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Asphalt pavement short-term rutting analysis and prediction considering temperature and traffic loading conditions

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Abstract: The rutting simulation method considering temperature variance and traffic time distribution is developed through ABAQUS software. The short-term behavior of pavement rut under the effects of temperature and traffic loading is addressed. Then sensitivity analysis on the factors of temperature and traffic loading is conducted and a short-term rutting prediction model is developed. The results show that under the same conditions of temperature and the number of load repetitions, rut increases sharply with the contact pressure in a linear manner, while as for the heavy load situation, the increases likely to be more nonlinear and faster; the significant factors affecting rutting include daily maximum air temperature, daily solar radiation volume, daily minimum air temperature, tire-pavement contact pressure and the number of load repetitions. Finally, a short-term rutting prediction model reflecting the effects of air temperature and traffic loading is developed, and it can be used for prediction and pre-warning for pavement rut prevention.

Key words: short-term rutting; asphalt pavement; ABAQUS

Rut is one of the major distresses affecting asphalt pavement service performance and traffic safety. In recent years, the amount and severity of rutting in asphalt pavement have become more significant due to heavy truck traffic. Many methods have been proposed to evaluate high-temperature performance of asphalt mixtures, such as the traditional Marshall and Hveem test, the uniaxial and triaxial static and dynamic creep test, and the superpave direct shear test[1-2]. The development of accurate rutting prediction models is an ongoing pursuit of the pavement engineering community, resulting in many rutting prediction models ranging from purely mechanical models to empirical ones[3-5].

Generally, climate and traffic loading are two main factors for rutting in asphalt pavement[1-6]. The climate affects the pavement temperature and thus influences the performance of pavement materials, especially the asphalt mixtures. Traffic, axle weight (tire-pavement contact pressure) and loading times are changing all the time. But most rutting models are built on the constant parameters of pavement temperature and traffic load to predict long-term rutting[4-8]. Long-term rutting means rutting accumulated over a long period of time, even in a life period. In contrast, short-term rutting represents the distress developed over a short period of time (commonly one day or one month). And the sort of asphalt pavement behavior under different conditions of climate and traffic loading is overlooked.

Therefore, within the framework of a numerical model and the improved simulation procedure, which is reasonable and similar to the field situation, the simulation analysis of pavement rutting is conducted based on actual climate and traffic loads in this study. The rutting behavior under different conditions of temperature fields and loading is explored. The short-term rutting prediction model reflecting the effects of climate and traffic is developed.

1 Approaches and Parameters for Rutting Analysis

1.1 Rutting simulation procedure considering consecutive temperature and traffic load variation

The rutting simulation procedure concerning continuous temperature variance can be more effective and powerful to address the rutting simulation analysis especially in the short-term manner.

In addition, the traffic volume on the actual pavement also varies with the time of day. The daily traffic distribution is usually depicted as in Fig. 1, which is close to the normal distribution[9]. Although it may be different due to different seasons and different roads as well as other influential factors, the variance of daily traffic distribution is ignored in this study. So Fig. 1 is used for rutting analysis when considering the impact of daily traffic distribution.

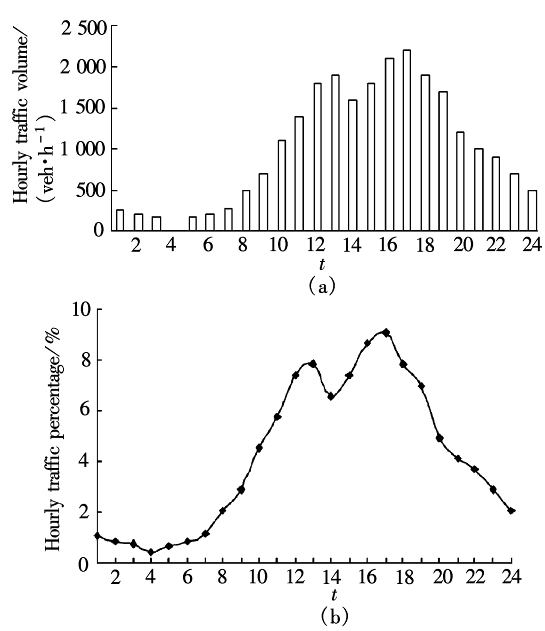

Fig. 1 Daily traffic distribution (1 to 24 for 1:00 to 24:00).
(a) Bar chart of daily traffic distribution; (b) Curve of percentage of hourly traffic

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The material models used in the simulation are the creep model and the elastic model. The total calculated deformation contains two parts, namely, a creep portion and an elastic portion. The rutting (permanent deformation) is caused mainly by creep deformation while the elastic portion is completely reversible and not attributable to rut depth. Therefore, the elastic portion should be subtracted from the total deformation to obtain the real rut depth (creep deformation).

The rutting simulation procedure can be implemented in ABAQUS. The steps are as follows.

1) The model for temperature field analysis (using uniform meshing for rutting simulation) with weather parameters is developed; all the boundary conditions are determined through the user subroutines FLUX and FILM; the transient temperature field of the pavement is analyzed; the 24-hour pavement temperatures corresponding to different weather conditions are collected; the ODB file of temperature field result data is created.

2) The integrated model for rutting analysis is developed as follows:

a) The model meeting the requirements of both precision and efficiency of the analysis is adopted;

b) The material parameters varying with temperature are defined in the property module (Only the parameter variations in asphalt mixtures is considered in this study);

c) The static analysis step is set up in the step module, and its analysis step time is set as short as possible (1×10^{-10} s is proposed);

d) The visco analysis step(s) is set up in the step module (The multi-step analysis process may be more reasonable according to different temperature conditions);

e) The contact pressure between tire and road is applied in the load module; the variable pavement temperature corresponding to each visco step is defined (importing the corresponding temperature data obtained in step 1) in the rutting model using an ODB file);

f) Before operating each analysis step, the ABAQUS will automatically interpolate the material parameter based on the current temperature value of each node, and put the interpolated parameter into the simulation model to execute the creep analysis;

3) In the above process, the elastic portion should be subtracted from the total calculated deformation of each node, obtaining the creep deformation of the pavement, which is the real rutting.

The creep analysis is nonlinear and generally requires a lot of iterations. Variance of material properties with temperature should be also considered. It requires an extremely large room to store the output data. Therefore, in this paper, only the displacement, creep strain and stress of asphalt surface nodes are set as output requests. After modifying the corresponding values in the INP file and setting up the files of each combined model, the combined rutting simulation under different conditions of temperature and traffic loading can be implemented easily. The combined model files with unified names can be automatically executed one by one through the batch process instruction in the Windows Operating System.

1.2 Simulation model

Considering precision and efficiency, the width, depth, element type, meshing and the creep tolerance of the FEA model, are defined as 2.5 m in width, using finite elements in the first 1.0 m depth when using infinite elements in other portions, with partial fine meshing and a creep tolerance of 5×10^{-4}.

1.3 Simulation parameters

1.3.1 Thermal parameters

Due to the fact that the thermal behavior of asphalt mixtures varies little with their types, the values of the thermal parameters of all the surface asphalt layers are shown in Tab. 1.

Taking the weather data of the Nanjing region as an example, its statistical meteorological data (see Tab. 2) is used to analyze the temperature fields under different weather conditions.

Tab. 1 Thermal parameters of temperature field analysis

Parameters	Asphalt layers	Cement-stabilized aggregate base	Lime-treated soil subbase	Subgrade
Thermal conductivity $k/(\mathrm{J\cdot(m\cdot h\cdot ℃)^{-1}})$	4 680	5 616	5 148	5 616
Density $\rho/(\mathrm{kg\cdot m^{-3}})$	2 300	2 200	2 100	1 800
Thermal capacity $C/(\mathrm{J\cdot(kg\cdot ℃)^{-1}})$	924.9	911.7	942.9	1 040.0
Solar radiation absorptivity α_s	0.90			
Pavement emissivity ε		0.81		
Heat convection coefficient $h_c/(\mathrm{W\cdot(m^2\cdot ℃)^{-1}})$		$3.7v_w+9.4$		
Absolute zero T_Z/℃		−273		
Stefan-Boltzmann constant $\sigma/(\mathrm{J\cdot(h\cdot m^2\cdot K^4)^{-1}})$		$2.041\,092\times 10^{-4}$		

Tab. 2 Average values of statistical meteorological data (30 years, Nanjing region, China)

Month	Daily average air temperature/℃	Daily maximum air temperature/℃	Daily minimum air temperature/℃	Daily solar radiation volume/$(\mathrm{MJ\cdot m^{-2}})$	Daily effective sunlight hour/h	Daily average wind speed/$(\mathrm{m\cdot s^{-1}})$
May	21.5	27.8	15.2	25.7	9.3	2.7
June	25.6	31.2	20.1	22.9	9.8	2.7
July	29.2	35.6	22.8	26.3	10.7	2.6
August	28.8	35.3	22.3	25.1	11.5	2.7
September	23.9	29.6	18.3	24.3	8.7	2.4

Note: The data refer to China database of natural resources.

1.3.2 Mechanics parameters

The Bailey-Norton creep law is commonly used to analyze creep deformation, which is expressed by the time hardening creep model,

$$\dot{\varepsilon}_{cr} = Aq^n t^m \tag{1}$$

where q and t are the one-dimensional stress and the loading time, respectively; A, n and m are the model parameters. Commonly, $A > 0$, $n > 0$, $-1 < m \leqslant 0$. The model is expressed by creep strain rate in the FEA software ABAQUS.

The data of dynamic triaxial creep tests under different temperatures (20 to 60 ℃, interval of 10 ℃) and different stress levels are processed by the statistic software SAS to calculate the values of the creep model parameters A, n and m under different temperatures, as shown in Tab. 3.

Tab. 3 Creep and elastic parameters of asphalt mixtures

Asphalt mixture	Temperature/℃	A	n	m	R^2_{adj}	Resilient module E/MPa	Poisson ratio μ
SMA-13	20	6.536×10^{-11}	0.937	−0.592	0.932 6	870	0.25
	30	3.325×10^{-9}	0.862	−0.587	0.945 8	620	0.30
	40	1.446×10^{-8}	0.792	−0.577	0.942 0	554	0.35
	50	1.390×10^{-6}	0.414	−0.525	0.924 4	530	0.40
	60	1.464×10^{-5}	0.336	−0.502	0.904 8	526	0.45
Sup20	20	4.580×10^{-11}	0.944	−0.596	0.926 4	910	0.25
	30	2.461×10^{-9}	0.796	−0.585	0.922 5	752	0.30
	40	3.673×10^{-8}	0.773	−0.570	0.936 4	600	0.35
	50	4.802×10^{-6}	0.595	−0.532	0.849 3	440	0.40
	60	7.778×10^{-5}	0.384	−0.441	0.910 3	380	0.45
Sup25	20	4.590×10^{-11}	0.922	−0.581	0.936 4	1031	0.25
	30	3.461×10^{-9}	0.859	−0.576	0.920 7	900	0.30
	40	1.956×10^{-8}	0.830	−0.562	0.906 2	710	0.35
	50	1.200×10^{-6}	0.322	−0.522	0.801 5	500	0.40
	60	3.755×10^{-5}	0.210	−0.418	0.899 2	390	0.45

The elastic model and typical recommended parameter values are taken into account with regard to layers underneath the base, ignoring temperature influence, as shown in Tab. 4[10].

Tab. 4 Elastic parameters of base and subgrade

Materials	Elastic module E/MPa	Poisson ratio μ
Cement-stabilized aggregate base	1 200	0.20
Lime-treated soil subbase	300	0.30
Subgrade	45	0.40

2 Analysis on Short-Term Rutting

The pavement temperatures from May to September are employed in the rutting simulation procedure. The standard load conditions are used as shown in Tab. 5.

Tab. 5 Load condition used for rutting simulation

Load parameters	Value
Traveling speed/(km·h^{-1})	60
Tire-pavement contact length/cm	19.2
Loading time/ms	11.520
Accumulated loading time/s (represent the load repetitions)	4 320.0
Tire-pavement contact width/cm	18.6
Axial load/kN	100
Contact pressure/MPa	0.7
Number of load repetitions	37.5 (10 000)

The results shown in Fig. 4(a) indicate the relationship between rutting and loading time (load repetitions) in July. The positive R_{d1} and the negative R_{d2} are the concave and the convex rut depth, respectively. R_d is their sum. Before 8:00, due to low pavement temperature and light traffic, the rutting depth was relatively slight. After 10:00 as the pavement temperature rose and the traffic volume increased, the rutting depth increased rapidly. After 19:00, the pavement temperature declined and the traffic volume also began to decrease, and the rutting depth nearly stopped increasing.

Fig. 4(b) shows the comparison of rutting among months from May to September. UA5-7P is the concave rut under the standard contact pressure of 0.7 MPa and the temperature field of May, UA6-7P is different from that in June; while UC5-7P is the convex rut under the standard contact pressure of 0.7MPa and the temperature field of May, UC6-7P is different from that in June.

The results in Fig. 5 show that traffic loading has a more powerful influence on rutting under high temperature conditions. The relationship between rut-depth and contact pressure is studied on the assumption of constant temperature and loading time in pervious efforts.

Thus, during high temperature seasons, the vehicles, particularly, the low-speed overloading ones, should be avoided off the highway and be encouraged to travel in the evenings when temperature is low. That wILL be helpful both to protect the pavement and avoid the potential traffic accident occurrence. Through regulating traffic (especially the low-speed and overloading part) under high temperature conditions, the occurrence probability of rutting will be sharply reduced. To accomplish this goal, different levels of toll rate at different time are applied; i. e., the extra fee will be charged for the vehicles traveling at the high temperature periods of time while a lower toll rate for the traveling vehicles when temperature is low.

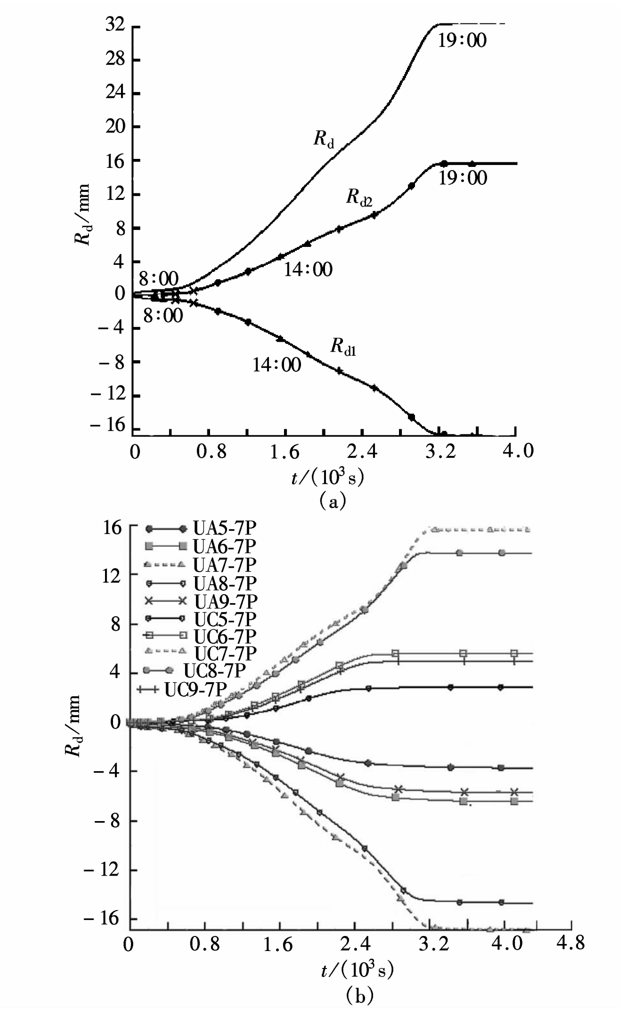

Fig. 4 Relationship between rutting depth and loading time considering traffic distribution. (a) July; (b) May to September

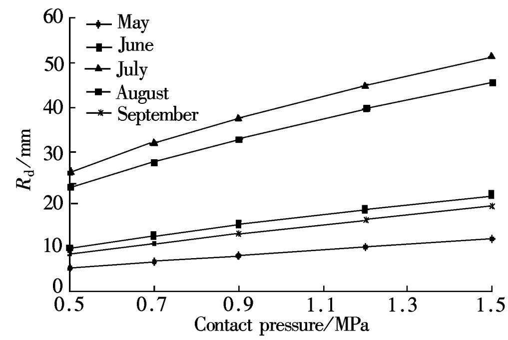

Fig. 5 Relationship between rutting depth and contact pressure

3 Significance Analysis on Climate and Traffic Load Factors

3.1 Climate factors

Climatic factors affecting rutting include daily maximum air temperature T_a^{max}, daily minimum air temperature T_a^{min}, daily solar radiation volume Q, daily effective sunlight hour c and daily wind speed v_w. Rutting usually occurs at the daily average air temperature of 20 ℃ or higher (May to September in Nanjing). Five months from May to September are selected in the study. The five average levels of climate in each month are calculated from yearly statistics (see Tab. 6).

3.2 Traffic load factors

In the case of traffic loading, the direct influence factors are contact pressure p between tire and pavement and accumulated loading time (load repetitions) t. Five levels of p are used for rutting simulation: 0.5, 0.7, 0.9, 1.2 and 1.5 MPa. The total accumulated loading time (load repetitions) t is set as a constant value of 4 320.0 s.

Tab. 6 Eleven levels of climate factors

Month	Daily average air temperature/℃	Daily maximum air temperature/℃	Daily minimum air temperature/℃	Daily solar radiation volume/(MJ·m^{-2})	Daily effective sunlight hour/h	Daily average wind speed/(m·s^{-1})
May	21.5	27.8	15.2	25.7	9.3	2.7
June	25.6	31.2	20.1	22.9	9.8	2.7
July	29.2	35.6	22.8	26.3	10.7	2.6
a1	27.0	32.0	22.0	24.0	10.7	2.6
a2	29.0	34.0	24.0	26.3	10.7	2.6
a3	29.5	35.0	24.0	26.3	10.7	2.6
a4	30.5	36.0	25.0	27.0	11.5	2.7
a5	31.0	37.0	25.0	28.0	11.5	2.7
a6	33.0	39.0	27.0	30.0	11.5	2.7
August	28.8	35.3	22.3	25.1	11.5	2.7
September	23.9	29.6	18.3	24.3	8.7	2.4

3.3 Significance analysis

A method similar to the analysis of variation in statistics is introduced to address the significance analysis, in which the relationship between rutting and all the factors is simply assumed to be linear. Then the stepwise multiple regression analysis is carried out to analyze the significance of each factor. Tab. 7 shows the results of significance analysis through the statistics software SAS.

Through the F-test of each factor, the levels of significance of daily maximum air temperature T_a^{max}, contact pressure p, daily solar radiation volume Q and daily minimum air temperature T_a^{min} are all lower than 10^{-4}, but for daily effective sunlight hour c and daily wind speed v_w, the levels of significance exceed the critical value 0.15. And thereby the significant factors affecting rutting include daily maximum air temperature T_a^{max}, tire-pavement contact pressure p, daily solar radiation volume Q and daily minimum air temperature T_a^{min}, as well as accumulated loading time t. The effect of daily effective sunlight hour c and daily wind speed v_w, however, shows less significance.

Tab. 7 Results of significance analysis

Independent variable	Increment of R^2	R^2	Partial regression sum of squares S_i	Residual sum of squares S_E	F value	Level of significance P
T_a^{max}	0.746 3	0.746 3	321.270 1	4 066.349 16	155.87	$<10^{-4}$
p	0.189 4	0.935 7	45.691 2	1 031.045 93	153.08	$<10^{-4}$
Q	0.018 2	0.953 9	20.687 1	739.353 62	20.12	$<10^{-4}$
T_a^{min}	0.012 2	0.966 1	4.798 4	543.953 41	17.96	$<10^{-4}$

Note: The levels of significance of both c and v_w are higher than the critical value 0.15, so they are not significant.

4 Prediction Model of Short-Term Rutting

Under the same temperature and accumulated loading time, rut-depth increases linearly with the contact pressure. And rutting usually develops very rapidly at the early stage of loading and the slope of increment falls with the loading time nearly to zero at the end of loading. A simple rutting prediction model is proposed as follows:

$$R_d = A(a + T_a^{max} + bT_a^{min} + cQ) \times p \times (t^2 + dt^3) \quad (2)$$

where A, a, b, c, d are nonlinear regression coefficients.

The results of multiple regression analysis of the rutting prediction model by the statistics software SAS are shown in Tabs. 8 and 9.

$$R_d = 2.809 \times 10^{-7} \times (-77.632\,4 + T_a^{max} + 1.374\,2T_a^{min} + 1.360\,8Q) \times p \times (t^2 - 1.700 \times 10^{-4}t^3) \quad (3)$$

$$R_d = 5.361 \times 10^{-7} \times (-34.978\,1 + T_a^{max} + 0.570\,0T_a^{min}) \times p \times (t^2 - 1.700 \times 10^{-4}t^3) \quad (4)$$

Tab. 8 Results of multiple regression analysis of rutting prediction model

Independent variable	Regression coefficient	Standard deviation	95% confidence interval	
A	2.809×10^{-7}	7.923×10^{-7}	2.654×10^{-7}	2.965×10^{-7}
a	−77.632 4	2.026 6	−81.604 7	−73.660 0
T_a^{min}	1.374 2	0.062 1	1.252 6	1.495 9
Q	1.360 8	0.051 8	1.259 3	1.462 2
t^3	-1.700×10^{-4}	2.465×10^{-7}	-1.700×10^{-4}	-1.700×10^{-4}

Tab. 9 Results of variation analysis of rutting prediction model

Sources of variation	Degree of freedom	Sum of squares	Mean square	F value	Level of significance P
Regression sum of squares S_R	5	$9.939\,796 \times 10^6$	$1.987\,959 \times 10^6$	$0.214\,375 \times 10^6$	$<10^{-4}$
Residual sum of squares S_E	29.435×10^3	$0.272\,958 \times 10^6$	9.273 3		
Total sum of squares S_T	29.440×10^3	$10.212\,754 \times 10^6$			

It may be difficult to obtain the data on solar radiation volume in some regions and the air temperature can, to some extent, reflect the solar radiation volume. Therefore, a simplified rutting prediction model except the daily solar radiation volume is developed as follows:

$$R_d = A(a + T_a^{max} + bT_a^{min}) \times p \times (t^2 + ct^3) \quad (5)$$

where each variable has the same significance and units as those in Eq. (2). Tabs. 10 and 11 give the analysis results of the simplified rutting prediction model with SAS. Eqs. (2) and (4) do not address the retarded deformation since the viscoelastic behavior is ignored when the model is developed.

The tire-pavement contact pressure usually has a good correlation with axial load and tire pressure. And it can be calculated by

$$p = 0.290p_t + 0.004\,2P + 0.144\,8 \quad (6)$$

where p is the tire-pavement contact pressure, MPa; p_t is the tire pressure, MPa; P is the axial load, kN.

The accumulated loading time can be calculated by

$$t = \frac{NP}{0.36n_w pBv} \quad (7)$$

where N is the number of load repetitions; n_w is the axial number; B is the tire-pavement contact width, cm; v is the traveling speed, km/h.

In summer, when the average daily air temperature is over 20 ℃, the short-term or long-term rutting of asphalt pave-

Tab. 10 Results of multiple regression analysis of the simplified rutting prediction model

Independent variable	Regression coefficient	Standard deviation	95% confidence interval	
A	5.361×10^{-7}	7.415×10^{-7}	5.216×10^{-7}	5.506×10^{-7}
a	−34.978 1	0.321 5	−35.608 3	−34.347 8
T_a^{min}	0.570 0	0.021 3	0.528 4	0.611 7
t^3	-1.700×10^{-4}	-2.611×10^{-7}	-1.700×10^{-4}	-1.700×10^{-4}

Tab. 11 Results of variation analysis of the simplified rutting prediction model

Sources of variation	Degrees of freedom	Sum of squares	Mean square	F value	Level of significance P
Regression sum of squares S_R	4	$9.899\,718 \times 10^6$	$2.474\,930 \times 10^6$	$0.232\,727 \times 10^6$	$<10^{-4}$
Residual sum of squares S_E	29.436×10^3	$0.313\,036 \times 10^6$	10.634 5		
Total sum of squares S_T	29.440×10^3	$10.212\,754 \times 10^6$			

ment can be predicted by Eq. (2) or Eq. (4) based on the climate and traffic loading data of the object road. These data can be drawn from a specific day or the average data over a longer period of time (e.g. a month or a season) as long as it is ensured that the climate and traffic data are collected from the same period of time.

The rutting prediction model in this study is developed based on a typical sort of pavement structure and mixtures and the constant traffic distribution. Applicability of this model should be further validated for different traffic distributions, pavement structures and mixtures.

5 Conclusions

The rutting simulation procedure considering continuous temperature variance and traffic time distribution is developed to address the short-term behavior of pavement rutting under the effects of climatic and traffic loading, which is obviously more reasonable and effective for rutting prediction. The conclusions are listed as follows:

1) Under the same temperature and accumulated loading time (load repetitions), rut depth sharply increases with the tire-pavement contact pressure in a linear manner. While as for the overloading situation, the increase is likely to be more nonlinear and faster.

2) The significant factors of rutting include daily maximum air temperature T_a^{max}, daily solar radiation volume Q and daily minimum air temperature T_a^{min}, tire-pavement contact pressure p and accumulated loading time t (load repetitions). The effects of daily effective sunlight hour c and daily wind speed v_w, however, is less significant.

3) The short-term rutting prediction model reflecting the effects of climate and traffic loading is developed for prediction and pre-warning of pavement rutting.

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考虑温度和交通特性的沥青路面短期车辙分析与预估模型

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摘要:利用有限元程序 ABAQUS 分析了沥青路面车辙随温度和交通变化的关系,重点分析了这种关系的短期发生过程. 分析过程中进行了路面车辙的温度和交通敏感性分析,并进行了针对其短期发生过程的预估模型研究. 结果表明:在同样的交通和温度环境下,车辙深度随车辆轮胎压力呈线性增加特性,而在重载作用下则呈非线性特性;影响路面车辙的主要因素有日最高温度、日辐射量、日最低温度、轮胎压力以及荷载作用次数. 最后给出了反映温度和交通特性的沥青路面短期车辙预估模型,该模型可以用于车辙的预估和预警.

关键词:短期车辙;沥青路面;ABAQUS

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