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Research Article

Analysis of Coupling Effect and Heavy Load of High-Temperature Stability of Asphalt Mixture

Lu Bai,[1] **Yong-sheng Zhang**,[2] **and Dai-song Luo**[2]

[1]*School of Civil Engineering, Xuchang University, Xuchang 461000, China*
[2]*China Academy of Transportation Science, Beijing 100029, China*

Correspondence should be addressed to Lu Bai; lubai526@126.com

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To study the variation in the high-temperature stability of asphalt mixtures under extreme high temperature and heavy load, rut tests and analyses were carried out with both the APA (asphalt pavement analyzer) test and CLWT (Chinese wheel load test). In this paper, the relationship model between the dynamic stability of asphalt mixtures and the temperature, load, and binder viscosity is established; this model provides a method for evaluating the temperature stability of asphalt mixtures under nonstandard temperature conditions. The results revealed that the dynamic viscosity of an SBS-modified asphalt binder showed an exponential relationship with temperatures varying from 55°C to 70°C. Under a temperature condition from 55°C to 70°C and a pressure of 0.7 MPa, the dynamic stability of the asphalt mixture increased linearly with increasing temperature. The dynamic stability of the asphalt mixture exhibited a temperature inflection point at 65°C, and the decay rate was increased. The APA test results, which were used to evaluate the anti-rutting performance of the asphalt mixture on the basis of the ratio of the rutting depth difference to action times from 6000 to 8000, showed a good correlation with the CLWT test results. With a high temperature of 65°C and the pressure increasing from 0.7 MPa to 1.3 MPa, the dynamic stability of the asphalt mixture exhibited exponential decay. The variation laws of dynamic stability with temperature, load, and asphalt binder viscosity were revealed by complex logarithmic variation.

1. Introduction

Rutting not only influences the appearance and smoothness of the pavement of a road surface but also causes discomfort and potential safety hazards to road users; these problems are mainly the results of deformations in asphalt mixtures under high temperatures and heavy traffic loads. According to investigations, the temperature in the pavement structure layer in most areas of southern China exceeds 65°C [1]. Therefore, to study the performance of high anti-rutting asphalt mixtures, it is necessary to analyze the variation law of the dynamic stability of the asphalt mixtures with temperature. It has been shown that the rutting depth increased by approximately 1.8 times when the temperature was increased by 5°C from 40°C to 60°C, and the rutting depth increased by roughly the same multiple as the axle load [2]. Li Xi analyzed the influence of the true coupling of temperature and load on the rutting of asphalt pavement and concluded that the dynamic stability of the asphalt mixture as obtained by the Marshall method dropped suddenly at 60°C, and the maximum reduction rate of the dynamic stability of the asphalt mixture obtained by the rotary testing machine method (GTM) appeared at 70°C [3]. Sun and others carried out rutting tests with a wheel rutting tester for AC-20 under different temperatures from 40°C to 70°C and wheel pressures and confirmed that wheel pressure and temperature had a significant effect on the rutting resistance of asphalt mixtures [4]. Using new rutting test equipment with changing wheel speed and load to simulate the influences of overload and temperature (loading time) on asphalt mixtures, Jiang Li found that increasing the load time was equivalent to raising the experimental temperature and that using the temperature conditions in the specification to verify the high-temperature stability of asphalt mixtures for

uphill sections with long and large longitudinal slopes was unreasonable [5]. Through a simple performance dynamic modulus test (SPT), a standard rutting test, a Hamburg rutting test, a French rutting test, and an asphalt pavement analyzer rutting test, Sheng Li evaluated the rutting resistance of asphalt mixtures in the middle and lower courses of three semirigid base asphalt pavements of a full-scale test track road in Beijing, China, and concluded that the APA rutting test was the optimal testing method for evaluating the rutting performance of semirigid base asphalt pavements [6]. By simulating nano-ZnO modifier and improving the physical properties of asphalt with the molecular dynamics simulation technology, Manman Su found that nano-ZnO particles increased the bulk modulus, shear modulus, and elastic modulus of asphalt system and improved the high-temperature performance of asphalt [7]. Wang and others studied the rutting resistance of pouring semiflexible pavement under different loads and temperatures and put forward the stability correction index to evaluate the rutting resistance of it [8]. With the increase of tire contact pressure from 0.7 MPa to 1.5 MPa, the maximum deformation of the conventional asphalt pavement was 60% higher than that of high modulus asphalt concrete (HMAC) pavement; therefore, a heavy load is more harmful to the conventional pavement structure [9].

Meanwhile, the index used for evaluating the high-temperature performance and performance under heavy loads of GAC in hot regions still needs to be discussed. Li Zhi developed a design method for the gradation of asphalt mixtures under heavy loads and confirmed that this modification of gradation was successful in resisting rutting [4]. F P. Pramesti utilized a four-point bending test to predict fatigue cracking of GAC and developed a new calibration factor to describe the fatigue life of GAC mixtures [10, 11]. Based on this method, Zhang Yongsheng suggested that the index for evaluating the high-temperature performance and performance under heavy loads of GAC used in the Wu Shen Expressway in Guangdong Province should be reconsidered [12]. According to the test results obtained under conditions of different temperatures and loads and the two synchronous conditions, Shi Liwan analyzed the developing rules and established the relationship between the rutting evaluation index and test conditions [13]. By analyzing the influence of high viscosity additive dosage on key property indices, Li and others recommended appropriate dosage and dynamic viscosity standards aimed at different temperatures and load conditions and found a double-logarithmic relation of dynamic stability with dynamic viscosity [14]. Dai and others analyzed the sensitivity of dynamic creep permanent deformation parameters to dynamic stability and concluded that the viscosity coefficient η_1 was positively correlated with the change of dynamic stability(DS) and most sensitive to DS [15]. By establishing the rutting prediction formula across different months and analyzing indoor rutting tests of different types of asphalt mixtures under different temperatures, Li and others analyzed the rutting development on an asphalt pavement under the distribution of pavement temperature field and the actual traffic load and the coupling effect of temperature and load [3]. To evaluate the deformation resistance of modified asphalt mixture under high temperature and heavy load, Ji and others carried out the triaxial repeated load test on two asphalt mixtures under multi-temperature (50°C, 60°C, and 70°C) and multi-load (0.7, 0.8, 0.9, and 1.0 MPa) conditions and proposed two indices, the flow number and nonlinear fitting index, which had negative and positive correlation with temperature and load, respectively [16].

In the above studies, many researchers have suggested establishing the relationship between the DS and viscosity of asphalt binders, temperature, or load. However, an evaluation index to describe the relationship between the DS and viscosity of asphalt binders, temperature, and load is in demand because it can be used to evaluate the anti-rutting performance of asphalt mixtures under nonstandard high-temperature and heavy-load conditions. First, CLWTs and APA tests were conducted at different temperatures to determine the crucial temperature of the anti-rutting performance of GAC mixtures. Then, the correlation between the results from the CLWT and APA test was confirmed. The relationship between DS and the viscosity of asphalt mixtures as well as traffic loads was also examined. Finally, the fitting results of DS were confirmed based on the temperature, traffic loads, and viscosity of modified asphalt used in GAC mixtures.

2. Test Programme

2.1. Gradation Design of Asphalt Mixture. It has been shown that the viscosity was an indicator of asphalt binder viscosity, and it was used to reflect the degree of friction damping of molecules in fluid against molecules flowing temporarily. The viscosity of asphalt binder at 60°C was generally considered to reflect the heat resistance of the binder in the high-temperature season, but it was shown that the temperature of asphalt pavement in China reached nearly 70°C. Therefore, it is necessary to perform experiments to establish the relationship between the viscosity of SBS and temperature.

To imitate the temperature in southern areas of China, such as Guangdong Province, the experimental temperatures were set as 55°C, 57°C, 60°C, 63°C, 65°C, 67°C, and 70°C. The modified asphalt tested was SBS (I-D). The equipment used for the test was the widely used vacuum capillary viscometer tester (VCVT) utilized in previous research [17]. Note that three different models of specimens were used in this experiment. The results of the viscosity of SBS (I-D) in relation to temperature are shown in Table 1.

The relationship between the temperature and viscosity of modified asphalt can be described by

$$\begin{aligned} \eta &= 6 \times 10^7 \times e^{(-0.12T)}, \\ R^2 &= 0.9615, \end{aligned} \tag{1}$$

where η is the viscosity of asphalt binder (Pa · s) and $R^2 = 0.9615$.

The aggregate of the asphalt mixture was limestone which was acquired from the Renhua area of Guangdong Province, and the design results of the asphalt mixture gradation GAC-20C are shown in Table 2.

Table 1: Viscosity of SBS-modified asphalt binder at different temperatures.

Temperature (°C)	Type of capillary	Average viscosity (Pa · s)
70	200	11219
67	200	23491
65	200	29950
63	200	31896
60	400	35533
57	400	67943
55	800	83750

Table 2: Design results of the GAC-20C gradation.

Mass percentage (%) through the following sieve holes (mm)												
Sieve holes (mm)	26.5	19	16	13.2	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
Mass percentage (%)	100	97.5	84.5	73	56	36	28	20	16	12	8	5

2.2. Rutting Test. The rutting tests based on the Chinese load wheel test (CLWT) and asphalt pavement analyzer (APA) were as follows [18–20].

2.2.1. CLWT for Rutting. The CLWT has been widely used to verify the high-temperature stability of asphalt mixtures. To imitate the high temperature in southern areas of China, such as Guangdong Province, the experimental temperatures were set as 55°C, 57°C, 60°C, 63°C, 65°C, 67°C, and 70°C. The sizes of the specimens used for the CLWT were 300 mm × 300 mm×50 mm cuboids, which were compacted by the wheel-grind method with an air void of 4.5%. The rutting test was performed after maintaining the specimens at a specific experimental temperature for no less than 6 hours. The rutting speed back and forth was set at 42 times/min, and the loading pressure was set as 0.7 MPa. The ratio of loading times to rutting deformation at 45 min and 60 min was chosen as the dynamic stability (DS). The DS was chosen as the index to evaluate the anti-rutting performance of the asphalt mixtures. The value of DS is calculated according to

$$DS = \frac{(t_2 - t_1) \times N}{d_2 - d_1} \times c_1 \times c_2, \quad (2)$$

where d_1 represents deformation at 45 min (mm), d_2 represents deformation at 60 min (mm), N represents loading times (42 times/min), c_1 represents modifying coefficient for the size of the specimen (1.0 was selected here), c_2 represents modifying coefficient for the type of experimenting equipment (1.0 was selected here), $t_1 = 45$ min, and $t_2 = 60$ min.

The results of the test under different temperatures are summarized in Table 3.

A linear function was generated to fit the relationships between DS and experimental temperature. The function and the coefficient are presented in the following equation:

$$DS = a_1 T + b_1, \quad (3)$$

where a_1 is −590.17, b_1 is 44328, and R^2 is 0.9929.

The linear relationship between DS and experimental temperature is shown in Figure 1.

Table 3: Results of the CLWT.

Temperature (°C)	55	57	60	63	65	67	70
DS (times/mm)	12230	10734	8491	6929	5887	4843	3276

It is obvious that DS decreases remarkably as the experimental temperature increases. The percentage decrease in DS is shown in Figure 2.

When the test temperature is between 55°C and 65°C, the DS of the asphalt mixture decreases by 30.57% and 30.67% for every 5°C increase in temperature. When the test temperature increased from 65°C to 70°C, the DS of the asphalt mixture sharply decreased by 44.35%. It was indicated that 65°C was the temperature inflection point of the dynamic stability of the asphalt mixture. When the pavement temperature exceeds 65°C, the dynamic stability of the asphalt mixture decreases sharply. Under loading, asphalt pavement is more prone to deformation.

2.2.2. APA Test. The sizes of the specimens used for the APA test were φ150 mm × 75 mm cylinders, which were formed by a Superpave gyratory compactor (SGC) with an air void of 4.5%. Specimens were maintained for 2 hours at the APA test temperature of 55°C, 57°C, 60°C, 63°C, 65°C, 67°C, or 70°C after 2 hours at normal temperature. The loading pressure of the experimental tire was 45 kg (101.5 lbs). The number of loading times was set as 8000. The initial pressure in the rubber tube was set as 0.7 MPa (100 psi). The loading speed back and forth was set as 42 times/min to be in accordance with the CLWT. The ratio of loading times to deformation of 6000 times and 8000 times was defined as dynamic stability in the APA test, which was referred to as DS1. The value of DS1 is calculated according to the following equation:

$$DS_1 = \frac{N_2 - N_1}{d_2' - d_1'}, \quad (4)$$

where d_1' represents deformation when loaded 6000 times (mm), d_2' represents deformation when loaded 8000 times (mm), N_1 represents loading times (6000), and N_2 represents loading times (8000).

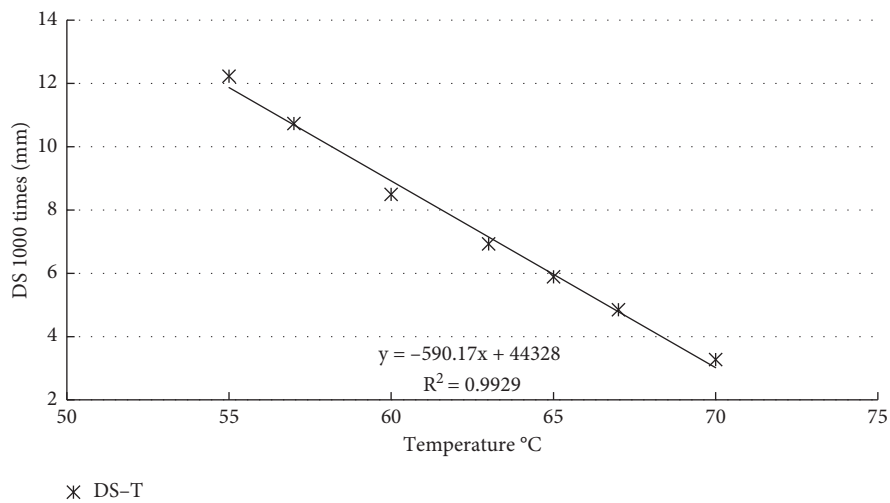

Figure 1: Relationship between DS and experimental temperature.

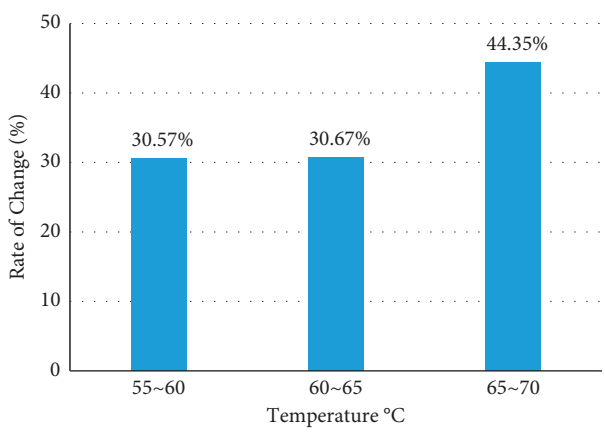

Figure 2: Percentage decrease in DS caused by the increase in temperature.

The results of DS_1 according to the experimental temperature are shown in Table 4.

The data from Table 4 show that the result obtained from the APA test is similar to that from the CLWT. A linear function was also generated to fit the relationship between DS1 and the experimental temperature. The function and the coefficient are presented in the following equation:

$$DS_1 = a_2 T + b_2, \tag{5}$$

where a_2 is −527.08, b_2 is 40185, and R^2 is 0.9939.

The linear relationship between DS_1 and the experimental temperature is drawn in Figure 3.

With the increase of pavement temperature field temperature, the viscosity of asphalt binder decreases, which results in the decline of adhesion between asphalt and aggregate and the decline of the resistance to deformation of asphalt mixture. It is obvious that DS decreases remarkably as the experimental temperature increases. The percentage decrease of DS_1 is shown in Figure 4. When the test temperature is between 55°C and 65°C, the DS_1 of the asphalt mixture decreases by 28.40% and 29.15% for every 5°C increase in temperature. When the test temperature increased from 65°C to 70°C, the DS_1 of the asphalt mixture sharply decreased by 39.15%. It was indicated that 65°C was the temperature inflection point of the dynamic stability of the asphalt mixture.

Table 4: Results of the APA test.

Temperature (°C)	55	57	60	63	65	67	70
DS_1 (times/mm)	11494	10181	8230	6791	5831	4910	3527

2.2.3. Correlations between APA Test and CLWT. To determine the anti-rutting performance of GAC mixtures under high temperature and high loading pressure, other experiments measuring the viscosity and DS under high loading pressure of asphalt mixtures need to be performed. However, only the APA test can be used to conduct the latter experiments. Therefore, the correlations between the results from the CLWT and APA test were conducted to determine whether the APA test experiments can replace the CLWT to determine the anti-rutting performance of GAC mixtures. Based on correlation analysis with Microsoft Office Excel, the relationships between the results from the two rutting tests were examined. The fitting function is shown in (6), while Figure 5 shows the two DS-temperature curves.

$$Y = 0.8926X + 600.04, \tag{6}$$

where R^2 is 0.9999.

The results of the two tests have good correlations with each other, so it is reasonable to perform rutting tests using APA to evaluate the anti-rutting performance of GAC mixtures under different temperatures and loading pressures. The following experiments are based on this assumption.

2.2.4. Experiments on Loading Pressures. Experiments aiming to evaluate the anti-rutting performance of GAC mixtures under heavy loading pressures were performed. The size of the specimens was the same as that used in APA

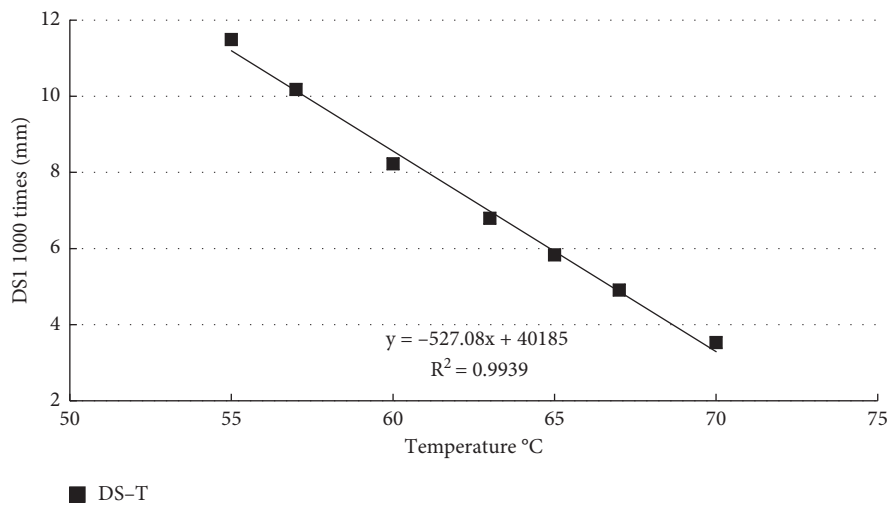

Figure 3: Relationship between DS_1 and experimental temperature.

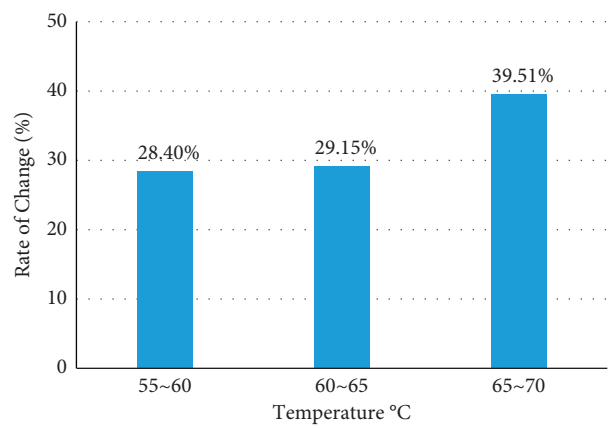

Figure 4: Percentage decrease in DS_1 caused by the increase in temperature.

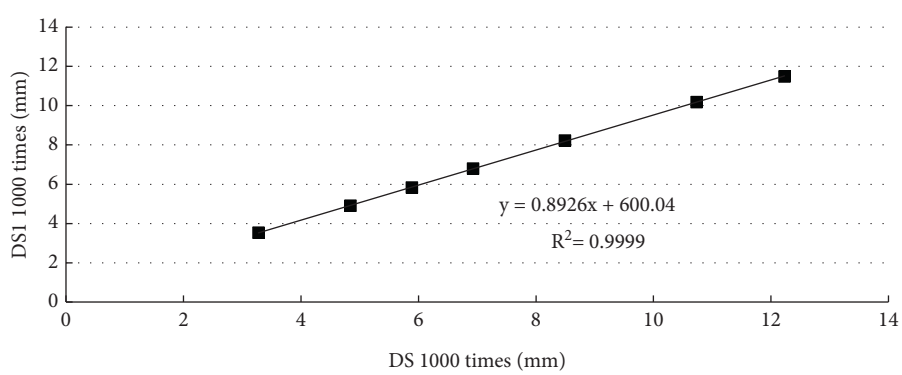

Figure 5: DS-temperature curves of the two tests.

in previous experiments. Four groups of tests were conducted with 3 specimens in each group. To imitate a heavy loading pressure, the pressures of the experiments were set as 0.7 MPa, 0.8 MPa, 0.9 MPa, 1.0 MPa, 1.1 MPa, 1.2 MPa, and 1.3 MPa, while the temperature was set as 65°C [1]. Note that 0.7 MPa is the standard axle load set in the specifications (JTG E20-2011) [21]. The number of loading times was 8000, and the loading speed was the same [22]. Table 5 shows the DS results under different loading pressures.

The relationship between DS and loading pressure can be fitted with

Table 5: Relationship between loading pressures and DS.

Loading P (MPa)	0.7	0.8	0.9	1	1.1	1.2	1.3
DS (times/mm)	5831	4210	3057	2485	1789	1460	1194

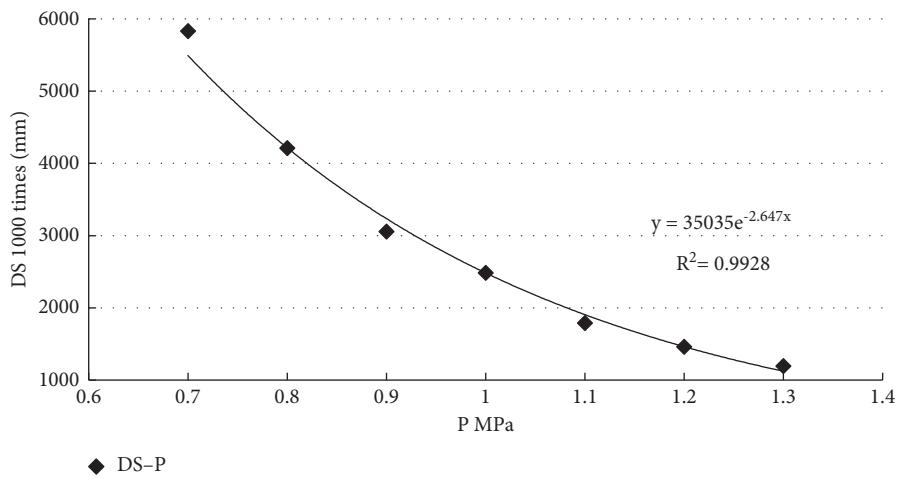

Figure 6: Relationship between loading pressures and DS.

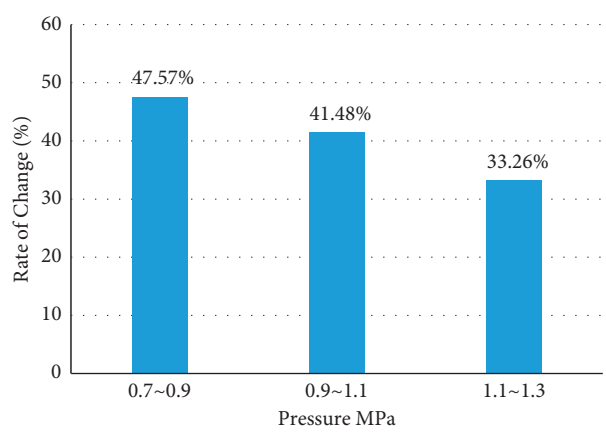

Figure 7: Percentage decrease in DS according to the increase in loading pressure.

$$DS = a_4 e^{-2.647P} + b_4, \quad (7)$$

where $a_4 = 35035$ and $R^2 = 0.9928$.

The DS-loading pressure curve is shown in Figure 6.

It can be seen from Figure 7 that when increasing the loading pressure from 0.7 MPa to 1.3 MPa by 0.2 MPa each time, the decrease in DS is 47.57%, 41.48%, and 33.26%, respectively. When compared with the drop in DS due to the increase in experimental temperature, it was concluded that the drop in DS of GAC mixtures mainly results from the rise in temperature (5°C each time), and the rise caused by changes in temperature is much less than that caused by the rise in loading pressure (0.2 MPa each time).

2.3. Influence of Asphalt Viscosity on DS of Asphalt Mixtures. It has been shown that the viscosity of the binder decreases and the strength of the asphalt mixture weakens with increasing pavement temperature. The results of the rutting test were combined with the results shown in Table 2 to determine the relationship between DS and the viscosity of modified asphalt. The results of the CLWT and APA test are shown in Figures 8(a) and 8(b).

It can be indicated from the two curves that the dynamic stability changes in the same trend with the change of asphalt viscosity. With the increase of temperature, the viscosity of asphalt and the dynamic stability of asphalt mixture decreases. The relationship between DS and the viscosity of modified asphalt can be described by

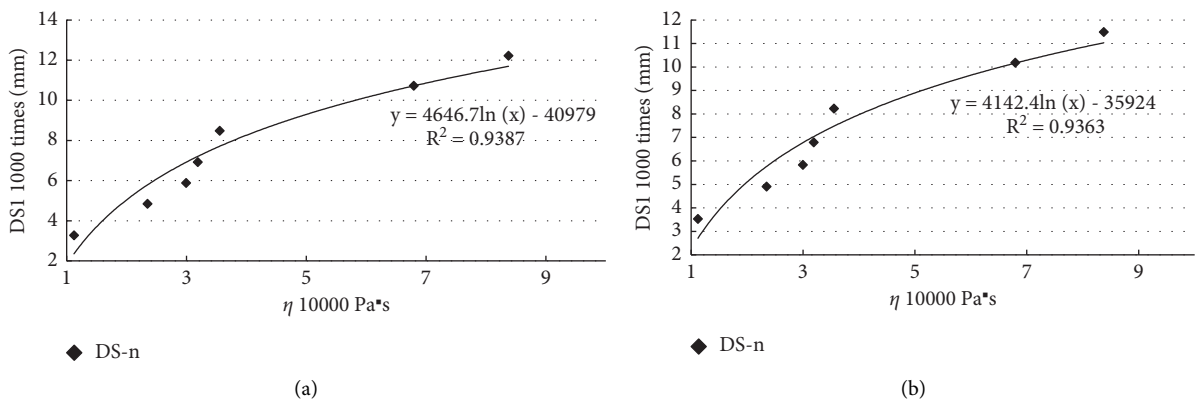

Figure 8: Relationship between DS and modified asphalt. (a) CLWT. (b) APA test.

$$DS = a_3 \ln(\eta) + b_3. \tag{8}$$

For the CLWT:

$$\begin{aligned} a_3 &= 4646.7, \\ b_3 &= -40979, \\ R^2 &= 0.9387. \end{aligned} \tag{9}$$

For the APA test:

$$\begin{aligned} a_3 &= 4142.4, \\ b_3 &= -35924, \\ R^2 &= 0.9363. \end{aligned} \tag{10}$$

2.4. High-Temperature Stability of Asphalt Mixtures under Coupling Action. Based on the fitting method referred to in previous studies [23], the relationship between the DS of GAC mixtures and the temperature, viscosity, and loading pressures is shown in (11) based on data from Tables 2–5:

$$\ln(DS) = a_4 \ln(T) + b_4 \ln(c_4 P + d_4) + m \ln \ \ln(\eta) + n, \tag{11}$$

where $a_4 = -3.0343$, $b_4 = -2.4358$, $c_4 = 0.2699$, $d_4 = -0.0124$, $m = 2.3732$, $n = 11.5707$, and $R^2 = 0.8312$.

The anti-rutting performance of the mixtures was related to dynamic stability. The higher the dynamic stability of the asphalt mixture is, the stronger the anti-rutting performance is. In this paper, the relationship between dynamic stability and different high temperatures, loads, and viscosities of asphalt binder is established, which will be used to determine the dynamic stability of asphalt mixtures under nonstandard conditions, and the coefficients in (11) are determined by using the experimental data of dynamic stability of different mixtures under the conditions of standard temperature, load, and viscosity.

3. Conclusions

In this paper, experiments were conducted to evaluate the anti-rutting performance of GAC mixtures under high temperature and heavy traffic loads. Tests based on both the CLWT and APA test were performed, and the results from these two tests were compared. The conclusions are drawn as follows:

(1) The results from both rutting tests suggest that the anti-rutting performance of GAC mixtures decreases remarkably when increasing the temperature or loading pressure. The results of the correlation analysis indicate that the APA test can replace the CLWT to evaluate anti-rutting performance. There is a good correlation between the two rutting test results.

(2) The comparison of the influences of temperature and loading pressure on DS suggests that the drop in DS resulting from an increase in temperature by 5°C is much larger than that resulting from an increase in loading pressure by 0.2 MPa.

(3) The dynamic stability of the asphalt mixture exhibited a temperature inflection point at 65°C, and the decay rate increased.

(4) Under the influence of high temperature, heavy load, and binder viscosity, the dynamic stability of asphalt mixtures was characterized by complex logarithmic variation.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest regarding the publication of this study.

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