from that in the entrance and exit area of the main line. In this situation, the values of τ_{AC-AC} are smaller than τ_{SMA-AC} as a whole.

However, it is quite different when loads were applied on the pavement in entrance and exit area of the tunnel that τ_{AC-AC} are almost 4 times of τ_{SMA-AC}(shown in Table 10). Because the values of τ_{AC-AC} are small, its effect on pavement would probably be small. When loads were applied on junction pavement, τ_{AC-AC} increases and also peaks just at the junction position. The maxima of τ_{AC-AC} in both process are nearly same, with difference of 0.91%, which is quite different from τ_{SMA-AC}.

Table 10. τ_{AC-AC} in entrance and exit area of main line when loads applied on pavement in entrance and exit area of the tunnel and pavement in junction parts

Load step	Into tunnel		Out of tunnel	
	Pavement in entrance and exit area of the junction part(MPa)	Pavement in entrance and exit area of the tunnel(MPa)	Pavement in entrance and exit area of the tunnel(MPa)	Pavement in entrance and exit area of the junction part(MPa)
1	0.1224	0.000232	0.000895	0.0115
2	0.1645	0.000179	0.000961	0.0173
3	0.1869	0.000210	0.001002	0.0319
4	0.2641	0.000228	0.001046	0.0982
5	0.2968	0.000223	0.001094	0.2583
6	0.1609	0.000207	0.001155	0.2995
7	0.0503	0.000183	0.001237	0.2185
8	0.0330	0.000158	0.001331	0.1783
9	0.0212	0.000131	0.001440	0.1674

6 Conclusion

In this paper, the 3-D FE model of the pavement structure in entrance and exit section was established considering viscoelastic property of asphalt mixture and the damping effect of the structure. Three chosen stress indexes were calculated under moving loads:

(1) τ_{AC-AC} in the entrance and exit area of tunnel is larger than that of regular pavement in the tunnel. It is probably because geomaterials suddenly changed in this area, therefore low cohesion between AC and PCC and inconsistent deformation of AC and PCC was caused. Besides, frequent acceleration and deceleration of moving loads further deepened the difference of τ_{AC-AC} between pavement in the entrance and exit area of tunnel and regular pavement in the tunnel.

(2) τ_{SMA-AC} of regular main line pavement and the entrance and exit area of main line are nearly all the same. When loads were applied on entrance and exit area of the tunnel, τ_{SMA-AC} in the process of leaving tunnel is almost 4~5 times of that in the other process. When loads were applied on junction pavement in entrance and exit area, maxima of τ_{SMA-AC} in two processes are quite different and that in the process of going into tunnels is 32.24% higher than the other.

(3) when loads were applied on the entrance and exit area of tunnel, values of τ_{AC-AC} are almost 4 times of that of τ_{SMA-AC}. However, τ_{AC-AC} is lower than τ_{SMA-AC} when loads were applied on the pavement in entrance and exit area of main line and regular main line pavement.

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