Scientific Research Publishing

World Journal of Engineering and Technology, 2019, 7, 48-57
http://www.scirp.org/journal/wjet
ISSN Online: 2331-4249
ISSN Print: 2331-4222

Finite Element Analysis of Thiopave Modified Asphalt Pavement

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How to cite this paper: Wang, X.S., Wang, J.J. and Qiu, Y.J. (2019) Finite Element Analysis of Thiopave Modified Asphalt Pavement. *World Journal of Engineering and Technology*, 7, 48-57.
https://doi.org/10.4236/wjet.2019.72B006

Received: April 15, 2019
Accepted: May 14, 2019
Published: May 17, 2019

Abstract

With the aim of studying the anti-rutting performance of Thiopave modified asphalt mixture applied to the upper layer of pavement, the strain-hardening creep model in ABAQUS finite element software was used to analyze the rutting under the condition of introducing temperature field. Compared with the calculation results of the rutting of ordinary asphalt pavement, it is found that Thiopave can improve the temperature sensitivity of asphalt mixture. With the increase of temperature, the rutting change of Thiopave modified asphalt pavement is smaller than that of ordinary asphalt. Thiopave also has a certain degree of improvement in the fatigue resistance of asphalt pavements, which can be applied to sections with high traffic volume in high temperature areas.

Keywords

Thiopave Modified Asphalt Mixture, Temperature Field, ABAQUS Finite Element, Temperature Sensitivity, Fatigue Resistance

1. Introduction

Due to the warming of the climate, the heavy load of vehicles has caused the rut damage of asphalt pavement more and more serious. It is especially important to find a road material with excellent performance against rutting. Yang Xiwu, Das *et al.* [1] [2] conducted a comprehensive study on the road performance and factors of sulfur-modified asphalt mixture, and found that SEAM (Sulphur Extended Asphalt Modifier, called sulfur diluted asphalt modifier) can improve high-temperature stability of asphalt mixture. As an upgraded alternative to SEAM [3], Thiopave, as an upgraded alternative to SEAM, supplemented with a small account of plasticiser and viscosity reducer, may further enhance the strength and durability of sulfur-modified asphalt mixture [4]. Thiopave modifier has a significant improvement on the high temperature stability of asphalt mixtures. At present, the numerical simulation of rut on asphalt pavement has achieved certain results, but there are few studies on the anti-rutting performance of Thiopave modified asphalt mixture applied to the upper layer of pavement. The strain-hardening creep model in ABAQUS finite element software was used to analyze the rutting under the condition of introducing temperature field in this paper. Under the repeated loading of the vehicle, study the influence law of temperature, load size and repeating times to the deformation of asphalt pavement. Explore the anti-rutting deformation performance of Thiopave asphalt mixture, make a contrast to ordinary asphalt pavement. And provide a certain technical reference for its practical application.

2. Establish Rutting Calculation Model

2.1. Pavement Structure

Calculating the rutting by the use of ABAQUS finite element software, it is assumed that the materials of each layer are uniform and isotropic, the asphalt surface layer conforms to the viscoelastic constitutive relation, and the other layers all satisfy Hooke's law [5]. The three-dimensional model is simplified to two-dimensional, and the width and depth of the road model are defined by finite size, 3.75 m and 3 m respectively. The layered-form of the semi-rigid base pavement is shown in **Figure 1**. When the upper layer adopts AH-70 ordinary asphalt mixture, the pavement structure is ordinary asphalt pavement structure, and the mesh division adopts CPE8R (eight-node bidirectional secondary plane strain quadrilateral element, reduction integral), and the unit finite element model is shown in **Figure 2**.

2.2. Constitutive Model

The strain-hardening creep model in ABAQUS finite element is adopted to analyse rutting calculation. The constitutive equation [5] is Equation (1).

$$\dot{\varepsilon}_{cr} = (Aq[(m+1)\bar{\varepsilon}_{cr}]^{m})^{\frac{1}{m+1}} \tag{1}$$

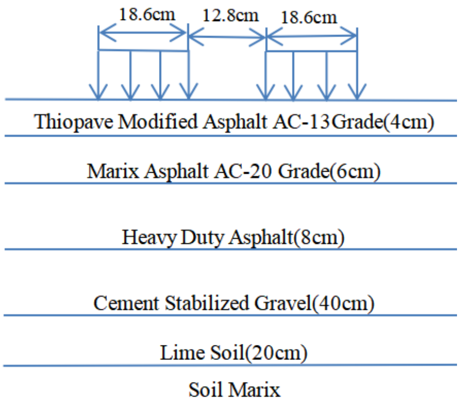


Figure 1. Pavement structure.

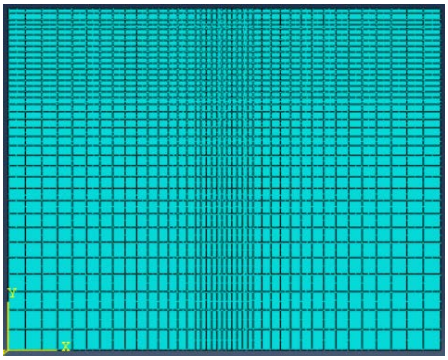


Figure 2. Finite element model.

where $\dot{\varepsilon}_{cr}$ is uniaxial equivalent creep strain rate; $\bar{\varepsilon}_{cr}$ is uniaxial equivalent creep strain; q is stress, MPa A, n, m are Model parameters, determined by indoor material creep test generally, A, $n > 0$, $-1 < m \leq 0$.

2.3. Model Parameter

It's assumed that the material parameters of soil foundation, lime soil and cement stabilized macadam base remain constant under different temperature. Anti-pressure rebound test and creep test were performed to determine the elastic and creep parameters of asphalt mixture [6]. The specific values are shown in **Table 1**, and the thermal parameters of the materials are shown in **Table 2**.

2.4. Boundary Conditions and Load Definition

The left and right sides of the model are set to zero displacement in the X direction, and the bottom boundary of model is fixed, as shown in **Figure 3**. Simplify vehicle load form from double-circle uniform load to double-round rectangular uniform load. The axle load takes the standard axle load BZZ-100 in the current road asphalt pavement design specification JTG D50-2017, Tire grounding pressure is 0.7 MPa. The rectangle has a length of 19.2 cm and a width of 18.6 cm. The distance between center of the two axes is 314 mm, as shown in **Figure 4**.

In this study, the effect of repeated loading of asphalt pavement rutting is simplified to a loading step to reduce the time of finite element analysis calculation, the calculation formula is as shown in Equation (2).

$$t = \frac{0.36\mathrm{NP}}{n_w pBv} \tag{2}$$

where t is Wheel load cumulative action time; N is times of wheel load; P is Vehicle axle weight; n_w is number of rounds of the axle; p is tire ground pressure; B is tire ground width; v is traffic speed. The load parameters can be obtained according to formula (2), as shown in **Table 3**.

2.5. Cite Temperature Field

Affected by the natural environment, the temperature of the road surface fluctuates greatly, while the deep sub-grade fluctuates slightly, it can be considered

Table 1. Material elastic parameters and creep parameters.

Material	Temperature (˚C)	Material Elastic Parameters		Creep Parameter		
		Compressive Resilience modulus/E (MPa)	Poisson's Ratio/μ	A	n	m
Thiopave modified asphalt AC-13 grade	20	1180	0.25	2.235E−11	0.905	−0.723
	30	985	0.30	9.877E−10	0.816	−0.658
	40	824	0.35	9.653E−09	0.698	−0.634
	50	778	0.40	8.558E−07	0.349	−0.586
	60	769	0.45	9.564E−06	0.251	−0.559
AC-20 Grade	20	910	0.25	4.580E−11	0.944	−0.596
	30	752	0.30	2.461E−09	0.796	−0.585
	40	600	0.35	3.673E−08	0.773	−0.570
	50	440	0.40	4.802E−06	0.595	−0.532
	60	380	0.45	7.778E−05	0.384	−0.441
Sup-25 grade	20	1031	0.25	4.590E−11	0.922	−0.581
	30	900	0.30	3.461E−09	0.859	−0.576
	40	710	0.35	1.956E−08	0.830	−0.562
	50	500	0.40	1.200E−06	0.322	−0.522
	60	390	0.45	3.755E−05	0.210	−0.418
Cement Stabilized Gravel	-	1200	0.20	-	-	-
Lime soil	-	300	0.30	-	-	-
Soil matrix	-	45	0.35	-	-	-

Table 2. Material thermal property parameter

parameter	AC Sup	CTB	LS	SG
Thermal conductivity K (J/(m·h·˚C))	4680	5616	5148	5616
Density ρ (kg/m^3)	2300	2200	2100	1800
Heat capacity/C (J/(kg·˚C))	924.9	911.7	942.9	1040.0
Solar radiation absorption rate α_s	0.90			
Road Reflectance/ε	0.81			
Absolute zero value/TZ (˚C)	−273			
Stefan-Boltzmann constant σ/J/(h·m^2·K^4)	2.041×10^{-4}			

that the temperature value remain constant [7]. According to the principle of heat transfer, the change of the road-surface heat is mainly affected by the short-wave radiation of the sun, the long-wave radiation of the road surface and

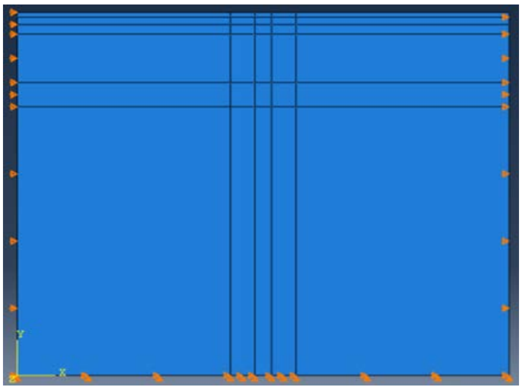


Figure 3. Boundary conditions.

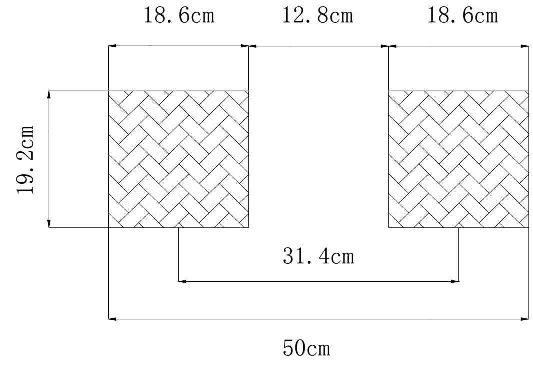


Figure 4. Rectangular uniform load.

Table 3. Rutting calculation model load parameters.

Tire Grounding Width/(cm)	18.6	Driving Speed (km/h)	80
Axle Load (KN)	100	Tire Grounding length (cm)	19.2
Ground Pressure (MPa)	0.7	Single Loading Time (s)	0.008641
Cumulative Standard Axle Load (Million times)	50	Total Loading Time (s)	4320

the atmosphere, and the heat convection [8]. The FILM and DFLUX subroutines in the ABAQUS software are applied to analyze solar radiation and road surface thermal convection exchange processes respectively, and atmospheric temperature is used to determine temperature field boundary conditions, establish transient and steady state analysis steps, and obtain asphalt surface temperature field files [9] [10]. In the rutting calculation model, owing to the elastic parameters and creep parameters are both take temperature variation into consideration, the asphalt temperature field file is imported into the corresponding analysis step to calculate the rutting [11].

3. Analysis of Factors Affecting Deformation of Asphalt Pavement

3.1. The influence of Temperature on Asphalt Mixture

The influence of temperature on asphalt mixture cannot be ignored. The increase of temperature will cause a rapid reduction of dynamic stiffness modulus of asphalt mixture in a short time. Accordingly, the ability of resistance to rutting deformation of pavement reduces, and the deformation expands gradually which will eventually lead to the damage of pavement. The permanent deformation under high temperature of asphalt mixture is main reason for rutting. The rutting usually occurs in summer when the temperature is higher than 25˚C - 30˚C. Road surface temperature fluctuates most with the increase of atmospheric temperature. **Figure 5** shows the atmospheric temperature variation during a day in high temperature season of Guangdong city. **Figure 6** shows the temperature variation of the asphalt road surface during a day.

It can be seen from **Figure 6** that asphalt pavement surface reached 55˚C at 2:00 pm. Then take 25˚C, 35˚C, 45˚C, 55˚C as representative, study the effects of different temperatures on rutting, and the effect is shown in **Figure 7(a)**, **Figure 7(b)**.

As is shown in **Figure 7(a)**, **Figure 7(b)**, the maximum rut deformation of ordinary asphalt pavement at 55˚C is more than twice that of Thiopave modified asphalt pavement at the same load. When the temperature raised from 25˚C to 55˚C, the maximum deflection of the wheel center of the Thiopave asphalt pavement and the ordinary asphalt pavement increased by 2.65 mm and 5.97 mm, respectively. The rutting variation of Thiopave modified asphalt pavement is much smaller than that of ordinary asphalt pavement with the increase of temperature. Therefore, we can make a conclusion that Thiopave modifier may improve the rutting resistance of asphalt mixtures by reducing its temperature sensitivity.

3.2. Effect of Tire Pressure on Asphalt Pavement Rutting

Load is one of the crucial factors of the rutting deformation of asphalt pavement. The more overloaded vehicles, the more severe the deformation of the rutting is. Keep the thickness and the corresponding material of each layer constant, analyzing the rutting caused by different tire pressures under the condition at

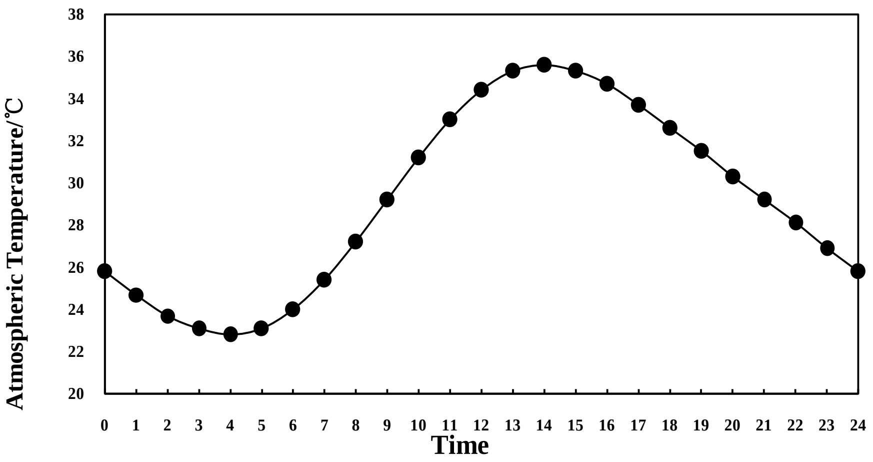


Figure 5. Atmospheric temperature variation a day.

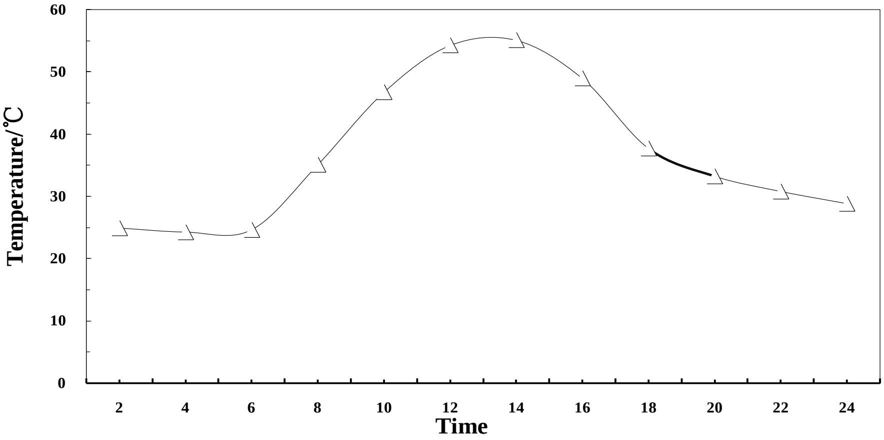


Figure 6. Pavement temperature variation a day.

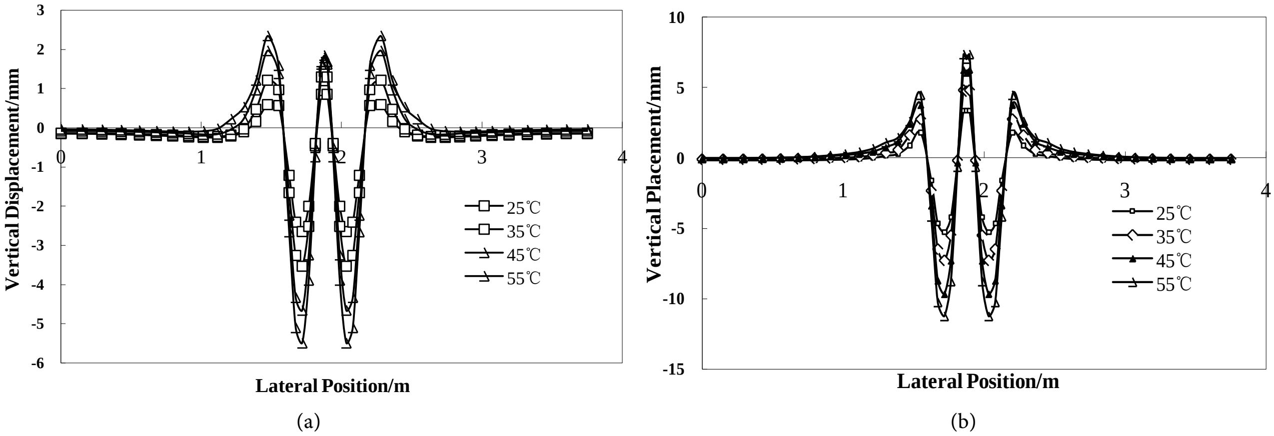


Figure 7. Vertical displacement under vary temperature. (a) Thiopave modified asphalt pavement; (b) Ordinary asphalt pavement.

500,000 times of the axle load and the atmospheric temperature was 30˚C. The results are shown in **Figure 8**.

From **Figure 8**, it can be seen that as the tire pressure increases from 0.7 MPa to 1.2 MPa, the rutting deformation of the Thiopave asphalt pavement increases from 3.7 mm to 5.2 mm, and the rutting deformation of the ordinary asphalt pavement increases from 9 mm to 12.8 mm, which means that deformation of the rut generated by Thiopave modification asphalt pavement is smaller than that of the ordinary asphalt pavement. The traffic volume has an important influence on the rutting deformation of asphalt pavement. The cumulative equivalent axis is positively correlated with the rutting deformation. Under the cyclic loads, the rutting deformation of the pavement will gradually increase. Also keep the thickness and corresponding material parameters of each layer constant, analyzing the rutting caused by different load under the condition that the axle load is 0.7 MPa and the atmospheric temperature is 30˚C. The results are shown in **Figure 9**, **Figure 10**.

It can be seen from **Figure 9** that the depth of rutting changes with the times of loading irregularly under the cyclic loading, which appears nonlinear growth.

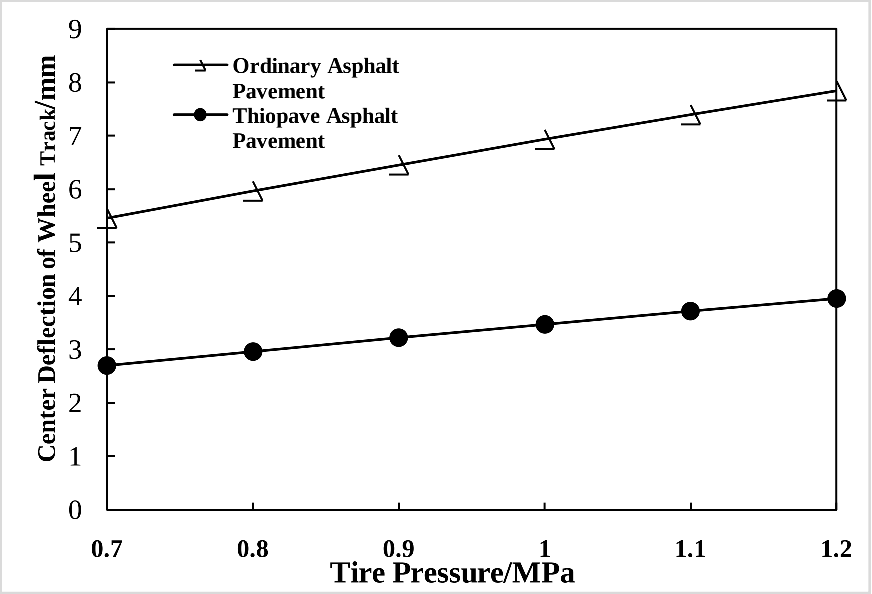


Figure 8. Maximum rut deflection under vary tire pressure.

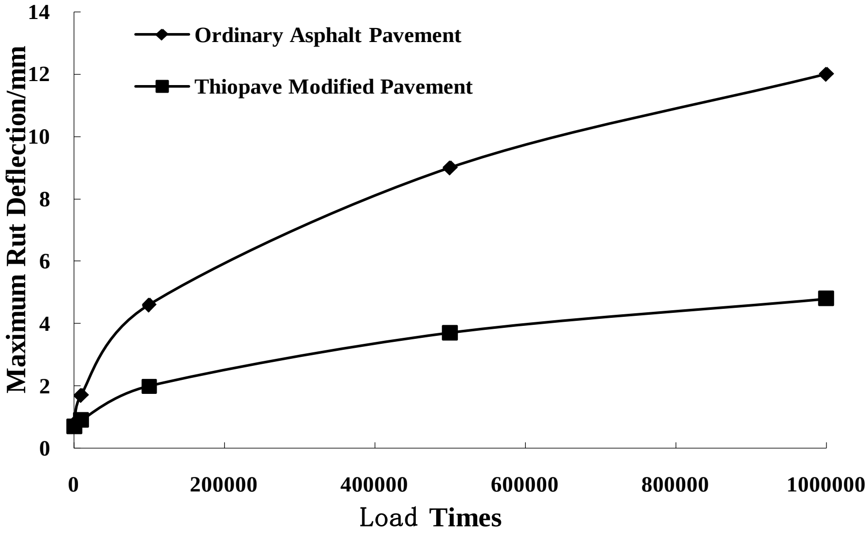
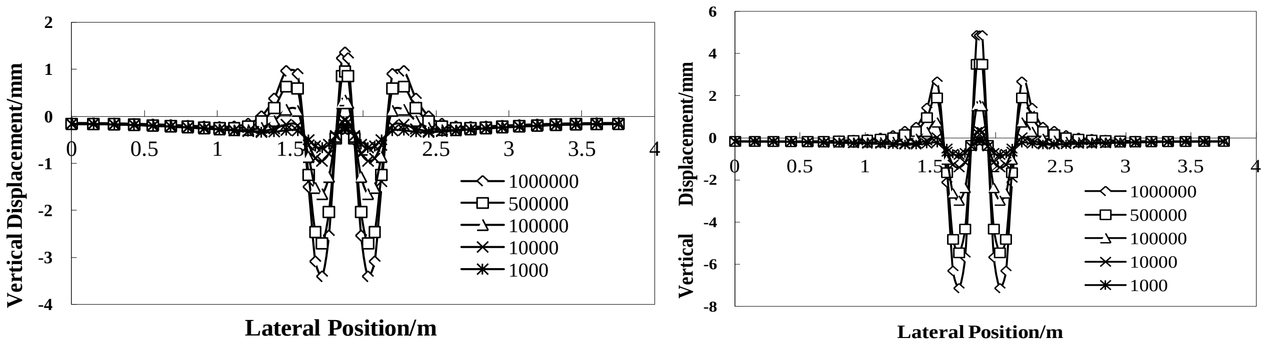


Figure 9. Rut variation under vary load times.

It can be seen from **Figure 10** that rutting deformation of pavement is small when the times of axle load less than 10,000. And the rutting deformation of Thiopave modified asphalt pavement is close to that of ordinary asphalt pavement. However, the depth of rutting increases gradually when the times of loading exceeds 10,000, a clear gap begins to emerge between two pavement structures. And the rut depth of the ordinary asphalt pavement is significantly larger than that of the Thiopave modified asphalt pavement. When the times of loading reach 1,000,000 times, the difference of the rut depth between two pavement structures reaches 7.2 mm. It can be seen from **Figure 10** that the upheaval on both sides of wheel track appears less obvious when the times of loading is less than 10,000, and the deformation of rutting mainly comes from vertical deflection.



(a) (b)

Figure 10. Vertical displacement under vary load times. (a) Thiopave modified asphalt pavement; (b) Ordinary asphalt pavement.

With the increase of the times of loading, the upheaval on both sides of the wheel track gradually increases. When the cyclic load reaches 1,000,000 times, the deflection and elevation of the Thiopave modified asphalt pavement are both smaller than that of ordinary asphalt pavement. And the amplitude of variation is also smaller than that of ordinary asphalt pavement.

4. Conclusions

a) The rutting deformation of Thiopave modified asphalt pavement increases with the increase of temperature and tire pressure, while the deformation of rutting is smaller than that of ordinary asphalt pavement.

b) In the early stage of cyclic loading, the rutting deformation of Thiopave modified asphalt pavement grew slowly and was relatively close to that of ordinary asphalt pavement. As the times of loading increases to 1,000,000 times gradually, the rutting of ordinary asphalt pavement reaches 12 mm, which is much larger than the that of Thiopave modified asphalt pavement 4.8 mm. It can be concluded that the fatigue resistance of Thiopave modified asphalt pavement is better than that of ordinary asphalt pavement. Therefore, it is recommended to use the Thiopave modified asphalt pavement on the road with large traffic volume to effectively reduce the road surface damage caused by rutting.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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