Hindawi
Advances in Materials Science and Engineering
Volume 2019, Article ID 1825643, 12 pages
https://doi.org/10.1155/2019/1825643

Research Article

Dynamic Characteristics of Warm Mix Foamed Asphalt Mixture in Seasonal Frozen Area

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Received 16 August 2018; Revised 14 November 2018; Accepted 26 December 2018; Published 5 February 2019

Academic Editor: Jun Liu

In order to study dynamic characteristics of warm mix foamed asphalt mixture in seasonal frozen area, cylinder dynamic modulus test of four kinds of mixture with two gradations and three kinds of asphalt was carried out by UTM-100. Then, the effects of test temperature, loading frequency, and foaming water consumption on dynamic modulus were analyzed. Finally, the compressive resilient modulus trial was made to compare mechanical properties. Results show that dynamic modulus for warm mix foamed asphalt mixture increases with rising temperature and decreased frequency. The inflection points of the dynamic modulus vs frequency curves at low temperature, normal temperature, and high temperature are 2 Hz, 10 Hz, and 15 Hz, respectively. Static modulus of SBS# modified and nonmodified warm mix foamed asphalt mixture is corresponding to the dynamic modulus 0.001 Hz–0.1 Hz and 0.00001 Hz–0.05 Hz. The effect on gradation type on the dynamic modulus of asphalt mixture is AC-20 > AC-13, and the degree of sensitivity of the water consumption to the master curve equation of dynamic modulus under different gradations is AC-13 > AC-20.

1. Introduction

The climate of seasonal freezing zone in China is mainly distributed in three northeastern provinces, Inner Mongolia, Gansu, Ningxia, northern Xinjiang, Qinghai, and Chuanxi, accounting for about 53.5% of the country's land area. Seasonal freezing zone weather conditions are relatively bad, temperature difference is very large, summer time is hot and rainy, and winter is cold and snowy. During construction under climatic conditions in the seasonal frozen zone, hot mix asphalt mixture on the external environment temperature requirements is more stringent, usually more than 10°C; therefore, in the low-temperature (<10°C) season, hot mixed asphalt mixture construction is generally not used in construction, unless special measures are taken; for example, in the Northeast region, the road surface construction will only be carried out from June to September. If the construction continues, it will not only bring difficulties to the construction but also affect the performance of asphalt pavement to shorten its service life; in a short period of time, there are different degrees of disease such as rutting, low-temperature shrinkage, and other characteristics [1, 2].

Therefore, a "green and environment-friendly" new warm mix asphalt mixture came into being. At present, the common mixing technology of asphalt mixture used at home and abroad is mainly divided into three categories: (i) organic viscosity reducing warm mixing technology [3]; (ii) foaming asphalt reducing viscosity temperature mixing technology [4, 5]; (iii) emulsified and dispersed asphalt viscosity reduction technology [6]. Most of them are added by adding additives (emulsifiers, viscosity reducers, foaming agents, etc.) to achieve the viscosity reduction of asphalt; the same is the most widely used and most mature warm mix technology in China (i.e., emulsified asphalt warm mixing method and organic additive method). The way is to add Sasobit or Evotherm isothermal mixing agent in the asphalt mixture to achieve the warm mixing effect of the mixture. Although their use allows the asphalt mixture to be mixed at low temperatures for low carbon emission reduction, these warming agent products are often expensive, which inevitably increases construction costs and production difficulty. The warm mix foam technology is now favored by road industry researchers and road builders. Although the warm mix foam technology belongs to the field of warm mix technology, because it uses water, it replaces the expensive warm mix agent, so that the construction temperature is lowered and the construction period is extended without increasing the cost of construction.

The technology was born in the late 1990s. In 1995, British Shell International Petroleum Co., Ltd. and Norwegian Kolo Veidekke Company invented a two-stage process to produce warm mix asphalt mixture, and in two trials [7] in Norway in May 1999 and May 2000, the first large-scale production in September 2000, after the research and application of warm mixed foam technology has developed rapidly in Europe. China's research on warm mixed foam technology is relatively late. In 2010, the Hebei Province Changzhou Municipal Engineering Company introduced asphalt foaming equipment from Meeker Company of the United States and paved a section of warm mixed foam asphalt pavement [8]. In 2013, Liaoning Province paved a test section of about 900m in the north stone line of Liaoyang City [9].

Considering that there are not many research institutions and test section paving for warm mix foamed asphalt mixture in China, only Hebei, Liaoning, and other places have carried out related research, although there are certain indoor and experimental roads in terms of road performance [10–12]. There are few research studies on dynamic characteristics, especially after the promulgation of JTG D50-2017 for Highway Asphalt Pavement Design Specification; asphalt mixture design uses dynamic modulus, so it is necessary to study the dynamic modulus of warm mix foamed asphalt mixture under the condition of seasonal frozen zone, in order to provide design basis for highway industry research and road construction personnel.

2. Dynamic Modulus and Its Main Curve Introduction

Compared with the stillness springback modulus, the dynamic modulus can better reflect the change of the stress of asphalt pavement under dynamic load, which has been paid much attention by many scholars at home and abroad [13–15]. $|E^*|$ is the ratio of stress peak σ_0 to strain peak ε_0 in the modulus test, and dynamic modulus $|E^*|$ and phase angle φ at specific temperature and frequency conditions can be obtained by the dynamic modulus test, in order to better describe the stress and strain under the action of sinusoidal load, different loading frequencies, and different temperatures; at any time of the change law, the specific calculation formula such as (1)~(2), wherein T_{i} is the lag time between stress and strain, T_{p} is the period of time stress. In this paper, only the dynamic modulus index of temperature-mixed foam asphalt mixture is studied:

$$\varphi = \frac{T_i}{T_p} \times 360^{\circ}, \tag{1}$$

$$\left|E^*\right| = \frac{\sigma_0}{\varepsilon_0}. \tag{2}$$

Due to the limitations of the test methods and test equipment, it is not possible to test the dynamic modulus of the asphalt mixture over a wide temperature and time, for which a dynamic modulus master curve is introduced. The core of the dynamic modulus master curve lies in the time-temperature equivalent principle of the mixture [16], and the key to the time-temperature equivalent principle lies in the determination of the shift factor.

By panning the corresponding dynamic modulus at the original frequency to the corresponding frequency at the reference temperature, that is, reduced frequency, in which the relationship between the shift factor and the reduced frequency is shown in formula (3), the method of the shift factor is numerous, and in this paper, the Arrhenius equation [17] is selected for fitting calculation (formula (4)) and for the dynamic modulus main curve determination using the sigmoidal model [18] to fitting (formula (5)), and then formula (3) after the logarithm, combining formula (4), can finally get the dynamic modulus of the main curve equation (formula (6)):

$$\frac{f_{\mathrm{r}}}{f} = \alpha(T), \tag{3}$$

$$\log(\alpha(T)) = \frac{\Delta E_{\mathrm{a}}}{2.303R}\left(\frac{1}{T} - \frac{1}{T_{\mathrm{r}}}\right), \tag{4}$$

$$\log\left(\left|E^*\right|\right) = \delta + \frac{\alpha - \delta}{1 + e^{\beta + \gamma \log(f_{\mathrm{r}})}}, \tag{5}$$

$$\log\left(\left|E^*\right|\right) = \delta + \frac{\alpha - \delta}{1 + e^{\beta + \gamma\left\{\log(f_{\mathrm{r}}) + \left(\Delta E_{\mathrm{a}}/2.303R\right)\left((1/T) - \left(1/T_{\mathrm{r}}\right)\right)\right\}}}, \tag{6}$$

where f_{r} is the reduced frequency at the reference temperature, Hz; f is the test frequency, Hz; $\alpha(T)$ is the shift factor, which represents the translation distance from the dynamic modulus curve to the reference temperature at the temperature of the main curve; ΔE_{a} is the activation energy; R is the general gas constant, 8.314 J/(K mol); T is the test temperature, K; T_{r} is the reference temperature, K; δ is the logarithm of the minimum dynamic modulus $|E^*|_{\min}$; α is the logarithm of the maximum dynamic modulus $|E^*|_{\max}$; and β and γ are the regression coefficients.

3. Material Composition

3.1. Raw Material. With the foamed asphalt production equipment, as shown in Figure 1, three kinds of asphalt 70#, 90#, and SBS modified 90# (referred to as SBS#) were used for foaming tests, the results of which are shown in Table 1. The test mineral aggregate is basalt coarse aggregate, limestone fine aggregate, and mineral filler. The tested

Figure 1: PL-2 foam asphalt production equipment.

indicators meet the technical requirements of "Technical Specifications for Highway Asphalt Pavement Construction" (JTG F40-2004). The gradation design of AC-13 type and AC-20 type commonly used in the seasonal frozen area was selected, and the corresponding grading composition is shown in Table 2.

3.2. Mixture Design. For the test, three types of asphalt and two kinds of grading are used to prepare different types of warm mix foamed asphalt mixture; that is, 70#, 90#, and SBS# asphalt are mixed with AC-20 foam mixed asphalt mixture, SBS# asphalt mix AC-13-type mixed foamed asphalt mixture, as shown in Figure 2, and the dynamic modulus test was carried out, as shown in Table 3. It can be seen from Table 3 that the temperature of the mixing foam is reduced by 15°C–30°C compared to the ordinary hot mix asphalt mixture.

4. Design Scheme

In view of the special climatic environment in the seasonal frozen zone, in order to investigate the temperature adaptability of the temperature mixing foam technology, using UTM-100 test equipment (Figure 3), select three kinds of temperature: −15°C, 20°C, and 45°C; the simulations of the dynamic modulus low temperature, normal temperature, and high temperature tests of the warm mix foamed asphalt mixture were carried out separately. At the same time, in order to simulate the influence of vehicle speed on the mechanical properties index of the temperature mixed asphalt pavement, the antipermanent deformation ability of the temperature mixed foam asphalt mixture under different vehicle speeds is evaluated by changing the different test frequencies. First of all, change the different foaming water consumption (WC); the water consumption amounting P_1 and P_3 are, respectively, taken at the optimum foaming water consumption P_2; the unexpanded ordinary hot mixed asphalt mixture is used for the comparison test; and the unfoamed state is recorded as P_0, and its specific design scheme is shown in Tables 4 and 5.

Using the static pressure method to form a diameter of 100 mm and height of 150 mm specimens, it was cured at room temperature for 24 hours; the position of the test piece sticking device is polished with gauze, so that the stone here can be exposed for easy adhesion. Use AB glue to install a nail every 120° around the test piece, and the distance between the upper and lower nails is 70 mm ± 1 mm, a total of six. After the glue is formed into strength, about 10 min, the test piece can be removed and used indoors for about 12 hours, as shown in Figure 3.

After the test piece is cured, in accordance with the selected test temperature, keep the incubator for 4~5 h until the internal temperature of the test piece reaches the specified requirements and fix the displacement sensor between the two nails; after the installation is completed, put it into the test incubator for about 10 minutes and then perform the uniaxial compression dynamic modulus test after the temperature is stable, as shown in Figure 4.

5. Study on Dynamic Modulus of Warm Mix Foamed Asphalt Mixture

The dynamic modulus of the mixed foamed asphalt mixture and the hot mixed asphalt mixture was compared and analyzed from low-temperature, normal-temperature, and high-temperature environments, respectively, and the variation law of the two with the load frequency was explored.

5.1. Influence of Load Frequency on Dynamic Modulus

5.1.1. Low-Temperature Environment (−15°C). It can be seen from Figures 5–8 that the dynamic modulus of different kinds of warm mix foamed asphalt mixture increases with the increase of frequency in the low-temperature environment. With the increase of foaming water consumption, the dynamic modulus varies, and the larger foaming water consumption is not conducive to the growth of the dynamic modulus of the warm mix foamed asphalt mixture. Taking the dynamic modulus under the optimal foaming water consumption as an example, for 10 Hz frequency, the dynamic moduli of 70#, 90#, SBS#AC-20, and SBS#AC-13 hot mix asphalt mixture are 31044 MPa, 33173 MPa, 28718 MPa, and 23444 MPa, respectively; the dynamic modulus of the corresponding warm mix foamed asphalt mixture is 28873 MPa, 26135 MPa, 28175 MPa, and 21046 MPa, respectively, which is reduced by 7.0%, 21.2%, 2.0%, and 10.2%, respectively, and the range of decrease is in the range of 2.0% to 21.2%.

For dynamic modulus at different frequencies, the frequency 2 Hz is an inflection point. When the frequency is lower than 2 Hz, the dynamic modulus develops faster. When it increases to 2 Hz, it can reach more than 80% of the 25 Hz dynamic modulus. Once it is higher than 2 Hz, the dynamic modulus increases little, so in the low-temperature environment, for different types of mixed foamed asphalt, the frequency of 2 Hz is the turning point of the dynamic modulus curve in a low-temperature environment.

5.1.2. Normal-Temperature Environment (20°C). From Figures 9–12, it is found that the dynamic modulus with

Table 1: Technical indexes of foamed asphalt for test.

Asphalt type	Asphalt temperature (°C)	Water consumption (%)	Pressure (MPa)	Expansion rate (times)	Half-life (seconds)
70#	160	2.0	0.4 0.5	19.0	34.3
90#	150	2.0	0.4 0.5	21.0	33.8
SBS#	170	3.0	0.4 0.5	14.5	15.0

Table 2: Grading composition of test.

Type	Mass percentage through the following mesh											
	26.5	19	16	13.2	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
AC-20 grading range	100	90–100	78–92	62–80	50–72	26–56	16–44	12–33	8–24	5–17	4–13	3–7
AC-20 grading range	100	98.8	85.5	73.1	61	40.7	22	16.3	11.8	9.8	6.2	4.1
AC-13 grading range	100	100	100	90–100	68–85	38–68	24–50	15–38	10–28	7–20	5–15	4–8
AC-13 grading range	100	100	100	98	78.7	52.4	32.6	23.7	16.4	13.5	7.7	4.7

(a) (b)

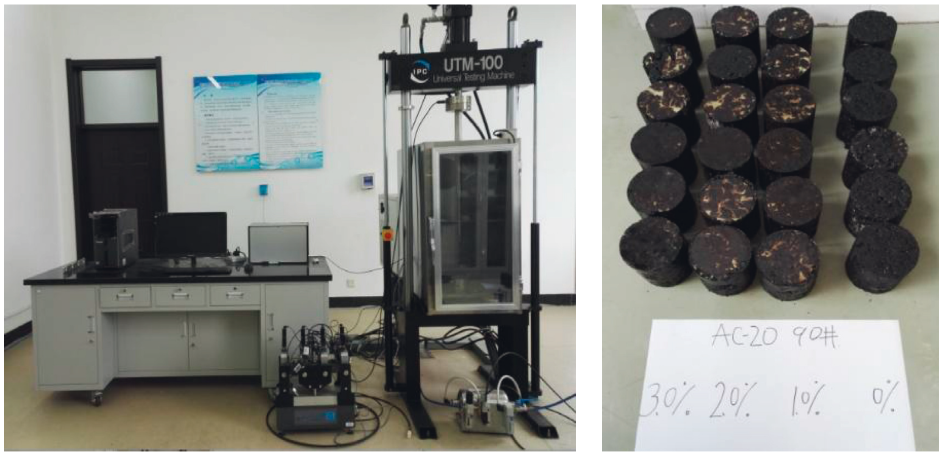
Figure 2: Specimens for mixing and preparation of foam asphalt mixture.

Table 3: List of the best oil-stone ratio of warm mix foamed asphalt mixture.

Gradation	Asphalt type	Mixing type	Optimum mixing temperature (°C)	Reduction in temperature (°C)	Best asphalt aggregate ratio (%)	±Asphalt-aggregate ratio (%)	VV (%)	VMA (%)	VFA (%)
AC-20	70#	HMA	150	20	4.0	+0.2	3.9	13.2	70.5
		FWMA	130		4.2		4.1	13.5	69.6
AC-20	90#	HMA	160	15	4.3	0	4.0	13.4	70.2
		FWMA	145		4.3		4.1	13.1	70.4
AC-20	SBS#	HMA	175	30	4.5	+0.3	4.1	13.7	70.2
		FWMA	145		4.8		3.9	13.3	69.7
AC-13	SBS#	HMA	175	25	4.5	0	4.0	14.1	71.6
		FWMA	150		4.5		4.1	14.2	70.8

frequency changes at normal temperature is similar to the low-temperature condition. In addition to a slight increase in the dynamic modulus of the SBS#AC-20 warm mix foamed asphalt mixture with a water consumption of 2.0%, the dynamic modulus of the warm mix foamed asphalt mixture under different foaming water consumptions is smaller than that of the hot mix, and the degree is different. The analysis is also carried out with the dynamic modulus of each of the best foaming water consumption, under the condition of 10 Hz frequency; the dynamic modulus of 70#AC-20, 90#AC-20, SBS#AC-20, and SBS#AC-13 hot mix asphalt mixture is 12959 MPa, 10745 MPa, 9244 MPa, and 7721 MPa, respectively; the dynamic modulus of the corresponding warm mix foamed asphalt mixture is 9711 MPa, 9209 MPa, 8568 MPa, and 6324 MPa, respectively, which is reduced by 25.1%, 14.3%, 7.3%, and 18.1%, respectively, and the reduction range fluctuates from 7.3% to 25.1%.

In the process of changing the dynamic modulus of various warm mix foamed asphalt mixtures with frequency, the dynamic modulus increases faster when the frequency is less than 10 Hz, and the growth rate slows down when it is greater than 10 Hz. When the frequency is 10 Hz, the



(a) (b)

Figure 3: UTM-100 equipment and foam asphalt mixture preparation test piece.

Table 4: Research and design scheme of dynamic characteristics of warm mix foamed asphalt mixture.

Working conditions	Test temperature		
	Low temperature: −15°C	Normal temperature: 20°C	High temperature: 45°C
Test frequency	0.1 Hz, 0.2 Hz, 0.5 Hz, 1 Hz, 2 Hz, 5 Hz, 10 Hz, 20 Hz, 25 Hz		
Foaming water consumption	P_0, P_1, P_2, P_3		
Applied load	Continuous uninterrupted half-vector waveform		
Confining pressure	No		

Table 5: Foaming water consumption corresponding to each code of the mix foamed asphalt mixture.

WC	70#AC-20	90#AC-20	SBS#AC-20	SBS#AC-13
P_0	0	0	0	0
P_1	1.5%	1%	2%	2%
P_2	2.0%	2%	3%	3%
P_3	2.5%	3%	4%	4%

dynamic modulus can reach more than 80% of the 25 Hz frequency. It is not difficult to find that the frequency of 10 Hz is a turning point of the dynamic modulus curve under normal-temperature environment.

5.1.3. High-Temperature Environment (45°C). In high-temperature environment (45°C), the dynamic modulus of different types of warm mix foamed asphalt mixture is reduced compared with the unfoamed hot mix asphalt mixture. The effect of different water consumption on the dynamic modulus of warm mix foamed asphalt mixture is also different, as shown in Figures 13–16. In terms of the optimal foaming water consumption, when the frequency is 10 Hz, the dynamic modulus of 70#, 90#, SBS#AC-20, and SBS#AC-13 hot mix asphalt mixture are 2219 MPa, 1812 MPa, 2509 MPa, and 2148 MPa, respectively; the dynamic modulus of the corresponding warm mix foamed asphalt mixture is 2298 MPa, 1613 MPa, 2065 MPa, and 1881 MPa, respectively; the respective changes are 3.7%, −11.0%, −17.7%, and −12.4%, and the variation range is in the range of +5% to −20%.

For the above four different types of warm mix foamed asphalt mixture, the dynamic modulus increases with the increase of frequency, wherein when the frequency is less than 15 Hz, the dynamic modulus grows faster, and when the frequency is greater than 15 Hz, the dynamic modulus tends to be stable. It is not difficult to find that 15 Hz is an inflection point of the dynamic modulus curve of the warm mix foamed asphalt mixture in the high-temperature environment; in addition, with the increase of foaming water consumption, the dynamic modulus of each type of mixture has different trends, but both show that the higher foaming water consumption is not conducive to the growth of the dynamic modulus of the warm foamed asphalt mixture. The reason for this phenomenon may be that when the water consumption for foaming is large, the half-life is shorter, the contact time with the aggregate during the mixing process cannot be guaranteed, the bonding is insufficient, and too much moisture will weaken the cohesive force of the asphalt and the aggregate, resulting in a decrease in dynamic modulus under the coupling of high temperature and dynamic load.

5.2. Effect of Ambient Temperature and Foaming Water Consumption on Dynamic Modulus. From the above-mentioned changes of the four different types of mixed foamed asphalt mixture in Figures 17–20, the dynamic modulus decreases with the increase of temperature; this

(a) (b)

Figure 4: Adhesive and test of foam asphalt mixture specimens.

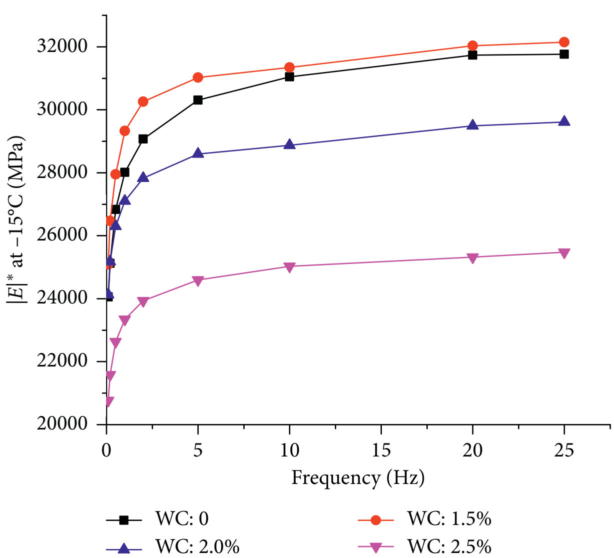


Figure 5: 70#AC-20-type low-temperature dynamic modulus.

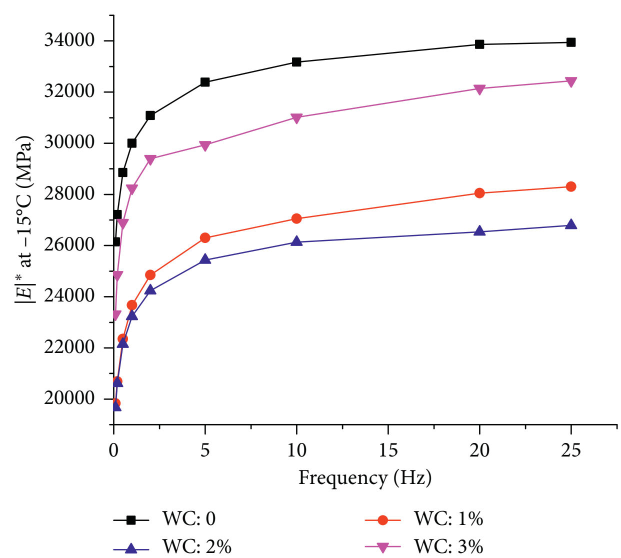


Figure 6: 90#AC-20-type low-temperature dynamic modulus.

phenomenon is mainly caused by the elastic viscoplasticity of the asphalt mixture. When the temperature is high, it is in a viscoplastic state. When the load is repeatedly applied, it is prone to plastic deformation, resulting in a decrease in dynamic modulus. On the other hand, in the low-temperature state, the asphalt mixture is basically in an elastic state; under the action of repeated load, the specimen is in the elastic recoverable deformation stage, there is no plastic deformation, and thus the dynamic modulus is increased.

In addition, the warm mix foam technology is used, and the dynamic modulus of the asphalt mixture is lower than that of the hot mix asphalt mixture. In the low-temperature environment, the influence of the grading type on the dynamic modulus of the warm mixed foam asphalt mixture is particularly prominent. The dynamic modulus of the AC-20 foam asphalt mixture changes greatly, while the AC-13 dynamic modulus does not change substantially; while in the normal temperature or normal-temperature environment, the dynamic modulus of the four types of foamed asphalt mixture does not change much, and the gradation has little effect; the result is likely to be AC-20-type grade coarse aggregate more, so that the mixture is not uniform, in the case of low temperature sensitivity to water.

6. Dynamic Modulus Master Curve Analysis

According to the test data of dynamic modulus under different temperatures and different frequencies, the Sigmoidal

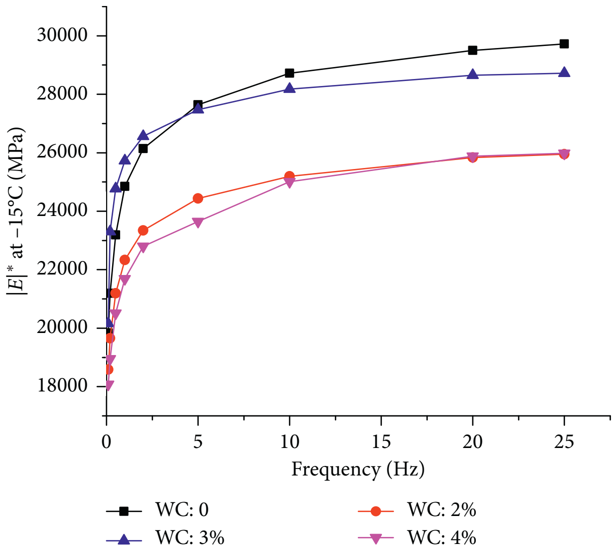


FIGURE 7: SBS#AC-20-type low-temperature dynamic modulus.

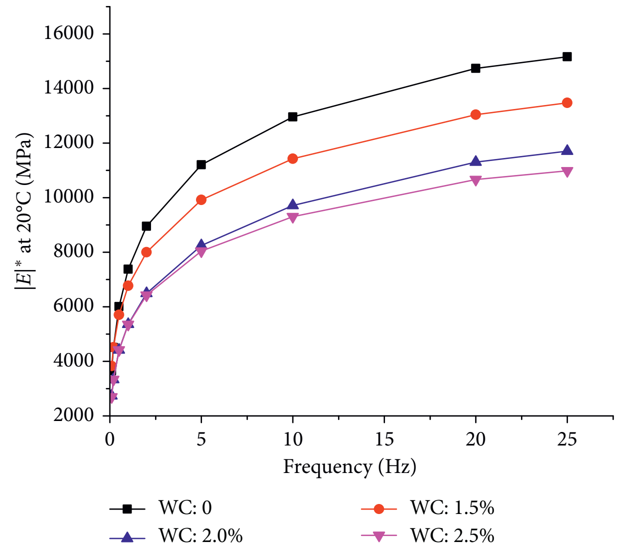


FIGURE 9: 70#AC-20-type normal-temperature dynamic modulus.

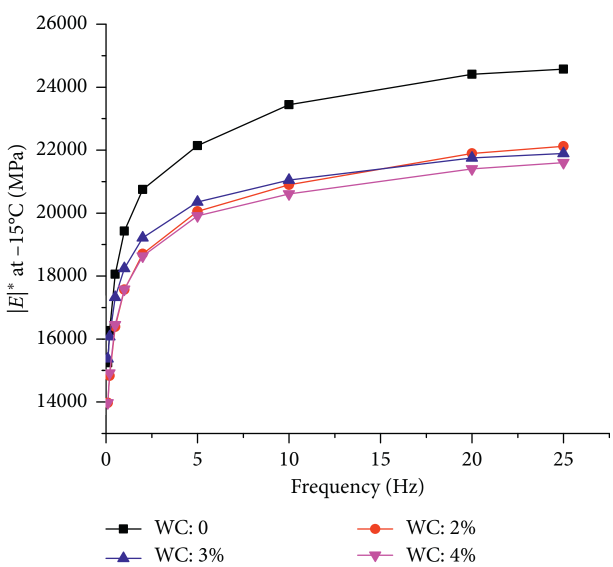


FIGURE 8: SBS#AC-13-type low-temperature dynamic modulus.

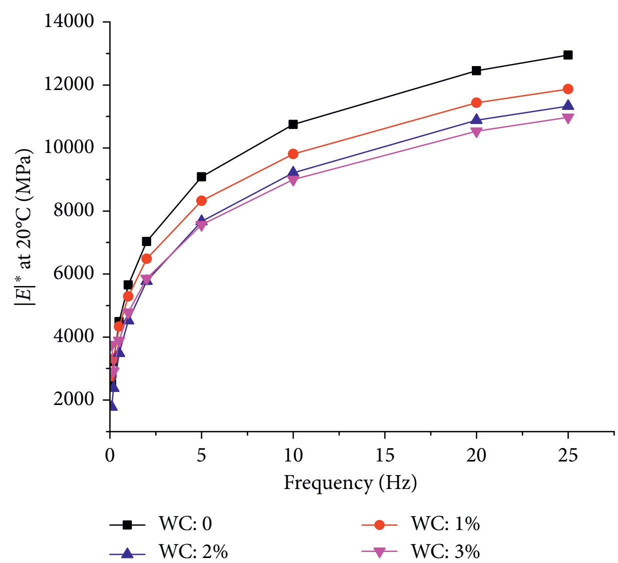


FIGURE 10: 90#AC-20-type normal-temperature dynamic modulus.

model is used to analyze the dynamic modulus master curve of the warm mix foamed asphalt mixture by means of the time-temperature equivalent transformation principle (Figures 21–24).

The dynamic modulus master curve reveals the variation of the mechanical properties of the material with the load frequency, while the shift factor reflects the mechanical influence of the test temperature on the material. The combination of the two can fully describe the mechanical properties of the warm mix foamed asphalt mixture with frequency and temperature, and the nonlinear least squares fitting solution is solved at the reference temperature—normal temperature 20°C. The specific results are shown in Table 6.

From the above chart, the following conclusions can be drawn.

The shift factor varies with different foaming water consumption and test temperature. When the temperature is >20°C, it is positive, and negative when temperature is ≤20°C. Among them, the fluctuation range of −15°C $\log(\alpha(T))$ is 3.9–5.2, and the fluctuation range of 45°C $\log(\alpha(T))$ is −3.0~−2.3.

(a) The larger foaming water consumption makes the master curve of the dynamic modulus of the warm mix foamed asphalt mixture lower, and the modulus value is smaller. It may be that the water remains in the mixture when the water consumption is too much, which weakens the cohesive force of the asphalt mixture.

(b) The effect of foaming water consumption on the dynamic modulus master curve equation is more

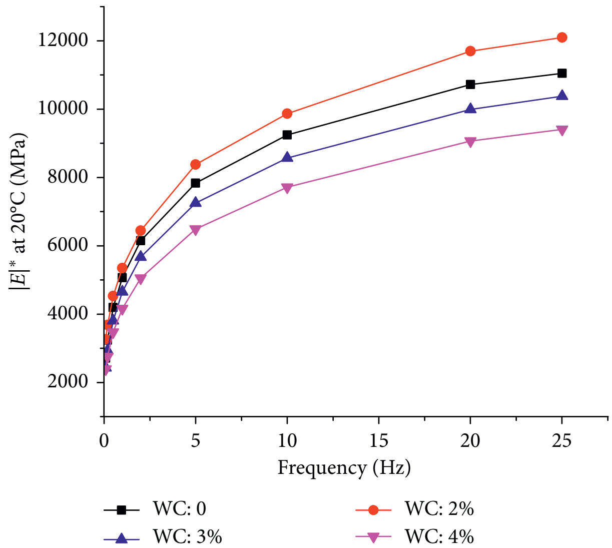


Figure 11: SBS#AC-20-type normal-temperature dynamic modulus.

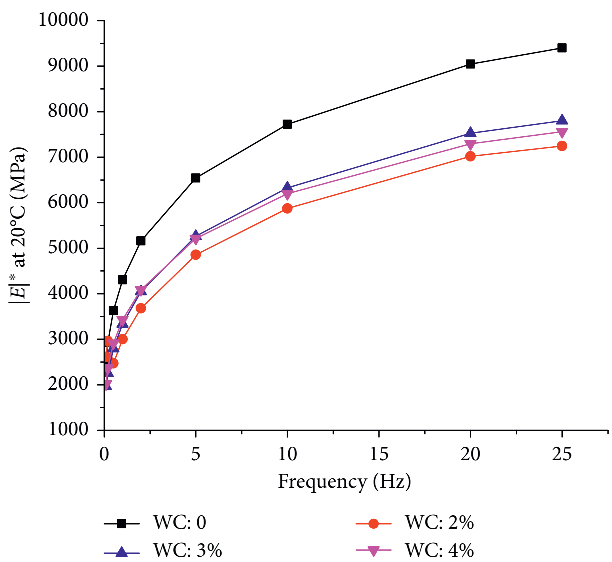


Figure 12: SBS#AC-13-type normal-temperature dynamic modulus.

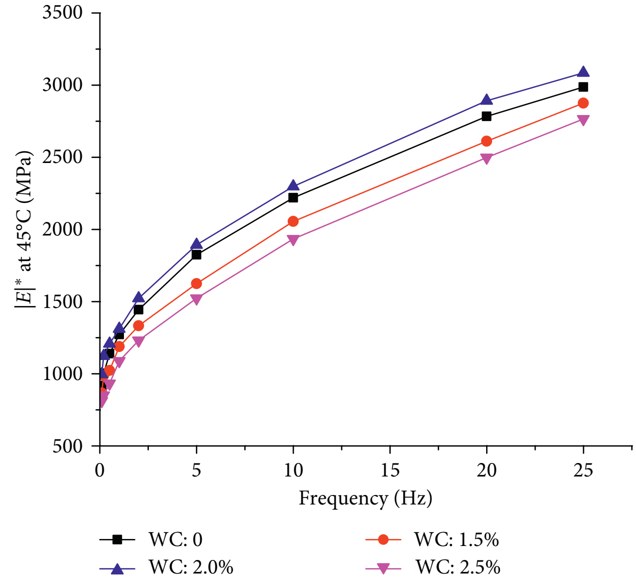


Figure 13: 70#AC-20-type high-temperature dynamic modulus.

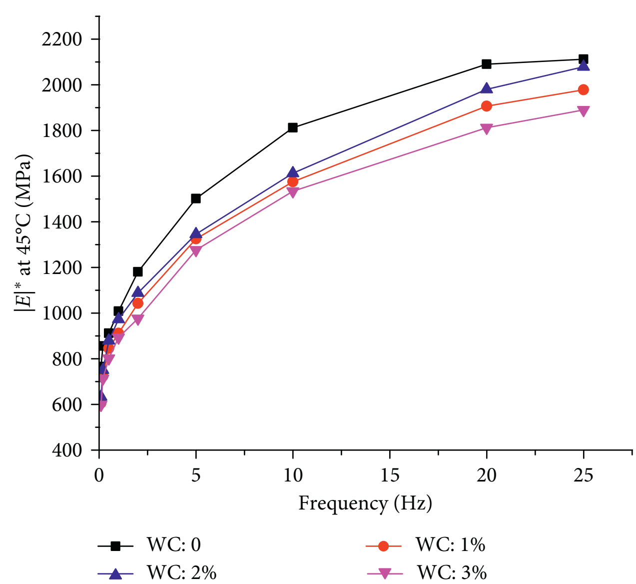


Figure 14: 90#AC-20-type high-temperature dynamic modulus.

prominent, especially the curve trend of low-temperature high-frequency region and its significance degree: AC-13 > AC-20.

7. Comparative Analysis of Compressive Rebound Modulus

In order to compare the dynamic modulus tests, the static compression modulus is tested to test the modulus of resilience of different types of mixed foamed asphalt mixtures to study the effect of load mode on the mechanical properties of the mixture, and the results of the test are shown in Table 7.

According to Table 7, after foaming the AC-20-type warm mix foamed asphalt mixture, compared with the corresponding hot mix asphalt mixture, its antipressure rebound modulus is slightly reduced, but the reduction is smaller; the law is similar to the corresponding dynamic modulus; for the SBS#AC-13-type warm mix foamed asphalt mixture, the antipressure rebound modulus increases and the growth rate is about 16.6%, which may be the effect of different gradations; for the 70#AC-20 type of warm mix foamed asphalt mixture with a water consumption of 2.0%, the modulus is small, which may be caused by test error.

In addition, the static modulus of 20°C for different types of warm mix foamed asphalt mixture is approximately 1200 MPa to 1700 MPa; combined with formulas (1)–(4), it can be predicted that the reduction frequency under the

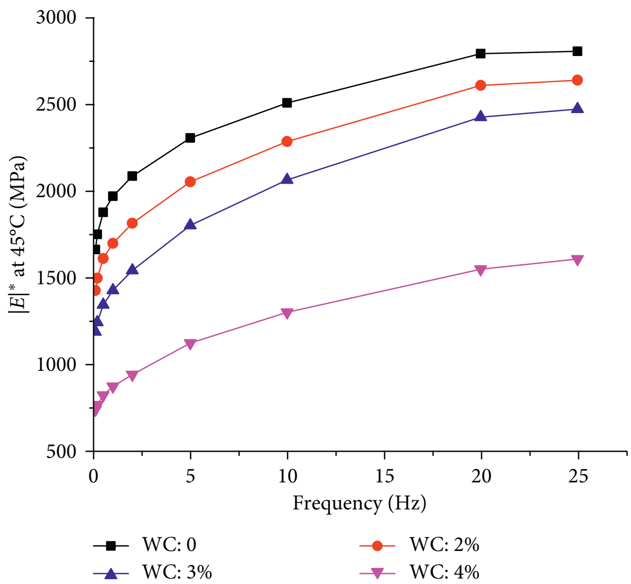


FIGURE 15: SBS#AC-20-type high-temperature dynamic modulus.

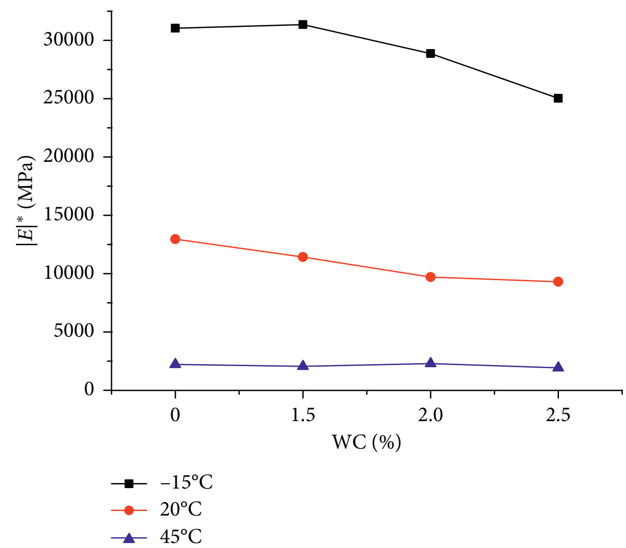


FIGURE 17: 70#AC-20-type dynamic modulus varying with water consumption and temperature.

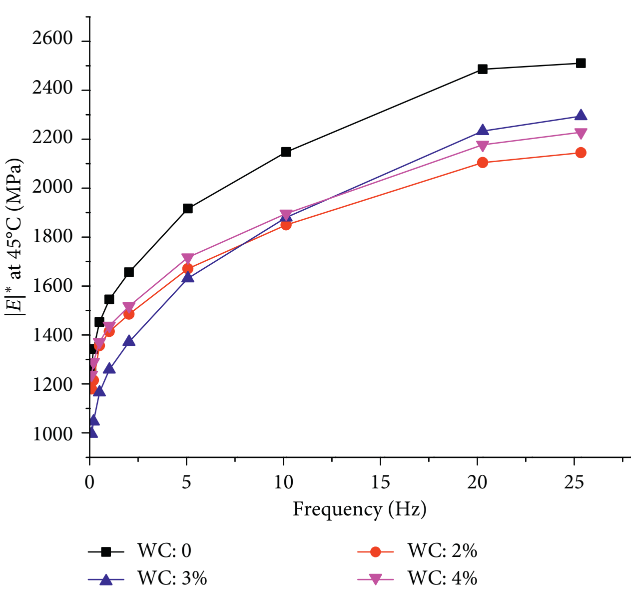


FIGURE 16: SBS#AC-13-type high-temperature dynamic modulus.

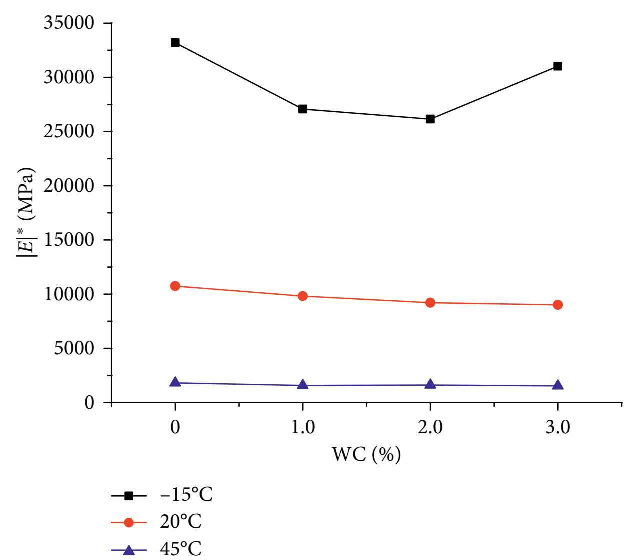


FIGURE 18: 90#AC-20-type dynamic modulus varying with water consumption and temperature.

corresponding modulus of unmodified warm mix foam asphalt mixture is 0.001 Hz–0.1 Hz, and the reduction frequency of the corresponding modulus of SBS# modified warm mix foamed asphalt mixture is 0.00001 Hz–0.05 Hz. The main cause of this phenomenon is caused by the static compression elastic modulus test method, and the load rate changes slowly, loaded in 7 levels and maintained for a certain period of time under each load, which is quite different from the stress mode of the asphalt pavement, and the test causes plastic damage of the mixture, which has an adverse effect on the static modulus test; it can be seen that the selection of dynamic modulus index for the design of warm mixed foam asphalt pavement has certain scientific significance.

8. Conclusions

(1) According to the time-temperature equivalent transformation principle of the mixture, using the Arrhenius equation and the Sigmoidal model, the dynamic modulus master curve and the shift factor are determined, and it provides a parameter basis for the dynamic analysis and structural design of the warm mix foamed asphalt mixture.

(2) The dynamic modulus change rule of the warm mix foamed asphalt mixture is similar to that of the ordinary asphalt mixture and has temperature-frequency dependence. As the frequency increases

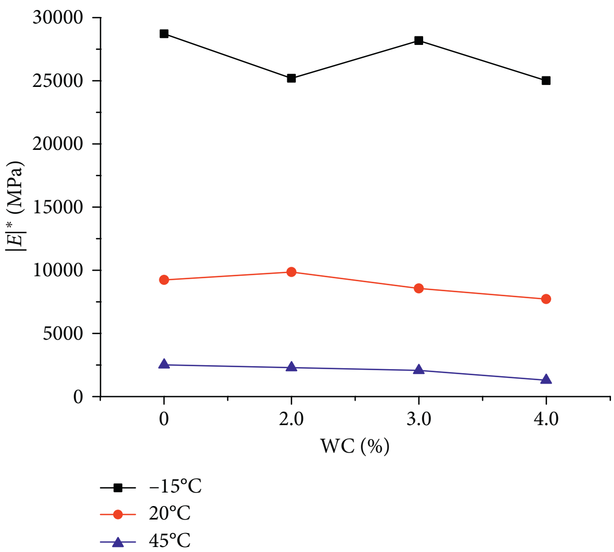


Figure 19: SBS#AC-20-type dynamic modulus varying with water consumption and temperature.

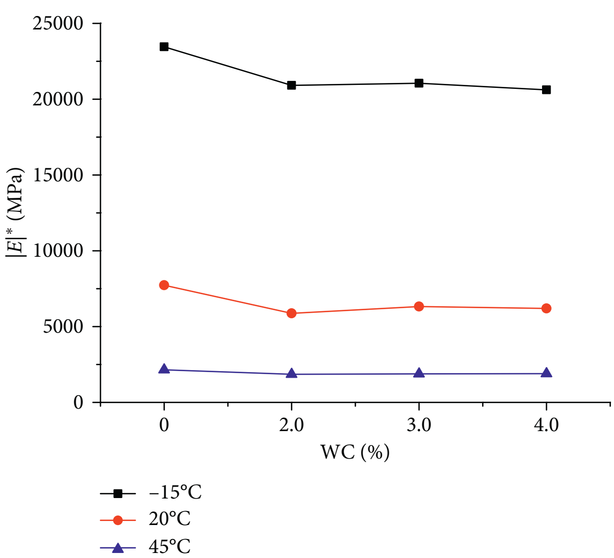


Figure 20: SBS#AC-13-type dynamic modulus varying with water consumption and temperature.

and the temperature decreases, the dynamic modulus increases and vice versa. For special climate of the seasonal frozen zone, based on UTM-100 dynamic modulus test, the curve inflection points of dynamic modulus with frequency under low temperature, normal temperature, and high temperature environment are 2 Hz, 10 Hz, and 15 Hz, respectively.

(3) The static modulus of the unmodified and SBS# modified warm mix foamed asphalt mixture corresponds to the dynamic modulus of the reduced frequency of 0.001 Hz to 0.1 Hz and 0.00001 Hz to 0.05 Hz, respectively. The effect of grading type on the dynamic modulus of warm mix foamed asphalt mixture is particularly prominent, and the degree of

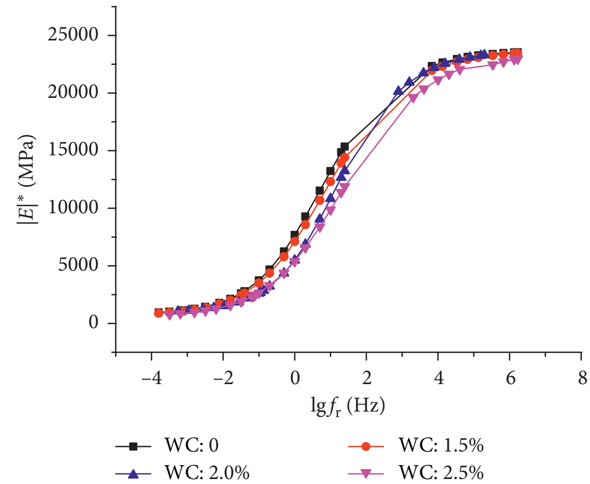


Figure 21: 70#AC-20-type dynamic modulus main curve.

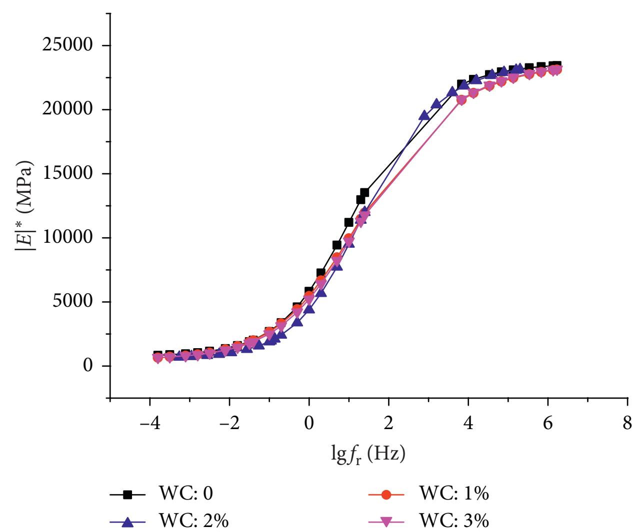


Figure 22: 90#AC-20-type dynamic modulus main curve.

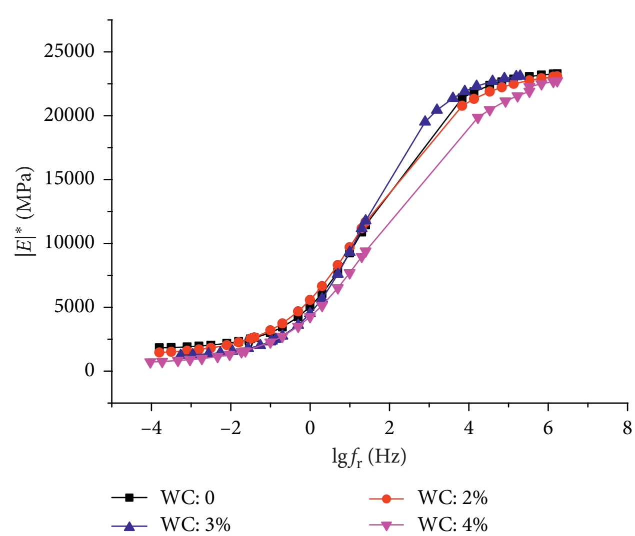


Figure 23: SBS#AC-20-type dynamic modulus main curve.

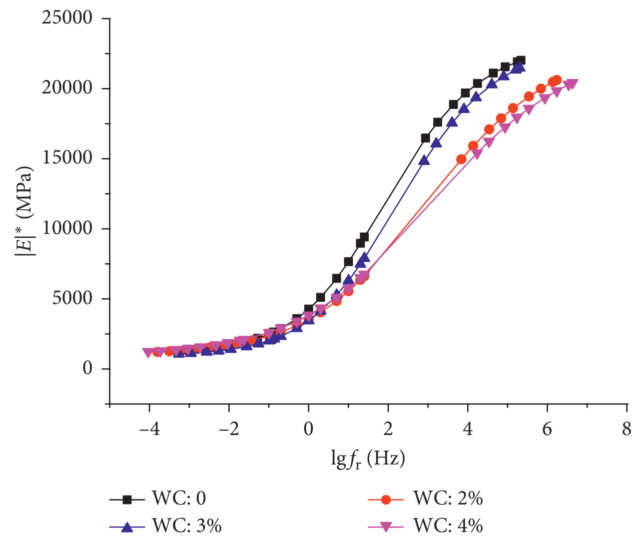


Figure 24: SBS#AC-13-type dynamic modulus main curve.

Table 6: Dynamic modulus master curve parameters and shift factor of warm mix foamed asphalt mixture at 20°C.

Type	Foaming water consumption (%)	Test temperature—$\log(\alpha(T))$			Master curve parameter				
		−15°C	20°C	45°C	Δ	ΔEa	β	γ	α
70#AC-20	0	4.8310	0	−−2.7999	5.0343	200000	−0.7275	−0.8663	6.6537
	1.5	4.8310	0	−2.7999	4.9836	200000	−0.6765	−0.8175	6.6853
	2.0	3.8985	0	−2.2595	5.1103	161397	−0.2191	−0.9408	6.6793
	2.5	4.3083	0	−2.4970	4.8939	178360	−0.4402	−0.7569	6.5959
90#AC-20	0	4.8310	0	−2.7999	5.0142	200000	−0.4054	−0.9003	6.7006
	1	4.8310	0	−2.7999	4.8252	200000	−0.5230	−0.7450	6.6009
	2	3.8985	0	−2.2595	4.9240	161397	−0.1873	−0.9362	6.5937
	3	4.8310	0	−2.7999	4.8489	200000	−0.4525	−0.7641	6.7143
SBS#AC-20	0	4.8310	0	−2.7999	5.4014	200000	0.3658	−0.9476	6.6181
	2	4.8310	0	−2.7999	5.2679	200000	−0.0236	−0.8046	6.5544
	3	3.8985	0	−2.2595	5.2151	161397	0.1793	−1.0002	6.6544
	4	5.2280	0	−3.0300	4.8991	216438	−0.1813	−0.6800	6.5614
SBS#AC-13	0	4.8310	0	−2.7999	5.1803	162959	0.1900	−0.7660	6.5706
	2	4.8310	0	−2.7999	5.1432	200000	0.3727	−0.5703	6.5712
	3	3.8985	0	−2.2595	5.1061	161397	0.3399	−0.7445	6.5391
	4	5.2280	0	−3.0300	5.1197	216438	0.2284	−0.5060	6.5420

Table 7: Antipressure rebound modulus of different types of temperature mixed foam asphalt mixture.

Foaming water consumption (%)	70#AC-20	90#AC-20	SBS#AC-20	SBS#AC-13
P_0	1548	1605	1571	1340
P_1	1402	966	1235	1401
P_2	1331	1464	1462	1562
P_3	1496	1576	1403	1663

significance is AC-20 > AC-13; and the order of sensitivity of foaming water consumption to the dynamic modulus master curve equation of different grades is AC-13 > AC-20.

(4) In this study, dynamic modulus was used as the evaluation index for studying the dynamic characteristics of warm mix foamed asphalt mixture. In the future, the phase angle index can be increased to study the viscoelastic characteristics theory of warm mix foamed asphalt mixture from the fine microscopic point of view.

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.

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