

# Calculation of effective temperature for pavement rutting using numerical simulation methods

Zhu Tanyong Ma Tao Huang Xiaoming

(School of Transportation, Southeast University, Nanjing 210096, China)

**Abstract:** In order to predict the long-term rutting of asphalt pavement, the effective temperature for pavement rutting is calculated using the numerical simulation method. The transient temperature field of asphalt pavement was simulated based on actual meteorological data of Nanjing. 24-hour rutting development under a transient temperature field was calculated in each month. The rutting depth accumulated under the static temperature field was also estimated and the relationship between constant temperature parameters was analyzed. Then the effective temperature for pavement rutting was determined based on the rutting equivalence principle. The results show that the monthly effective temperature is above 40 °C in July and August, while in June and September it ranges from 30 to 40 °C. Rutting development can be ignored when the monthly effective temperature is less than 30 °C. The yearly effective temperature for rutting in Nanjing is around 38.5 °C. The long-term rutting prediction model based on the effective temperature can reflect the influences of meteorological factors and traffic time distribution.

**Key words:** transient temperature field; long-term rutting; effective temperature; numerical simulation; finite element method

**DOI:** 10.3969/j.issn.1003-7985.2016.03.017

Rutting caused by repeated loads at high temperature is a typical distress in asphalt pavement. It is the accumulation of irrecoverable deformation mainly in the asphalt layer, which not only reduces the service life of the asphalt pavement, but also leads to serious safety issues for road users<sup>[1-2]</sup>.

The temperature distribution in asphalt pavement has significant effects on the permanent deformation characteristics of the asphalt layer, owing to the temperature susceptibility of asphalt concrete<sup>[3]</sup>. Mainly three types of methods are used to evaluate the influence on pavement rutting caused by the combination of temperature variation

and traffic loads. The first method is to calculate the accumulated deformation caused by varying traffic loads under complex environmental conditions, which requires a great number of tests and weather data<sup>[4]</sup>. This method is complicated, since it needs an accurate database of the pavement temperature field, which is not yet established in China<sup>[5-6]</sup>. The second method is to predict the rutting development based on a representative temperature calculated as the average pavement temperature at a certain depth<sup>[7-8]</sup>. The main disadvantage of this method is that the temperature at a certain depth cannot reflect the actual distribution of pavement temperature and the induced error is difficult to estimate. The third method is to employ the conception of effective temperature for pavement rutting. According to Ref. [9], the effective temperature for pavement rutting is defined as a single test temperature at which an amount of permanent deformation will occur equivalent to that measured by considering each season separately throughout the years. Compared with the first method, the application of effective temperature is greatly simplified and can reflect the influence caused by meteorological factors as well.

This paper aims to propose a numerical method to calculate the effective temperature for pavement rutting, taking Nanjing as an example. Based on actual meteorological data of Nanjing, a numerical model was established to simulate the short-term (24 h) temperature field of asphalt pavement in each month. The short-term behavior of pavement rutting was simulated considering continuous temperature variation and traffic time distribution. Then the monthly effective temperature for rutting was determined by comparing the rutting depth calculated from both static and transient temperature fields based on the rutting equivalence principle. Furthermore, the yearly effective temperature was calculated using the same method. The long-term (15 years) rutting prediction model was established to estimate the rutting development in the service life.

## 1 Approaches and Parameters for Rutting Simulation

### 1.1 Calculation model

The selected pavement structure, as shown in Fig. 1, is the typical structure of highways in Jiangsu Province, China. To optimize the calculation precision and efficien-

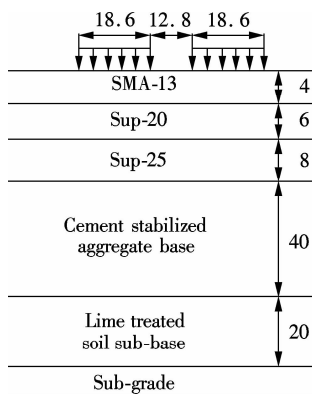
**Received** 2015-12-03.

**Biographies:** Zhu Tanyong (1989—), male, graduate; Huang Xiaoming (corresponding author), male, doctor, professor, huangxm@seu.edu.cn.

**Foundation items:** The National Natural Science Foundation of China (No. 51378121), the Fok Ying Tung Education Foundation (No. 141076), the Scientific Innovation Research of College Graduates in Jiangsu Province (No. KYLX\_0164).

**Citation:** Zhu Tanyong, Ma Tao, Huang Xiaoming. Calculation of effective temperature for pavement rutting using numerical simulation methods[J]. Journal of Southeast University (English Edition), 2016, 32 (3): 362 – 367. DOI: 10.3969/j.issn.1003-7985.2016.03.017.

cy, the finite element model was defined as 3.75 m in width and 3 m in depth with partial meshing and a creep tolerance of  $5 \times 10^{-4}$ .



**Fig. 1** Pavement structure (unit: cm)

## 1.2 Calculation parameters

### 1.2.1 Thermal parameters

Due to the fact that the thermal behavior of asphalt concrete changes little with their types, the thermal parameters of structural layers are shown in Tab. 1<sup>[10]</sup>. The meteorological data of Nanjing is presented in Tab. 2, the data refers to the Chinese database of natural resources.

### 1.2.2 Mechanics parameters

Because the pavement rutting mainly occurs in the asphalt layer, the dynamic creep test and compressive resilience modulus test were conducted on different types of asphalt concrete at various testing temperatures. The Bailey-Norton creep law is widely used to analyze the permanent deformation, in which the creep strain is a function of time, temperature and stress level<sup>[10]</sup>. The creep model is shown as follows:

**Tab. 1** Thermal parameters of temperature field analysis

Parameters	Asphalt layers	Cement stabilized aggregate base	Lime treated soil subbase	Subgrade
Density $\rho/(\text{kg} \cdot \text{m}^{-3})$	2 300	2 200	2 100	1 800
Thermal conductivity $k/(\text{J} \cdot (\text{m} \cdot \text{h} \cdot ^\circ\text{C})^{-1})$	4 680	5 616	5 148	5 616
Thermal capacity $C/(\text{J} \cdot (\text{kg} \cdot ^\circ\text{C})^{-1})$	924.9	911.7	942.9	1 040
Solar radiation absorptivity $a_s$		0.90		
Pavement emissivity $\varepsilon$		0.81		
Heat convection coefficient $h_c/(\text{W} \cdot (\text{m}^2 \cdot ^\circ\text{C})^{-1})$		$(3.7v_w + 9.4)^*$		
Absolute zero $T_z/^\circ\text{C}$		-273		
Stefan-Boltzmann constant $\sigma/(\text{J} \cdot (\text{h} \cdot \text{m}^2 \cdot \text{k}^4)^{-1})$		$2.041\ 092 \times 10^{-4}$		

Note: \*  $v_w$  is the wind speed, m/s.

**Tab. 2** Average values of meteorological data in 30 years (Nanjing)

Month	1	2	3	4	5	6	7	8	9	10	11	12
Daily average air temperature/ $^\circ\text{C}$	2.5	4.4	9.1	16.0	21.5	25.6	29.2	28.8	23.9	18.0	10.9	4.7
Daily maximum air temperature/ $^\circ\text{C}$	10.9	13.4	19.1	24.7	27.8	31.2	35.6	35.3	29.6	23.2	17.7	12.7
Daily minimum air temperature/ $^\circ\text{C}$	-5.9	-4.6	-0.8	7.2	15.2	20.1	22.8	22.3	18.3	12.7	4.1	-3.3
Daily solar radiation volume/ $(\text{MJ} \cdot \text{m}^{-2})$	10.4	13.9	16.5	23.3	25.7	22.9	26.3	25.1	24.3	18.0	13.2	10.4
Daily effective sunlight hour/h	7.1	6.9	7.2	8.4	9.3	9.8	10.7	11.5	8.7	9.1	7.8	7.5
Daily average wind speed/ $(\text{m} \cdot \text{s}^{-1})$	2.4	2.7	3.0	2.8	2.7	2.7	2.6	2.7	2.4	2.2	2.3	2.3

$$\varepsilon_{\text{cr}} = Aq^n t^m \quad (1)$$

where  $q$  is the stress level;  $t$  is the loading time;  $A$ ,  $n$  and  $m$  are the regression parameters in the creep model. The regression parameters were determined from creep deformation curves measured by dynamic creep tests under different testing temperatures. The testing temperatures range from 20 to 60  $^\circ\text{C}$  at the interval of 10  $^\circ\text{C}$ . The typical recommended parameters for structural layers below the asphalt layer are shown in Tab. 3. The parameters  $A$ ,  $n$  and  $m$  for SMA-13, Sup-20 and Sup-25 mixtures under different temperatures are shown in Tab. 4.

**Tab. 3** Structural parameters of base and subgrade

Structural layer	Resilient modulus $E/\text{MPa}$	Poisson ratio $\mu$
Cement stabilized aggregate base	1 200	0.2
Lime treated soil subbase	300	0.3
Subgrade	45	0.4

## 2 Results and Discussion

### 2.1 Temperature field

Fig. 2 plots the transient temperature fields in 24 h un-

**Tab. 4** Creep and elastic parameters of asphalt concretes

Asphalt mixture	Temperature/°C	A	n	m	Resilient modulus E/MPa	Poisson ratio $\mu$
SMA13	20	$6.536 \times 10^{-11}$	0.937	-0.592	870	0.25
	30	$3.325 \times 10^{-9}$	0.862	-0.587	620	0.30
	40	$1.446 \times 10^{-8}$	0.792	-0.577	554	0.35
	50	$1.390 \times 10^{-6}$	0.414	-0.525	530	0.40
	60	$1.464 \times 10^{-5}$	0.336	-0.502	526	0.45
Sup-20	20	$4.580 \times 10^{-11}$	0.944	-0.596	910	0.25
	30	$2.461 \times 10^{-9}$	0.796	-0.585	752	0.30
	40	$3.673 \times 10^{-8}$	0.773	-0.570	600	0.35
	50	$4.802 \times 10^{-6}$	0.595	-0.532	440	0.40
	60	$7.778 \times 10^{-5}$	0.384	-0.441	380	0.45
Sup-25	20	$4.590 \times 10^{-11}$	0.922	-0.581	1 031	0.25
	30	$3.461 \times 10^{-9}$	0.859	-0.576	900	0.30
	40	$1.956 \times 10^{-8}$	0.830	-0.562	710	0.35
	50	$1.200 \times 10^{-6}$	0.322	-0.522	500	0.40
	60	$3.755 \times 10^{-5}$	0.210	-0.418	390	0.45

der different weather conditions in each month. The pavement temperature fluctuates with the periodic diurnal temperature and solar radiation. According to the temperature variation curves at different depths of the pavement structure, the maximum temperature appears at the road surface. The amplitude of the temperature variation curve decreases gradually with the increase in the depth of the pavement structure. Due to the time effect of heat conduction, the temperature response is relatively lagging behind as the pavement depth increases. With the enhancement of the solar radiation in the morning, the pavement temperature grows over time, and the maximum temperature of the road surface appears around two o'clock in the afternoon. After the intensity of solar radiation reaches the maximum, the temperature in the pavement surface begins to drop, while the internal temperature of the pavement structure continues to increase. In the evening, without solar radiant heat, pavement heat transfers to air due to the thermal balance. Before dawn, temperatures at various depths of pavement structure draw closer.

## 2.2 Rutting development

The calculation results of the temperature field are employed in the rutting model to simulate the short-term rutting development in each month. The calculation time of the creep model is the total time of traffic loads which can be calculated by multiplying the pulse width time of repeated loads by the loading repetitions. When the design running speed is 80 km/h, the duration of each axle load is  $0.008\ 64\ \text{s}^{[10]}$ . The loading conditions are used as shown in Tab.5.

Typically, the traffic volume in the actual expressway

is not evenly distributed, and the distribution of the daily traffic volume is usually depicted as shown in Fig. 3, which is similar to actual traffic distribution.

Assuming that  $5 \times 10^5$  axle loading repetitions are applied on the asphalt pavement in 24 h, the accumulated loading time in each day is 4 320 s in total. The typical 24-hour rutting development of each month is plotted in Fig.4. Since rutting mainly occurs at high temperatures, the accumulation curves of permanent deformation from December to March are omitted from discussions. Rutting distress is extremely serious in July and August, which tallies with the actual situation. A certain amount of permanent deformation also occurs in June. Therefore, proper preventive measures should be taken to control the development of rutting before summer arrives.

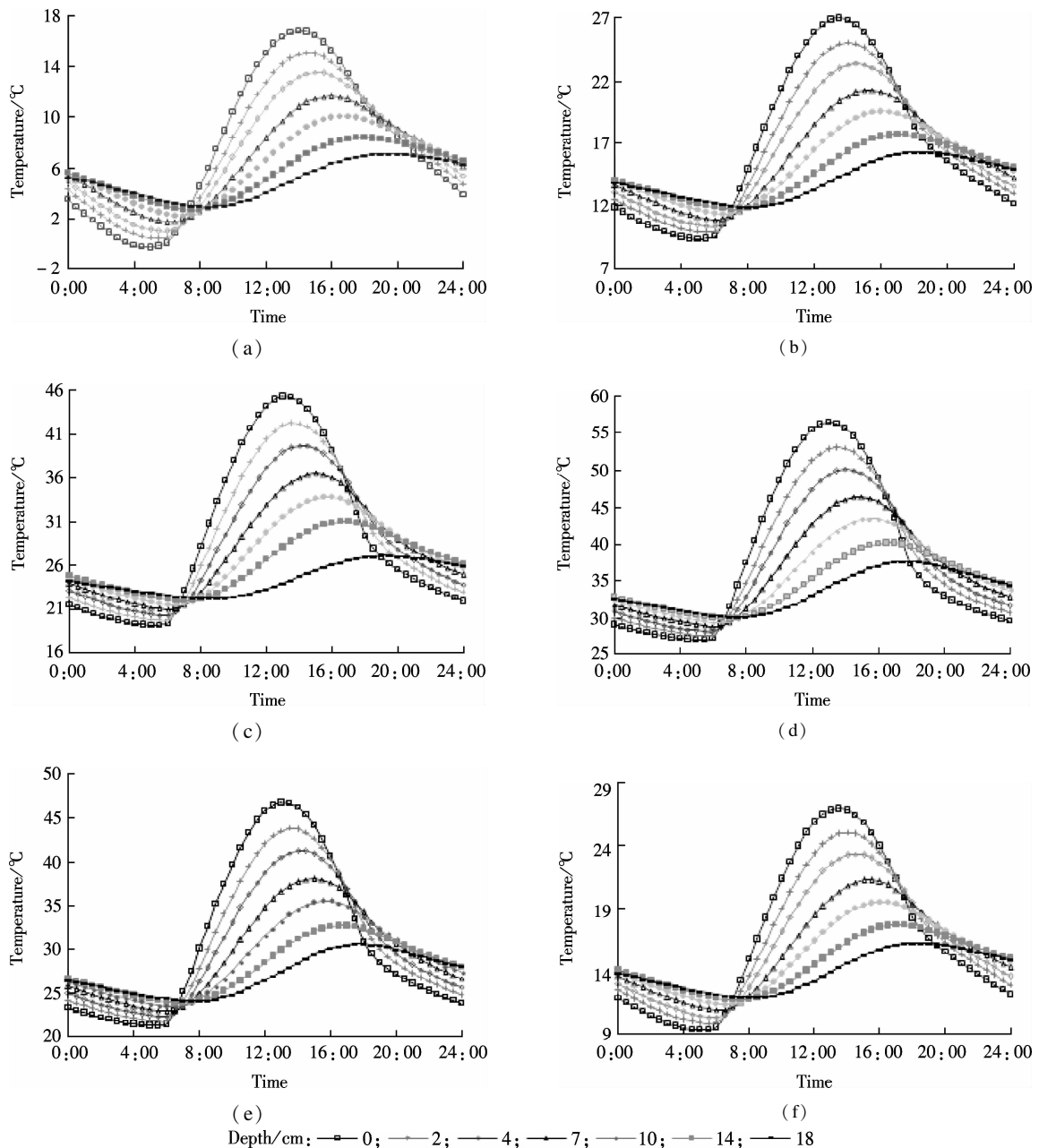
As shown in Fig. 4, before 8:00 in the morning, the rutting depth is comparatively slight due to the low temperature and light traffic volume. From 8:00 to 12:00, as the temperature and traffic volume rise, pavement rutting begins to accelerate at a low speed. Rutting mainly occurs from 12:00 to 17:00, owing to the high temperature and heavy traffic volume in the afternoon. After 18:00, the rutting depth almost remains stable until the next morning.

## 2.3 Monthly effective temperature for pavement rutting

Rutting models were built on constant parameters of the pavement temperature (20, 30, 40, 50, 60 °C) under the same loading conditions in addition, and the calculation results are presented in Fig. 5. The results show that

**Tab. 5** Loading conditions used for rutting prediction

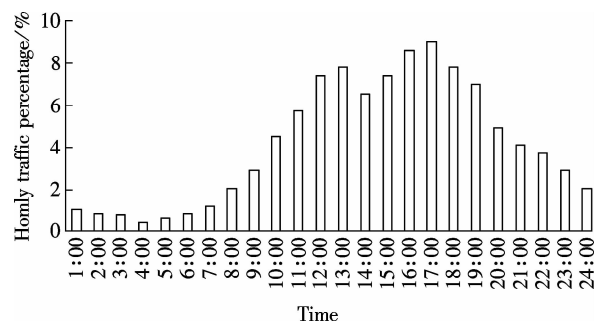
Load parameters	Running speed /(km · h <sup>-1</sup> )	Loading time /10 <sup>-3</sup> s	Tire-pavement contact width/cm	Tire-pavement contact length/cm	Axial load /kN	Contact pressure /MPa
Value	80	8.64	18.6	19.2	100	0.7



**Fig. 2** Temperature variation curves at various depths of asphalt pavement. (a) January; (b) March; (c) May; (d) July; (e) September; (f) November

the rutting depth is a power function of temperature. The accumulation of pavement rutting accelerates with the increase in temperature. In this paper, the monthly effective temperature for pavement rutting is a single temperature for a month at which the amount of permanent deformation will occur equivalent to that measured in the transient temperature field throughout the month. Based on the relationship between the pavement temperature and the rutting depth, the monthly effective temperature can be back-calculated by substituting the rutting depth calculated under the transient temperature field into the equation presented in Fig. 5. The calculation results of monthly effective temperatures are presented in Fig. 6. Owing to the slight development of pavement rutting at the tem-

perature of 20 °C, the effective temperatures in winter are set to be 20 °C in Fig. 6.



**Fig. 3** Daily traffic distribution

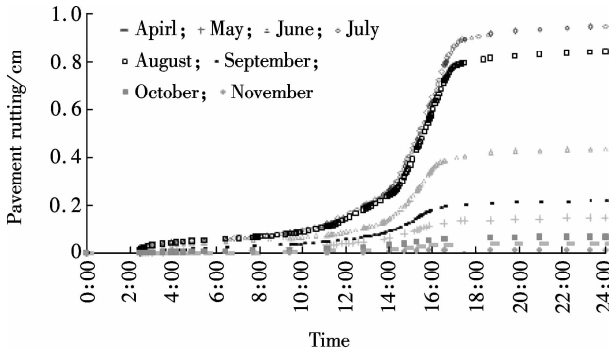


Fig. 4 24-hour rutting development in each month

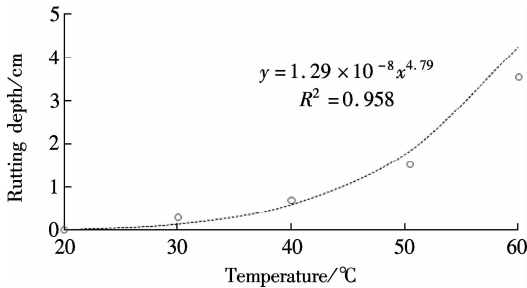


Fig. 5 Relationship between rutting depth and constant temperature in pavement

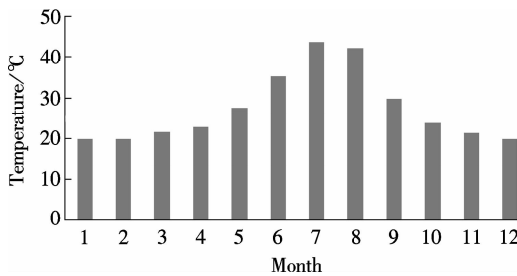


Fig. 6 Monthly effective temperature for pavement rutting

As shown in Fig. 6, the effective temperature in June and July is higher than 40 °C, while in May and September, it ranges from 20 to 30 °C. The value of monthly effective temperature can reflect precisely the severity of rutting distress in each month. By comparing the monthly effective temperature with the 24-hour rutting depth in each month, the risk of rutting development can be ignored when the effective temperature is lower than 30 °C.

## 2.4 Yearly effective temperature for pavement rutting

To estimate the yearly effective temperature for pavement rutting, monthly effective temperatures are utilized to simulate long-term rutting development. In China, the design life of pavement structure is 15 years. The predicted traffic volume of an expressway during its lifespan is shown in Tab. 6. According to Tab. 6, after the expressway opens to traffic, the traffic volume grows rapidly by approximately 8% a year. Along with the increasing service life, the traffic growth slows down. At the end of the design term, the traffic growth falls to an annual rate

of 5%. Although the yearly traffic volume distribution is not evenly distributed due to different seasons, the variance of traffic distribution in each month is ignored to simplify the long-term rutting model. The equivalent single axle load is  $2.129 \times 10^7$  times, and the corresponding loading time is 183 946 s in total.

Tab. 6 Predicted traffic volume in service life

Year	Load repetition/ $10^4$	Year	Load repetition/ $10^4$
1	84	9	150
2	91	10	161
3	98	11	169
4	106	12	177
5	114	13	186
6	122	14	195
7	131	15	205
8	140		

The yearly rutting development pattern is shown in Fig. 7, pavement rutting reveals ladder-like increases in each year. Rutting generated in July and August accounts for the largest proportion, which is consistent with the reality. Based on the monthly effective temperature, a 15-year rutting depth can be calculated in the rutting model as shown in Fig. 8. For a newly opened expressway, the rutting depth accumulates rapidly because asphalt concrete is in the initial densification stage under traffic loads. After being open to traffic for approximately 5 years, permanent deformation develops slowly at an almost constant increase rate every year. By comparing rutting depth developed under different constant temperature conditions, the yearly effective temperature for pavement rutting can be determined. As shown in Fig. 8, the amount of rutting depth accumulated under the constant temperature of 38.5 °C is equivalent to that calculated from the transient temperature field throughout the lifespan. Therefore, according to the definition, the temperature of 38.5 °C can be used as the effective temperature for pavement rutting in the city of Nanjing. However, according to the current specification of asphalt pavement design, the rutting depth should be lower than 1.5 cm during service life. Therefore, the predicted rutting depth does not meet the design requirements in China.

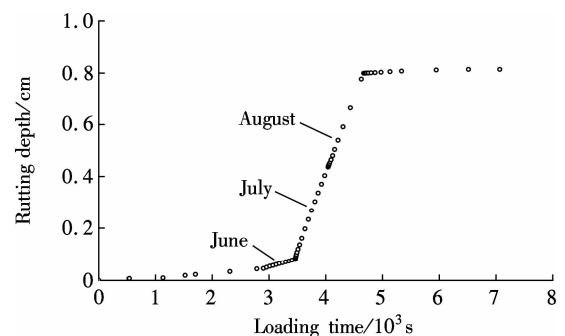


Fig. 7 Rutting development in the first year

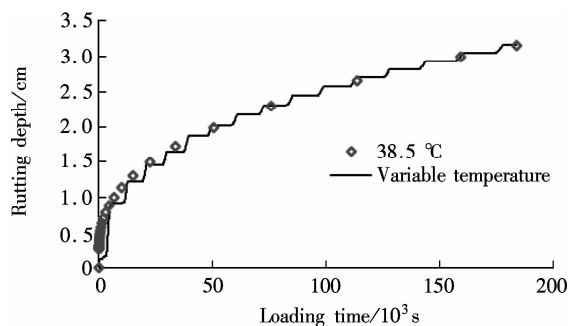


Fig. 8 Rutting development over 15 years under static and transient temperature fields

### 3 Conclusions

The rutting simulation model considering temperature variation and traffic time distribution was established through using ABAQUS software. Effective temperature for pavement rutting was calculated to predict the long-term rutting of asphalt pavement. Based on the calculation results, some major conclusions can be drawn as follows:

1) The monthly effective temperature is above 40 °C in July and August, while in May and September, it ranges from 30 to 40 °C. Values of monthly effective temperatures for rutting reflect precisely the severity of rutting distress. The rutting development can be ignored when the monthly effective temperature is lower than 30 °C.

2) The development of pavement rutting reveals ladder-like increases each year. For a newly opened expressway, the rutting depth accumulates rapidly in the first 5 years, but the accumulation of permanent deformation begins to slow down after that.

3) The yearly effective temperature for pavement rutting in Nanjing is about 38.5 °C. It should be noted that only the weather and traffic conditions in Nanjing is considered in this research. Further investigation is needed to study the effective temperature for rutting in other places.

### References

- [1] Huang X M, Zhang Y Q. A new creep test method for asphalt mixtures [J]. *Road Materials and Pavement Design*, 2010, **11**(4): 969–991. DOI:10.3166/rmpd.11.969-991.
- [2] Xu T, Wang H, Li Z D, et al. Evaluation of permanent deformation of asphalt mixtures using different laboratory performance tests [J]. *Construction and Building Materials*, 2014, **53**: 561–567. DOI:10.1016/j.conbuildmat.2013.12.015.
- [3] Marasteanu M, Clyne T, McGraw J, et al. High-temperature rheological properties of asphalt binders [J]. *Transportation Research Record*, 2005, **1901**: 52–59. DOI: 10.3141/1901-07.
- [4] Sun L J. *Asphalt pavement structural behavior theory* [M]. Beijing: China Communications Press, 2005. (in Chinese)
- [5] Yao Z K. Study on designing indexes and parameters for asphalt pavement [R]. Shanghai: School of Transportation Engineering, Tongji University, 2008. (in Chinese)
- [6] Zou X L, Tan Z M. Study on structural design procedure of asphalt pavements [R]. Shanghai: School of Transportation Engineering, Tongji University, 2011. (in Chinese) [6]
- [7] Tan Z M, Yu X H. Fatigue equivalent temperature for asphalt pavements [J]. *Journal of Tongji University (Natural Science)*, 2013, **41**(2): 197. (in Chinese)
- [8] Yu X H. Study on equivalent temperatures of asphalt pavement [D]. Shanghai: School of Transportation Engineering, Tongji University, 2011. (in Chinese)
- [9] Cominsky R J, Huber G A, Kennedy T W, et al. The superpave mix design manual for new construction and overlays [R]. Washington DC, USA: National Research Council, 1994.
- [10] Huang X M, Yang Y W, Li H, et al. Asphalt pavement short-term rutting analysis and prediction considering temperature and traffic loading conditions [J]. *Journal of Southeast University (English Edition)*, 2009, **25**(3): 385–390.

## 基于数值模拟方法的沥青路面车辙等效温度计算

祝谭雍 马 涛 黄晓明

(东南大学交通学院, 南京 210096)

**摘要:** 为了有效地预测沥青路面长期车辙, 提出了运用数值模型计算车辙等效温度的方法. 根据南京市实际气象数据模拟了沥青路面瞬态温度场, 并在此基础上计算了一年中各月份气候条件下连续 24 h 的车辙发展情况. 分析了稳态温度场下车辙深度与路面温度之间的关系, 并基于车辙等效原理获得了沥青路面车辙等效温度. 结果显示: 七、八月份的车辙等效温度超过 40 °C, 六月、九月则在 30~40 °C 之间, 当车辙等效温度不足 30 °C 时, 车辙发展可以忽略不计. 南京全年的车辙等效温度约为 38.5 °C, 基于车辙等效温度的概念, 应用长期车辙预估模型可以反映出气象状况和交通条件对于车辙的影响.

**关键词:** 瞬态温度场; 长期车辙; 等效温度; 数值模拟; 有限元方法

**中图分类号:** U416.2