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Original scientific paper

Preparation of Low Rolling Resistance Modified Asphalt and Analysis of Its Rolling Resistance and Viscoelasticity

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Abstract: Tire tread of running vehicles generates rolling resistance with the pavement, thereby influencing energy consumption. Thus, developing low rolling resistance pavement can improve the service function of tires. Common matrix asphalt and high module binder modifier (HMB-W) was used to obtain low rolling resistance of asphalt and effectively reduce energy consumption. Its low rolling resistance performance was analyzed via internal heat-generating test, rolling resistance test, and dynamic shear rheological test. Then, a rolling resistance model was constructed to evaluate its thermal losses. Test results show that compared with styrene-butadiene-styrene (SBS) modified asphalt and its mastic, the heat generation rates of HMB-W modified asphalt and its mastic are reduced by 14.4% and 15.5%, respectively. Thus, energy loss can be effectively reduced. The generated heat quantity and power loss were reduced by 3.7% and 5%, respectively, compared with the SBS modified asphalt. In addition, the low rolling resistance is evident. HMB-W asphalt has low-temperature sensitivity and superior high-temperature stability. Under the same stress level, the complex shear module *G** of HMB-W asphalt is evidently higher than that of SBS modified asphalt. Under the same temperature condition, the energy stored is high when HMB-W asphalt goes through elastic deformation with small viscosity loss.

Keywords: low rolling resistance modified asphalt; low rolling resistance model; pavement engineering; rolling resistance; viscoelasticity

1 INTRODUCTION

Polymer modified asphalt is generally applied to existing asphalt pavement to improve the damage resistance. However, under the action of repeated load, dynamic heat generation occurs inside the modified asphalt due to the mechanical energy of vehicle load. As the temperature rises, the elasticity modulus of asphalt material is reduced, whereas the loss modulus is increased. Especially during summer, at high temperature, the elasticity loss of modified asphalt materials with high heat generation rate is serious. Viscous components are remarkably increased with easy flow and deformation, and aggregate particles experience displacement, thereby forming permanent deformation [1]. Reducing the internal heat-generating degree of modified asphalt is the key to relieving rutting problems of asphalt pavement. The use of low rolling resistance pavement generates a far-reaching effect on reducing energy consumption. Present studies on low rolling resistance mainly focus on the tire field. Specifically, rubber tires are modified through molecular structural design, and the rubber with low dynamic heat generation rate is acquired by changing or reducing its strain hysteresis based on the theory of viscoelasticity to produce low rolling resistance tires. The studies on tires are mainly based on the principle of rheology [2].

Damages of asphalt pavement, such as rutting, fatigue, and cracking, are directly related to rheological properties and viscoelasticity of asphalt [3]. Rheology is a science studying flow and deformation of time and temperature-dependent materials. In general, asphalt rheology is a science characterizing asphalt flow and deformation, including the determination and calculation of a series of asphalt viscoelasticity indexes. The studies on rolling resistance of asphalt pavement, which is the most extensively applied pavement, are still in the preliminary stage. Generally, damping characteristics and parameters of polymer materials are used to characterize the materials' ability to dissipate mechanical energy in the form of heat. This index can reflect the motion behaviour caused when the materials impede mechanical energy; it can also be used to characterize the energy dissipation degree of the polymer materials under the cyclic loading action [4]. On a pavement, 25% of the resistance borne by a running vehicle results from rolling frictional resistance; it is the power consumed by the moment of force generated by tire and pavement deformations. Pavement deformation consists of asphalt material and pavement structural deformations, which are dissipated by the mechanical energy of vehicle load in the form of internal heat generation of the material. The strain delay and energy loss of the asphalt material under sine alternating tensile stress load are primary factors leading to damping [5].

On this basis, a type of low rolling resistance asphalt was studied and developed. Its rolling resistance and elasticity were analyzed by combining internal heat-generating test. In addition, rolling resistance test and viscoelasticity test, and a rolling resistance model used to evaluate heat loss were constructed to lay a foundation for further exploring the pavement performance of its mixture.

2 STATE OF THE ART

When a vehicle is normally running on the pavement, its tires experience rolling on the pavement surface. The central symmetrical plane of tire outer edges is consistent with the rolling direction, the resistance opposite to the rolling direction is called tire rolling resistance, and the rolling resistance consists of tire deformation caused by pavement extrusion, pavement deformation occurring under loading action and tire-pavement reverse friction [6-8]. On the basis of truck fuel consumption, measurement of tire rolling resistance, and verified modelling via business software AVL-CRUISE, Laclair and Russell et al. [9-11] found that automobile fuel consumption could be saved by 4.77 lt/100 km on a secondary road and by 5.49 lt/100 km on the expressway when the rolling resistance was reduced by 1 kN. Present studies on regarding low rolling resistance pavement mainly focus on rubber tire field. Strain hysteresis of rubber is reduced, and low rolling resistance tires are produced based on the mechanical theory of viscoelasticity [12, 13]. For vehicles without a suspension system, Wang [14] established a radial spring tire-ground contact model, the time-domain model of filtered white noise pavement roughness, and energy loss model in the vehicle wheel vacant process. Then, he analyzed the energy loss caused by the wheel passing through an uneven road surface. For axle load, Jaime A. Hernandez [15] calculated the rolling resistance based on three values, namely, tire inflation pressure, temperature, and velocity. He proposed a mathematical expression via regression analysis, so as to predict the rolling resistance encountered by tires running on pavements, considering these variables.

Asphalt pavement is the most extensively applied road surface. Reducing energy consumption of pavement by investigating low rolling resistance modified asphalt has been the focus of emerging research fields on asphalt materials. Bi [16] investigated and developed low rolling resistance asphalt modifier HPT and determined the influence of different adulterate amounts on conventional indexes of modified asphalt through a series of tests. The study results showed that as the adulterate amount of HPT increased, the softening point of modified asphalt was elevated, the penetration and ductility were reduced, the viscosity was strengthened, the segregation characteristic was effectively improved, and the non-uniform dispersion phenomenon generated by SBS under high-temperature condition was relieved. Thus, SBS formed a net structure, and its performance was enhanced. If the low rolling resistance asphalt was standardized according to the I-D standard of SBS modified asphalt, then the adulterate amount of its low rolling resistance modifier HPT would be within 0.25% - 1.62%. Espinoza-Lque [17] probed the laboratory performance of two low rolling resistance modified asphalt mixtures specially designed by Denmark Road Bureau and explored their effects on reducing rolling resistance and tested their dynamic modulus. The cracking and rutting possibilities of the mixtures were evaluated via Illinois flexibility index test and Hamburg wheel track test, respectively. They found that the low rolling resistance modified asphalt mixture with low rolling resistance presented low modulus under low temperature, but high modulus under high temperature. It had higher flexibility index (*FI*) and lower permanent deformation than the matrix asphalt mixture.

At present, scholars have started studying the rolling resistance of asphalt materials. However, some researchers have investigated the damping characteristics of asphalt materials. Damping is the degree of energy loss of asphalt material under loading action, and stress-strain hysteresis is the internal cause for energy loss. Greater stress-strain hysteresis causes larger damping and energy loss, and smaller stress-strain hysteresis indicates smaller damping and energy loss [18-22]. Biligiri [23, 24] studied the damping characteristics of different pavements, collected and analyzed massive data through tests, obtained physical parameter damping of asphalt material and established the relation between phase angle and noise of pavement materials. Zhang [25] attempted to develop low-damping modified asphalt to reduce rolling resistance and internal heat generation during the automobile running process and to solve problems, such as fuel consumption and pavement damage. He also introduced loss factor, which characterized fuel consumption during automobile tire running process, into asphalt to characterize the internal heat generation and mechanical loss of asphalt materials. Four polymers with different molecular structures were selected as modifiers and combined with SBS to prepare low-damping modified asphalt. Polymer modifiers were selected through loss factor and complex modulus. The results of internal heat-generating test and rolling resistance test showed that the low-damping modifier could reduce power loss and internal heat generation of SBS modified asphalt. A microstructure analysis showed that the low-damping modifier enlarged the swelling area of the SBS phase. Thus, more light components in asphalt could fill into the SBS phase to increase the elasticity modulus of modified asphalt and reduce the internal heat generation. The results of the current studies on low rolling resistance modified asphalt have mainly involved the influence of the adulterate amount of low rolling resistance modifier on the performance of asphalt and mixture. However, few studies have probed into asphalt viscoelasticity.

To tackle the deficiencies of the existing studies, the analysis idea of rolling resistance and viscoelasticity of asphalt was proposed, that is, based on self-developed low rolling resistance modified asphalt, four different asphalt types, namely, HM[illegible]W asphalt, SBS modified asphalt, HM[illegible]W + mineral powder, and SBS modified asphalt + mineral powder were prepared. Then, internal heat-generating test and rolling resistance test were conducted. In accordance with rheological theory of pavement asphalt material and material viscoelasticity test method, the difference between low rolling resistance modified asphalt and SBS modified asphalt in terms of rheological properties was analyzed.

The remainder of this study is arranged as follows: Section 3 explains the related test materials and analysis method of the rolling resistance and viscoelasticity. Section 4 presents the result analysis of internal heat-generating test, rolling resistance test, and temperature sensitivity test. The final section summarizes the whole study and provides related conclusions.

3 METHODOLOGY

3.1 Preparation of the Low Rolling Resistance Modified Asphalt

The low rolling resistance asphalt pavement mainly modifies the rubber on the precondition of vehicle safety to relieve strain hysteresis of rubber tire and reduce the rolling resistance between the tire and the pavement. Therefore, the low rolling resistance asphalt modifies the asphalt through a certain method to mitigate pavement deformation and strain hysteresis to reduce rolling resistance. Asphalt, as common road material, has certain viscoelasticity. Asphalt is modified using several approaches to elevate the modulus of asphalt mixture and reduce the elastic deformation of pavement, its strain hysteresis is an effective means to realize low rolling resistance performance of asphalt pavement.

Hard asphalt with low penetration is considered low rolling resistance asphalt binder to elevate mixture modulus. With zero penetration and high softening point, natural asphalt is a superior material used to prepare low rolling resistance asphalt. Raw natural asphalt was selected in accordance with asphalt content and composition of four asphalt components and mineral substances of natural asphalt from different places of origin. Its particle size was reduced by unique processing methods. As a result, the surface effect of trichloroethylene undissolved particles became prominent, the specific surface area was enlarged, the surface activity was enhanced, and the particles were dispersed in asphalt through physical actions. Meanwhile, asphalt storage stability was further guaranteed through chemical stabilization. On this basis, a type of low rolling resistance modified asphalt was prepared. The concrete preparation process is presented in the following section.

The low rolling resistance modified asphalt was prepared using dispersing shearing machine and motor stirrer through a blending process. The matrix asphalt was initially heated to above 160 °C to obtain good fluidity. SBS, HPT, and extract oil were successively added at shear rate of 4000 rpm and temperature of 170 - 180 °C, and the shearing lasted 45 min. Lastly, the stabilizer was added at 180 °C and 700 rpm conditions for 150 min low-speed stirring. Then, low rolling resistance modified asphalt was acquired. In the low rolling resistance modified asphalt, the additive amounts of low rolling resistance modifier (calculated by asphalt mass), SBS, extract oil, and stabilizer were 1.5%, 4%, 5%, and 0.2%, respectively.

3.2 Conventional Performance Study on Low Rolling Resistance Modified Asphalt

The conventional performance indexes of the low rolling resistance modified asphalt, namely, penetration, ductility, softening point, density, and ageing performance were detected in accordance to the test method specified in Standard Test Methods of Bitumen and Bituminous Mixtures for Highway Engineering (JTG E20-2011). The virgin asphalt used in the study was KLMY Pen70 asphalt produced in China. Then, the results were compared with those of the conventional performance indexes of the prepared SBS modified asphalt (Tab. 1).

Table 1 Comparison of low rolling resistance modified asphalt and SBS modified asphalt

Test item		Unit	Test result		Scope for SBS modified asphalt according to standard requirement
			Low rolling resistance modified asphalt	SBS modified asphalt	
Penetration (25 °C, 5 s, 100 g)		0.1 mm	28.0	67.8	60 - 80
Softening point (25 °C)		°C	70.1	69.1	≥ 55
Ductility (5 °C, 5 cm/min)		cm	31.3	36.0	≥ 30
15 °C density		g/cm^3	1.30	[illegible].03	Measured
Flashing point		°C	278	[illegible]45	≥ 230
Elasticity recovery		%	77.7	[illegible]2.3	≥ 65
48 h Segregation		°C	1.5	2.0	≤ 2.5
After TFOT	Mass change	%	[illegible]	−0.142	≤ ±1.0
	Residual penetration ratio	%	76.0	71.7	≥ 60
	Residual ductility	cm	[illegible]3.5	24.1	≥ 20

Tab. 1 shows that:

1) The fluidity of the low rolling resistance modified asphalt was poor and the penetration was evidently lower than that of SBS modified asphalt because it was processed by modifying hard asphalt with low penetration. In addition, ductility and elasticity recovery of the low rolling resistance modified asphalt at 5 °C were reduced relatively when compared with those of SBS modified asphalt, probably ascribed to the characteristics of natural hard asphalt;

2) The comparison of the post-ageing performance indexes of the low rolling resistance modified asphalt and SBS modified asphalt showed that the residual penetration ratio and residual ductility of the low rolling resistance modified asphalt were higher than those of SBS modified asphalt. This finding indicated that the low rolling resistance modified asphalt had superior anti-ageing performance;

3) The 48 h segregation test result of the low rolling resistance modified asphalt was better than that of the SBS modified asphalt. This result suggested the favourable storage stability of the low rolling resistance modified asphalt because its main component was natural asphalt, and special processing technology was adopted.

3.3 Internal Heat-Generating Test Method

To simulate the effect of aggregate on the low rolling resistance modified asphalt, HMB-W was combined with mineral powder at a proportion of 50:50. Meanwhile, the SBS modified asphalt was combined with mineral powder at a proportion of 50:50, and then asphalt mastic was prepared. The prepared low rolling resistance modified asphalt, SBS modified asphalt, and their mastics were injected into a specially fabricated flexural and compression-type internal heat-generating test die, which was then heated at high temperature. Then, vulcanized flexural and compression-type internal heat-generating test model was used. The specimen was cylindrical with a diameter of 17.8 mm ±0.15 mm and height of 25.00 mm ±0.25 mm.

The stipulated compressive load was applied to the specimen via a balanced lever with high inertia, followed by high-frequency cyclic compression with constant amplitude. The temperature rise at the bottom of the specimen was measured using a thermocouple. This thermocouple could be used to determine heat generation situation of the specimen during the flexing process, and the cycle index was recorded when fatigue failure was generated.

After bearing a constant load, the specimen was initially compressed during the test process and the height change of the specimen was continuously tested. After the test, the permanent compressive deformation of the specimen could be calculated.

The flexural and compression-type internal heat-generating test model is shown in Fig. 1.

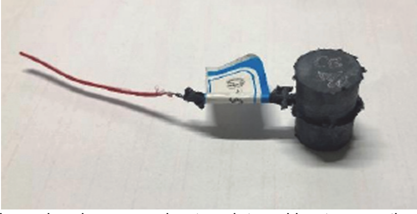


Figure 1 Flexural and compression-type internal heat-generating test model

The specimen was placed between two pressing plates fabricated using heat-insulating materials. The upper pressing plate was connected to an adjustable eccentric gear, and the oscillation frequency was generally 30 Hz ±0.2 Hz.

The load was applied through a lever placed on the cutter edge. A 24 kg weight was suspended at each of the two ends of the lever system to reduce the inherent frequency of the lever and to enlarge its rotational inertia. The lower pressing plate moved up and down relative to the lever by adjusting a calibrated vernier device. With reference marks at the pointer and lever ends, the lever system was maintained at a horizontal position during the test process.

The temperature rise at the bottom of the specimen was measured with the thermocouple installed at the center of the lower pressing plate.

3.4 Rolling Resistance Test Method

The rubber rolling resistance testing machine is a brand new test instrument designed on the basis of the original Dunlop Rotary Power Loss Machine, following the advanced modular design concept and combining computer technology servo control technology and infrared temperature measurement technology. The rubber rolling resistance testing machine is shown in Fig. 2, and its internal structure is shown in Fig. 3. The LRRMW and SBS modified asphalt were mixed into carbon black rubber using a rubber mixing mill (Fig. [illegible]), and the mixing ratio was 5% of the mass of carbon black rubber.

Figure 2 Rubber rolling resistance testing machine

The mixed rubber sample was placed into the die specially fabricated by the rubber rolling resistance testing machine in the rubber vulcanization machine. Then, it was heated at high temperature and vulcanized into a rolling resistance test model (outer diameter: 102 mm, inner diameter: 63.5 mm, and width: 19 mm).

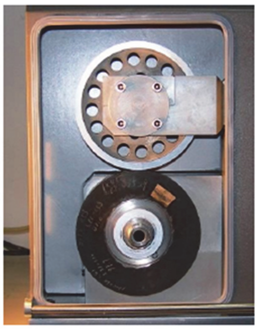


Figure 3 Internal structure of rubber rolling resistance testing machine

The circular wheel-shaped rubber specimen moving at constant speed closely contacted the steel drum under a given load to obtain a relative movement. The rubber specimen experienced deformation under the load. Then, the deformation gradually reached the maximum from point A to point B and gradually reduced to zero from point B to point C. The force of the rubber specimen during the deformation from point A to point B was higher than that during the recovery period from point B to point C due to rubber stress-strain action. This force was parallel to the load force with the same direction, namely, the power loss (J/r) of the rubber specimen. Then, the rolling resistance coefficient could be further solved. In accordance with the Test Methods of Rolling Resistance for Motor Vehicle Tyres, the two specimens were placed under rolling resistance test using the rubber rolling resistance testing machine.

3.5 Viscoelasticity Theory and Test Method

The main method of viscoelasticity analysis is based on a theoretical analysis of test characteristics. The test analysis mainly investigates the dependence of stress and strain to loading rate and sensitivity to temperature. The mechanical behaviour of the viscoelastic material is related to excitation time (t); thus, its stress and strain constitute a function of time. Assuming that the strain $\varepsilon(t)$ of the viscoelastic body at any time t under the action of external force depends on the stress $\sigma(t)$ until this time, the functional relation between stress and strain can be expressed in Eq. (1), as follows:

$$\sigma(t) = F_{-\infty}^{t}\left[\sigma(\tau)\right] \tag{1}$$

Dynamic viscoelasticity refers to the mechanical behaviour and characteristics of a viscoelastic object, as shown under the action of oscillation load (sine wave under normal circumstances); its mechanical property is between elastic solid and viscous fluid. The basic features of dynamic viscoelasticity analysis are small deformation, linear characteristic, time lag (phase difference), and complex number method. The most important parameters are modulus and compliance of complex number. Similar to the definition of elasticity modulus given in Hooke's Law, the ratio of complex stress to complex strain is generally defined as complex modulus in the dynamic viscoelasticity analysis; it is recorded as $R^*(i\omega)$. When oscillation excitation of $\varepsilon(t) = \varepsilon_0\sin(\omega t)$ was applied to the viscoelastic body, the time lag was generated between stress and strain, and phase angle difference δ existed.

Generally, the hysteresis effect of viscoelasticity is manifested by the time lag of strain to stress. Thus, when the phase angle difference of strain lagging behind stress is δ, time lag $t = \delta/\omega$. According to the constitutive equation of Maxwell model, the complex modulus can be obtained using Eq. (2), as follows:

$$R^*(i\omega) = \frac{\sigma^*(t)}{\varepsilon^*(t)} = \frac{\sigma_0}{\varepsilon_0} \cdot e^{i\sigma} = \\ = \left|R^*\right|(\cos\delta + i \cdot \sin\delta) = R_1(\omega) + iR_2(\omega) \quad (2)$$

where $|R^*|$ is the modulus of complex modulus $R^*(i\omega)$, and its expression is shown in Eq. (3), as follows:

$$\left|R^*\right| = \frac{\sigma_0}{\varepsilon_0} = \sqrt{R_1^2 + R_2^2} \quad (3)$$

Δ is the phase angle difference between oscillation excitation and response ($0 < \delta < \pi/2$), and the following Eq. (4) holds:

$$\tan\delta = \frac{R_2}{R_1} \quad (4)$$

The actual component R_1 of complex modulus $R^*(i\omega)$ is dynamic elasticity modulus or storage modulus, and it reflects storage and release of elastic energy and characterizes elastic property. Imaginary part R_2 is viscosity loss modulus or energy dissipation modulus, and it reflects loss and dissipation of viscous energy and characterizes viscous property of the material, $\tan\delta$ is loss tangent or loss factor. Greater elastic part R_1 indicates greater elasticity modulus and closer material to solid. Greater viscous part R_2 indicates smaller viscosity and closer material to fluid. In the compression test, the complex modulus is expressed in Eq. (5). In the shear test, the complex modulus is expressed in Eq. (6), as follows:

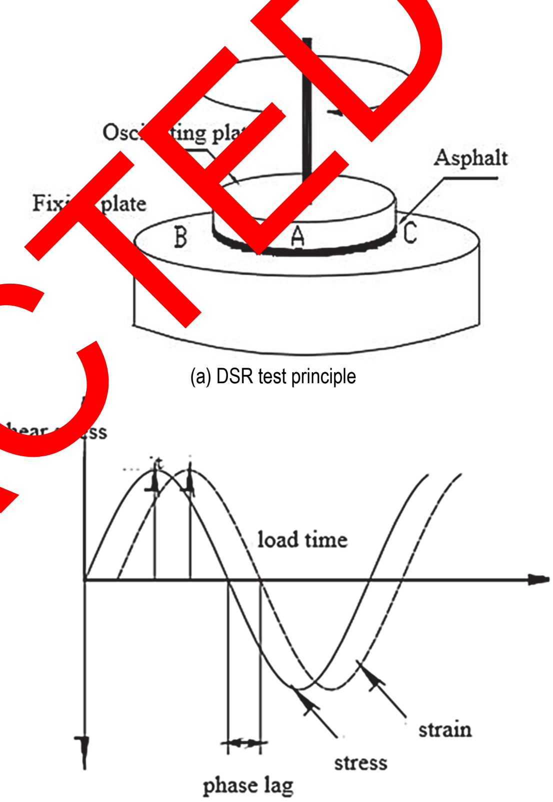
$$E^*(i\omega) = E_1 + E_2 \quad (5)$$

$$G^*(i\omega) = G_1 + G_2 \quad (6)$$

3.6 Dynamic Shear Rheometer Test

The dynamic shear rheometer (DSR) test can be used to determine complex shear modulus and phase angle of the asphalt to characterize its viscoelastic property. The complex shear modulus is shown in Eq. (7), and the phase angle δ is the phase angle difference between oscillation excitation and response. Since load is applied in the test, its working principle and stress-strain curve are presented in Fig. 1. The complex shear modulus consists of two parts, namely, dynamic elasticity modulus or storage modulus and viscosity loss modulus or dissipation modulus. Within the interval of linear viscoelasticity, greater elasticity modulus indicates a stronger elastic property of the material. Viscosity loss modulus characterizes viscosity loss modulus during the asphalt deformation process, and greater G_2 indicates greater viscosity loss of the asphalt material under stress action. Fig. 4 presents DSR test principle and stress-strain curve.

$$G^* = \tau_{max}/\gamma_{max} \quad (7)$$



(a) DSR test principle

(b) Stress curve

Figure 4 DSR test principle and stress-strain curve

4 TEST RESULT AND ANALYSIS

4.1 Internal Heat-Generating Test

The compression and flexural tests were carried out for the four samples, and the heat quantities generated inside them were tested (Tab. 2).

Table 2 Compression and flexural test data

Sample	Terminal dynamic maximum load / kg	Temperature rise at bottom / °C	Internal temperature rise / °C	Static load / kg	Terminal dynamic maximum load / kg
HMB-W	0.8	6.1	6.5	2.1	0.4
SBS modified asphalt	0.9	6.3	7.6	1.2	0.5
HMB-W + mineral powder	1.6	5.6	7.1	3.3	0.8
SBS modified asphalt + mineral powder	1.3	5.9	8.4	1.3	0.6

Tab. 2 shows that the temperature rise at the bottom of the low rolling resistance modified asphalt was 6.1 °C, which was lower than that of SBS modified asphalt (6.3 °C). In addition, the critical internal temperature rise at 6.5 °C of the low rolling resistance modified asphalt was much lower than that of SBS modified asphalt (7.6 °C), with reduction amplitude reaching 14.4%. In addition, compared with SBS modified asphalt mastic, the temperature rise at the bottom of the mastic prepared by mixing the low rolling resistance modified asphalt and mineral powder was reduced by 0.3 °C. Moreover, the reduction amplitude of the internal temperature rise was larger, at 1.3 °C, which was 15.5% of that of SBS modified asphalt. Evidently, by combining the four samples generated by the heat quantity, the low rolling resistance modified asphalt was small, and the energy consumed by internal friction was low when deformation occurred. Thus energy loss was effectively reduced, thereby verifying the low phase angle phenomenon in the previous section, the reason for small phase angle could be explained from macroperspective.

4.2 Rolling Resistance Test

The rolling resistance test of the two samples was implemented, and the test results are shown in Fig. 5 to Fig. 7.

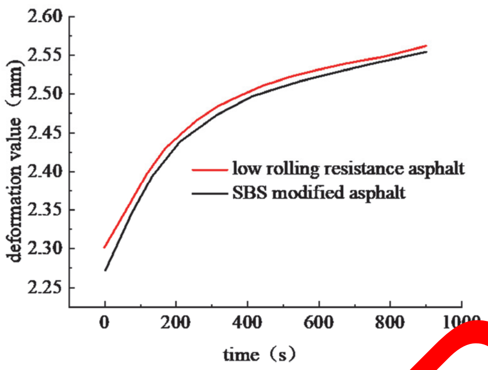


Figure 5 Deformation change in two asphalt rolling resistance models

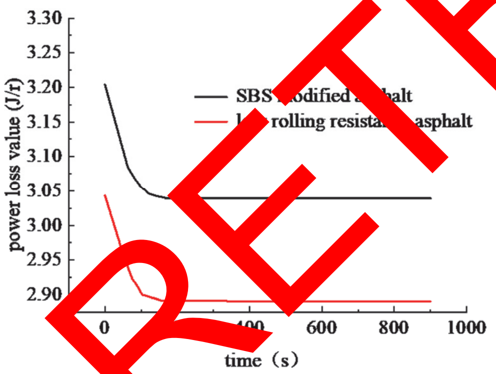


Figure 6 Power loss change in two asphalt rolling resistance models

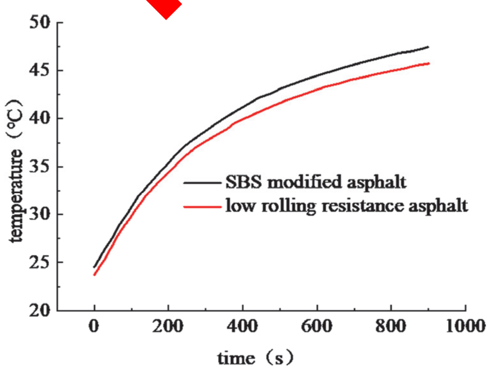


Figure 7 Temperature change in two asphalt rolling resistance models

As shown in Fig. 5, the deformation values of the rolling resistance models of the two samples were consistent. The increased amplitude in deformation value was initially enlarged and then slowed down with time. When the deformation value was 2.5 mm, the deformation would no longer change and reach critical values.

Fig. 6 shows that the power loss values of the rolling resistance models of both samples gradually declined with time. After 100 s, their loss values would no longer decrease. However, they would tend to be stable, following the inflection point. The power loss of the low rolling resistance modified asphalt was smaller than that of SBS modified asphalt, and its initial value, inflection point and final value were smaller than those of SBS modified asphalt. In addition, its power loss value was reduced by approximately 5%. Thus, the energy loss was effectively reduced.

Fig. 7 shows that the temperatures of the rolling resistance models of the two samples started rising from the initial value 25 °C. Their rising trends were consistent. However, the final temperature of the rolling resistance model of the low rolling resistance modified asphalt was smaller than that of SBS modified asphalt after 900 s, indicating that the temperature change amplitude was smaller than that of SBS modified asphalt mode during the rolling test. In the frictional process, the heat generated on its model surface was also small. According to the temperature value after the test, the heat quantity generated in the low rolling resistance modified asphalt model was lower than that of SBS modified asphalt model by 1.7 °C (by 3.7%). This finding corresponds to the internal heat-generating test data. Therefore, the heat generation rate could be decreased, and energy loss could be effectively reduced.

4.3 Temperature Sensitivity Test

4.3.1 Stress Scanning

Fig. 8 indicates the following:

1) At test temperature of 60 °C, the complex shear modulus G^* of the two asphalts attenuated with a continuous increase in stress. However, they did not go through rapid attenuation within the scope of vibration stress, that is 0 - 1000 Pa. Therefore, approximately, G^* did not present stress-dependent change. Furthermore, the interval of linear viscoelasticity was the scope of vibration stress, namely 0 - 1000Pa.

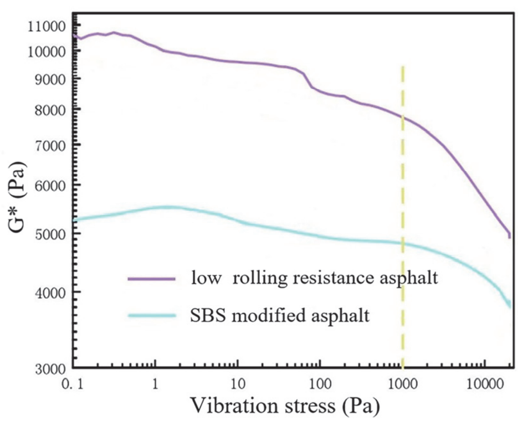


Figure 8 Stress scanning curves of two asphalt types

2) Under the same stress level, the complex shear modulus G^* of the low rolling resistance modified asphalt was evidently higher than that of SBS modified asphalt. Linear viscoelasticity theory in 3.1 indicates that the complex shear modulus G^* consisted of two parts, namely, dynamic elasticity modulus (storage modulus) and viscous loss modulus (dissipation modulus). Therefore, dynamic elasticity modulus (storage modulus) and viscous loss modulus (dissipation modulus) should be further investigated to compare the viscoelastic properties of these asphalts.

4.3.2 Temperature Scanning

The temperature scanning test of the low rolling resistance modified asphalt and SBS modified asphalt was carried out with a dynamic shear rheometer, the temperature scanning scope was 58 - 75 °C, the heating rate was 1 °C/min, and the scanning frequency was 10 rad/s. The temperature-dependent changes in dynamic elasticity modulus (storage modulus) G_1 and viscous loss modulus (dissipation modulus) G_2 are shown in Fig. 9 and Fig. 10. The test results were linearly fitted, as shown in Tab. 3.

As shown in Fig. 9 and Fig. 10 and Tab. 3:

1) The dynamic elasticity modulus (storage modulus) G_1 and viscosity loss modulus (dissipation modulus) G_2 of both asphalts declined as the temperature rose. The linear fitting results analysis of the curves shows that the absolute value of the curve slope of the low rolling resistance modified asphalt was small. This finding manifests that the sensitivity of the low rolling resistance modified asphalt to temperature was smaller than that of SBS modified asphalt and reflects its stable high-temperature performance.

2) The comparative test results of dynamic elasticity modulus (storage modulus) G_1 and viscosity loss modulus (dissipation modulus) G_2 of the two asphalts under the same temperature show that the value of the low rolling resistance modified asphalt was larger than the SBS modified asphalt. This finding indicates that the low rolling resistance modified asphalt had high dynamic elasticity modulus (storage modulus) G_1 under stress action. Thus, the elastic deformation of the pavement was small; the viscosity loss modulus (dissipation modulus) G_2 of the low rolling resistance modified asphalt was small, this finding suggests that its viscosity loss was small, viscoelasticity transformation was fast, and strain hysteresis was minor.

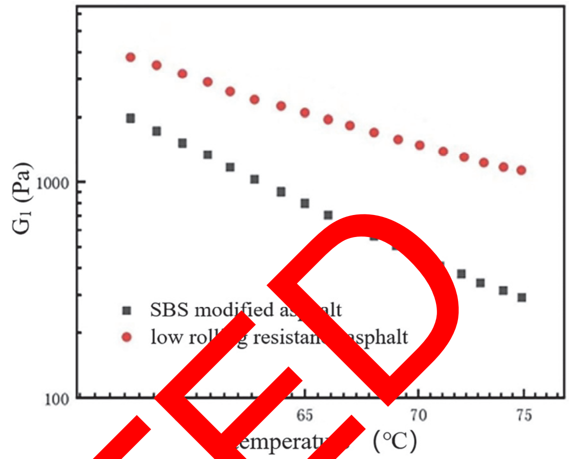


Figure 9 Temperature-dependent change curves of G_1 of two asphalts

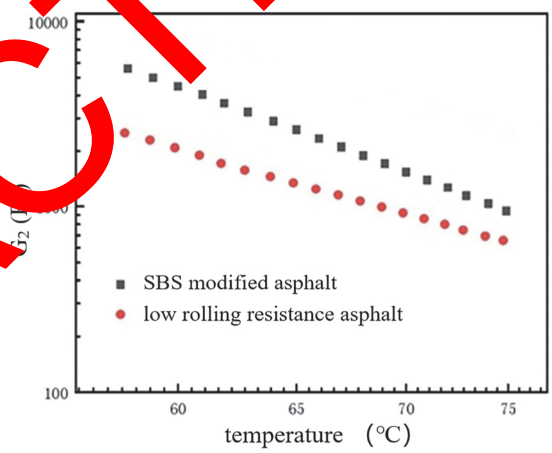


Figure 10 Temperature-dependent change curves of G_2 of two asphalts

Table 3 Linear fitting results and correlation coefficients

Asphalt type	Dynamic elasticity modulus (storage modulus)		Viscous loss modulus (dissipation modulus)	
	Fitting formula	R^2	Fitting formula	R^2
SBS modified asphalt	$Y = -7.537X + 16.284$	0.997	$Y = -6.364X + 16.284$	0.998
Low-rolling resistance modified asphalt	$Y = -4.526X + 11.842$	0.998	$Y = -5.251X + 13.121$	0.999

5 CONCLUSION

To evaluate the performance of low rolling resistance modified asphalt, internal heat-generating test and rolling resistance test were conducted. Besides, Dynamic shear tests in the form of stress scanning and temperature scanning were carried out for the low rolling resistance modified asphalt and SBS modified asphalt, and their difference in viscoelasticity was comparatively analyzed. The following conclusions could be drawn:

(1) The stress scanning results at the test temperature of 60 °C showed that both asphalts were within the scope of vibration stress with linear viscoelasticity interval of 0 - 1000 Pa. Under the same stress level, the complex shear modulus G^* of the low rolling resistance modified asphalt was evidently higher than that of SBS modified asphalt;

(2) The heat generation rate of the low rolling resistance modified asphalt was evidently lower than that of the low rolling resistance modified asphalt mastic, and that of the SBS modified asphalt was evidently lower than that of SBS modified asphalt mastic, indicating that the addition of the low rolling resistance modifier could effectively reduce energy consumption. According to the constructed asphalt rolling resistance model, the heat quantity generated was reduced by 3.7% comparison with that generated in the SBS modified asphalt, the power loss was reduced by 5%, and the low rolling resistance characteristic was evident;

(3) The curve fitting results of the temperature scanning test showed that the temperature sensitivity of the low rolling resistance modified asphalt was low with superior high-temperature stability. Under the same temperature level, the low rolling resistance modified asphalt had large G_1 and small G_2. This finding indicates

that the low rolling resistance modified asphalt not only had high dynamic elasticity modulus, which resulted in small elastic deformation of the pavement, but also small viscosity loss and fast deformation recovery. In addition, the strain hysteresis of the low rolling resistance asphalt pavement could be effectively mitigated.

In summary, the low rolling resistance modified asphalt had excellent low rolling resistance. The temperature scanning test results indicated its small temperature sensitivity and superior high-temperature performance. These findings laid a foundation for further analysing the pavement performance of low rolling resistance modified asphalt mixture under high and low–temperature conditions. However, as the low rolling resistance asphalt pavement mitigates the rolling resistance between the pavement and tire of a running vehicle, the vehicle may slip due to insufficient frictional force. Hence, the emphasis is placed on the anti-slide performance and waterproof performance of low rolling resistance pavement in the future research to ensure that vehicles can continue running safely with reduced energy consumption.

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