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Comparative Study on Complex Modulus and Dynamic Modulus of High-Modulus Asphalt Mixture

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Abstract: In the French high-modulus asphalt mixture design system, the complex modulus of the mixture under the conditions of 15 °C and 10 Hz is taken as the design index. However, in China, the dynamic modulus under the conditions of 15 °C, 10 Hz, 20 °C, 10 Hz and 45 °C, 10 Hz was taken as the stiffness modulus index of high-modulus asphalt mixture. The difference in modulus values between the two systems caused the pavement structure layer to be thicker and the construction cost to be higher in China. In order to find out the appropriate modulus value of high-modulus asphalt mixture suitable for China's modulus parameter conditions to better carry out the reasonable design and evaluation of high-modulus asphalt mixture in China, the modulus of four types of high-modulus asphalt mixtures under the two systems through the two-point bending complex modulus test of the CRT-2PT trapezoidal beam and the SPT uniaxial compression dynamic modulus test were analyzed in this paper. Under the premise of meeting the stiffness modulus index of the French high-modulus asphalt mixture, the relationship conversion models between the dynamic modulus and complex modulus of high-modulus asphalt mixture under different temperatures were established. According to the conversion models, the design evaluation value range of dynamic modulus suitable for China's condition was recommended. It is recommended that the dynamic modulus of China's high-modulus asphalt mixture at 15 °C and 10 Hz is not less than 16,000 MPa, the dynamic modulus at 20 °C and 10 Hz is not less than 14,000 MPa, and the dynamic modulus at 45 °C and 10 Hz is not less than 2500 MPa. Five kinds of high-modulus asphalt mixtures used in actual road engineering were tested to verify the reliability of the recommended dynamic modulus values based on the modulus conversion model, and the results are consistent with the recommended value range of the model.

Keywords: low-mark high-modulus mixture; complex modulus of trapezoidal beam; uniaxial compression dynamic modulus; conversion model

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1. Introduction

High-modulus mixture refers to an asphalt mixture with a complex modulus ≥14,000 MPa under the conditions of 15 °C and 10 Hz [1]. It was first proposed by French road workers and has been used in France for more than 20 years [2–7]. High-modulus mixture has become a research hotspot due to its excellent high temperature stability, strong resistance to water damage and good fatigue resistance, which has great advantages in reducing the thickness of pavement and saving resources [8,9]. Jong Lee [10] studied the use of high-modulus mixtures for long-life asphalt pavements. His work showed that the stiffness modulus of high-modulus mixtures is 50% higher than that of conventional asphalt mixtures, and that other road performances have been improved accordingly. The tensile strain of the high-modulus asphalt mixture structure layer is less than the allowable value of the long-life asphalt pavement. Arnold et al. [11]

developed the anti-rutting performance of high-modulus mixture EME (Enrobés à Module Elevé Class) for the rutting disease of road intersections. The test results show that the rutting resistance of the high-modulus mixture is 100 times higher than that of other mixtures. At the same time, this high-modulus mixture has a higher asphalt content, and the improvement of modulus and fatigue performance can reduce the thickness of the pavement by one third. Amjad et al. [12] studied the various aspects of hard asphalt high-modulus asphalt mixtures, which showed good fatigue and permanent deformation characteristics. Compared with conventional asphalt mixtures, its anti-fatigue damage ability is increased by 9.3%, and the modulus of resilience at 60 °C increased by 63%. Based on the Miner fatigue cumulative damage criterion, Jianping Xu [13] estimated the fatigue life of high-modulus pavement, and believed that the fatigue life of high-modulus pavement was 23.9% longer than that of conventional asphalt pavement.

In recent years, high-modulus asphalt mixtures have become more and more widely used in China. According to the LPC (Laboratoire Central des Ponts et Chaussées) Bituminous Mixtures Design Guide, the judgment of high-modulus mixture and the selection of modulus index should refer to the complex modulus of the trapezoidal beam under 15 °C and 10 Hz conditions [14]. However, In China, engineers and researchers believe that the dynamic modulus can better characterize the performance of asphalt mixtures [15–17]. They use the dynamic modulus of the mixture as the main reference parameter. In the engineering application of high-modulus mixtures, the selection of the stiffness modulus index of the mixture is more the dynamic modulus under the conditions of 15 °C, 10 Hz, 20 °C, 10 Hz and 45 °C, 10 Hz [18–21]. The CRT-2PT (Cooper Technology Two Point Trapezoidal Bending Test) complex modulus test and the SPT (Simple Performance Tester) dynamic modulus test are two different stiffness modulus tests; the SPT uniaxial compression dynamic modulus test is compression mode, while CRT-2PT trapezoidal beam complex modulus test is bending-tension mode. Different loading methods will cause big differences in test results. In China, if the high-modulus mixture is designed based on the complex modulus index value, the design of the pavement structure layer thickness will be too large, due to the small modulus value, and the construction cost will be greatly increased. Moreover, the complex modulus test equipment for trapezoidal beams is expensive, which is difficult to popularize in China. Some scholars have carried out a comparative study of dynamic modulus tests and trapezoidal beam complex modulus tests. Huang You et al. [22–24] selected four mixtures for the dynamic modulus test and the trapezoidal beam complex modulus test. The two test methods were evaluated from the test principle, operation process and test data. It is recommended to use the SPT dynamic modulus test for the compressive upper layer asphalt mixture, and the trapezoidal beam complex modulus test for the middle and lower layer mixture, which is mainly subjected to bending and tension. Although a large number of experimental studies have been conducted on the modulus of the mixture under the two test systems, there is no clear answer as to whether the modulus index of the French high-modulus asphalt mixture can be reached, and the range of the dynamic modulus technical index of high-modulus mixture suitable for Chinese characteristics has not been proposed.

Therefore, the modulus under the two evaluation systems through the two-point bending complex modulus test of CRT-2PT trapezoidal beams and the SPT uniaxial compression dynamic modulus test was analyzed in this paper. Under the premise of satisfying the complex modulus $\geq$14,000 Mpa under the conditions of 15 °C and 10 Hz, the conversion relationship model between the complex modulus of the trapezoidal beam and the uniaxial compression dynamic modulus was established. Based on the conversion model, a range of values suitable for the design and evaluation of the dynamic modulus of high-modulus mixtures in China was recommended and verified, which provides a reference for the design and evaluation of high-modulus mixtures in China using dynamic modulus parameters. It can effectively promote the wide application of high-modulus mixtures in engineering construction in China.

2. Materials and Experimental

2.1. Materials

The crushed limestone and its ground ore powder were used as aggregates and filler, the technical indicators of which meet the requirements of standard JTG-F40-2004 [21], respectively, as shown in Table 1.

Table 1. Properties of coarse and fine aggregate.

	Technical Index		Test Results	Index Requirements
Coarse aggregate	Apparent relative density	15–20 mm	2.762	≤2.50
		10–15 mm	2.732	
		5–10 mm	2.746	
		3–5 mm	2.758	
	Water absorption rate (%)	15–20 mm	0.45	≤3.0
		10–15 mm	0.32	
		5–10 mm	0.45	
		3–5 mm	0.63	
	Crushing value (%)	-	19.2	≤28
	Needle flake content (%)	15–20 mm	3.5	≤18
		10–15 mm	9.3	
		5–10 mm	10.7	
	Soft stone content (%)		0.55	≤5
	Washing method <0.075 mm particle content (%)	15–20 mm	0.3	≤1.0
		10–15 mm	0.6	
		5–10 mm	0.4	
		3–5 mm	0.9	
	Adhesion to asphalt, grade		5	≥4
Fine aggregate	Apparent relative density		2.644	≥2.5
	Sand equivalent (%)		67	≥60
	Angularity of fine aggregate (s)		36	≥30
	Methylene blue (g/Kg)		7	≤25

Two types of low-grade asphalt were used in the French high-modulus mixture. One is the hard asphalt with the label of 10/20, namely France 15# hard asphalt, the other is China 15# hard asphalt, which has similar performance to France 15#. The technical indicators of the two types of hard bitumen meet the requirements of standard JTG-F40-2004, and the test results are shown in Tables 2 and 3.

Table 2. Asphalt conventional technical indicators.

Pilot Projects		China 15#	France 15#
Penetration (100 g, 5 s, 25 °C)/0.1 mm		15.2	16.8
Softening Point (5 °C)/°C		64.25	66.6
Ductility (5 cm/min,15 °C)		Brittle	Brittle
Solubility/%		99.6	99.78
density (15 °C)/g/cm3		1.029	1.033
Flash point/°C		280	344
dynamic viscosity/Pa·s		6076	7219
RTFOT	Quality change/%	−0.31	0.051
	Residual penetration ratio/%	78	71.6

Table 3. Maximum deformation and elastic recovery rate.

Asphalt Material	9.75Psi		20Psi	
	Maximum Creep Deflection (mm)	Elastic Recovery Rate (%)	Maximum Creep Deflection (mm)	Elastic Recovery Rate (%)
China 15#	0.0039	82.1	0.0128	61.7
France 15#	0.0046	79.5	0.0104	65.4

2.2. Mix Design

EME-14 and AC-20, two types of typical high-modulus mixture gradations for France and China, suitable for the middle and lower layers, were selected in this study. According to the aggregate screening results and the actual high-modulus road engineering application situation, the design composite gradation was shown in Table 4.

Table 4. Synthetic gradation design of high-modulus mixture.

Particle Diameter (mm)	Mass Percentage of Particles Smaller Than a Certain Particle Diameter (%)				
	EME-14	HMAC-20	Design Upper Limit	Design Lower Limit	Design Median
26.5	100	100	100	100	100
19	100	93.8	100	90	95
16	100	88.4	-	-	-
13.2	99.4	81.3	-	-	-
9.5	90.2	69.2	82	66	74
4.75	48.8	43.6	64	41	52.5
2.36	33.1	29.6	43	28	35.5
1.18	26.4	24	-	-	-
0.6	16.6	16.3	-	-	-
0.3	11.2	12.1	-	-	-
0.15	8.5	7.9	-	-	-
0.075	6.5	6	8	6	7

The asphalt binder dosage is determined by the abundance coefficient K. The abundance coefficient K is a ratio of the conventional thickness of the asphalt film attached to the surface of the aggregate with an asphalt binder [25]. K has nothing to do with the density of gravel; according to the LPC Bituminous Mixtures Design Guide, the amount of asphalt is calculated and estimated by the abundance coefficient K, which satisfies $K \geq 3.4$. The asphalt binder dosage of high-modulus mixture was calculated according to Equations (1)–(3), shown in Table 5.

Table 5. Abundance coefficient calculation table.

Mixture Type	G (%)	S (%)	s (%)	f (%)	ρG	Oil-Stone Ratio/%	Abundance Coefficient
EME-14	37	50.4	4.2	7.7	2.730	5.7	3.46
HMAC-20	58.6	33.2	3.4	4.8	2.730	5.3	3.44

The relationship between the abundance coefficient K and the oil-stone ratio:

$$TL_{ext} = K \times \alpha \sqrt[5]{\sum} \quad (1)$$

$$100 \sum = 0.25G + 2.3S + 12s + 150f \quad (2)$$

$$\alpha = \frac{2.65}{\rho G} \quad (3)$$

where:

TL_{ext} is the percentage of admixture (whetstone ratio), %

K is specific surface area, m^2/kg

G is the ratio of aggregates with a particle size greater than 6.3 mm, %
S is the ratio of aggregates with a particle size of 0.25 mm~0.63 mm, %
s is aggregate ratio with a particle size of 0.063 mm~0.25 mm, %
F is the ratio of aggregates with a particle size of less than 0.063 mm, %
α is correlation coefficient related to aggregate density
ρG is density of aggregate, g/cm^3

2.3. Test Methods

2.3.1. High-Modulus Mixture Performance Index Verification Test

The performance of four kinds of high-modulus mixtures, EME-14 + France 15#, EME-14 + China 15#, HMAC-20 + France 15#, HMAC-20 + China 15#, under level 1 to level 4, was verified according to the LPC Bituminous Mixtures Design Guide to evaluate whether it meets the performance index requirements of high-modulus mixtures. The test methods were shown in Table 6. Under the premise of meeting the performance index of high-modulus mixture, using the SPT and CRT-2PT performance testing machines, the mixtures were subjected to a uniaxial compression dynamic modulus test and a two-point bending complex modulus test at different temperatures and frequencies. The modulus of the mixture under the two systems was analyzed according to the test schemes as shown in Table 7.

Table 6. High-modulus mixture performance index verification test plan.

Test Level	Test Item	Test Methods
Level 1	Rotational compaction void ratio (%)	EN 12697-31 [26]
	Water stability: Durex test (Compressive strength ratio, %)	EN 12697-12 (Method B) [27]
Level 2	High temperature stability: French wheel rutting test (30,000 times, 60 °C)	EN 12697-22 [28]
Level 3	Stiffness modulus: complex modulus (MPa, 15 °C, 10 Hz/0.02 s)	EN 12697-26 [29]
Level 4	Fatigue life: two-point bending fatigue of trapezoidal beam (10 °C, 25 Hz, 106 times, 130 με)	EN 12697-24 [30]

Table 7. Test schemes of mixture stiffness modulus under different evaluation systems.

Test Parameters	Test Plan	
	Complex Modulus of Trapezoidal Beam	Uniaxial Compression Dynamic Modulus
Test piece size	Height: 250 ± 1 mm, thickness: 25 mm ± 1 mm Top bottom: 25 ± 1 mm, bottom: 56 mm/70 mm ± 1 mm	Diameter: 100 mm, height: 150 mm standard specimen
Strain level	30 με	75–125 με
Test temperature	5, 15, 20, 30, 45 °C	5, 15, 20, 30, 45 °C
Test frequency	1, 5, 10, 15, 20, 25 Hz	0.1, 0.2, 0.5, 1, 2, 5, 10, 20, 25 Hz
Number of parallel tests	6	

2.3.2. Complex Modulus Test

According to the European Design Code [25,29], the CRT-2PT two-point trapezoidal beam bending test machine shown in Figure 1 was used to conduct the complex modulus test, which is realized by the two-point bending loading method. CRT-2PT adopts the strain control mode with sine wave waveform. The 30με strain level, 5 test temperatures of 5, 15, 20, 30, 45 °C and 6 loading frequencies of 1, 5, 10, 15, 20, 25 Hz were selected in the test. At the beginning of the test, the trapezoidal beam specimen was vertically installed and fixed in the temperature control box, and the top of the specimen was subjected to a constant sine wave load and reciprocated in the horizontal direction. At the same time, shear stress and bending moment were generated inside the specimen. The force state of the specimen was shown in Figure 2, close to the force state of the actual pavement.

During the test, the displacement and force changes of the specimen during the horizontal reciprocating movement were recorded by the displacement sensor and the stress sensor, which simulates the bending and tensile deformation of the bottom of the asphalt layer on the road surface to obtain the complex modulus of the mixture.



(**a**) (**b**)

Figure 1. Schematic diagram of 2PT (**a**) and SPT (**b**) loading equipment.

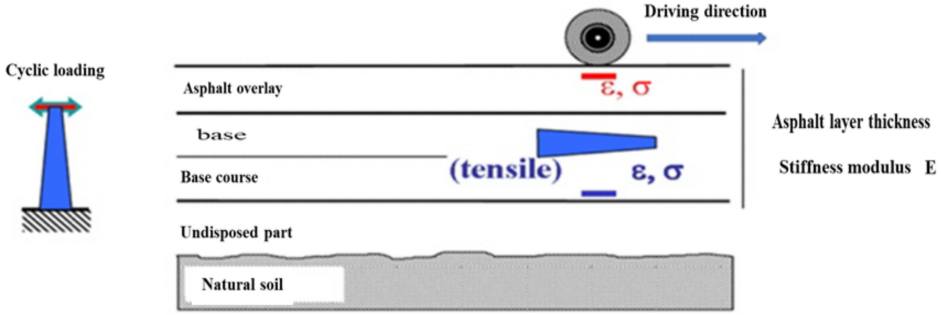


Figure 2. The principle of loading the complex modulus of trapezoidal beam in two-point bending.

During the test, the real and imaginary parts of the complex modulus of the asphalt mixture were calculated according to Equations (4) and (5).

$$E_1 = \gamma \times \frac{F}{z} \times \cos(\phi) \times \frac{\mu}{10^3} \times \omega^2 \quad (4)$$

$$E_2 = \gamma \times \frac{F}{z} \times \sin(\phi) \quad (5)$$

where: γ is shape factor; F is load force; z is displacement of the top of the specimen; μ is quality factor; ω is angular velocity; φ is the phase difference of the top displacement of the specimen/°.

γ and μ is calculated according to Equations (6) and (7).

$$\gamma = \frac{12L^2}{b(h_1 - h_2)} \times \left[(2 - \frac{h_2}{2h_1}) \times \frac{h_2}{h_1} - \frac{3}{2} - Ln\frac{h_2}{h_1} \right] \quad (6)$$

$$\mu = 0.135M + m \quad (7)$$

The meaning of h_1, h_2 and b is shown in Figure 3.

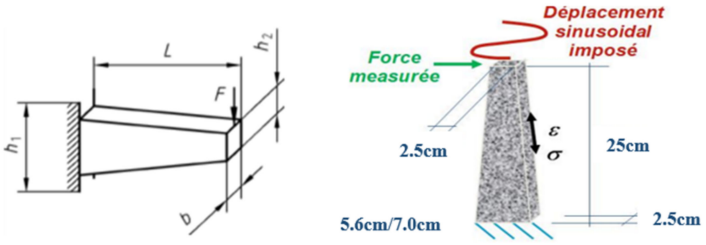


Figure 3. Dimensions of trapezoidal beam specimen.

The modulus and phase angle of the mixture's modulus were calculated according to Equations (8) and (9).

$$|E^*| = \sqrt{E_1^2 + E_2^2} \tag{8}$$

$$\phi = \arctan\frac{E_2}{E_1} \tag{9}$$

2.3.3. Dynamic Modulus Test

The SPT testing machine produced by IPC Global in Australia, as shown in Figure 1, was used to conduct the uniaxial compression dynamic modulus test. It applied axial and sinusoidal periodic loads to a standard cylindrical specimen with a height of 150 mm and a diameter of 100 mm, at different temperature and loading frequency, as shown in Figure 4. SPT adopted the strain control mode with a half-sine wave loading waveform. The SPT testing machine cannot accurately control the strain level, so the strain control value range 75–125 με recommended by the NCHRP9-29 was used in the test. A total of 5 temperatures of 10, 15, 20, 30, 45 °C and 9 loading frequencies of 0.1, 0.2, 0.5, 1, 2, 5, 10, 20, 25 Hz were selected. The sample was tested after keeping it at each temperature for 5 h. The sinusoidal periodic load can be calculated by Equations (10) and (11). By measuring the load and strain acting on the specimen during the last 5 loading cycles, the axial stress and strain amplitude were obtained, and then the axial recoverable deformation of the specimen and the dynamic modulus and phase angle were calculated according to Equations (12)–(14).

$$\sigma(t) = \sigma_0 \sin \omega t \tag{10}$$

$$\omega = 2\pi f \tag{11}$$

where: ω is loading angular frequency; t is time; f is loading frequency.

$$\sigma_0 = \frac{\overline{P}}{A} = 4\frac{\overline{P}}{\pi D^2} \tag{12}$$

where: σ_0 is stress amplitude; $\overline{P}$ is the average load amplitude; A is loading area; D is specimen diameter.

$$\varepsilon_0 = \frac{\Delta\bar{t}}{t_0} \tag{13}$$

where: ε_0 is strain amplitude; $\Delta\bar{t}$ is the average value of the axial deformation amplitude; t_0 is the measurement distance.

$$E_d = \frac{\sigma_0}{\varepsilon_0} \tag{14}$$

where: E_d is dynamic modulus.

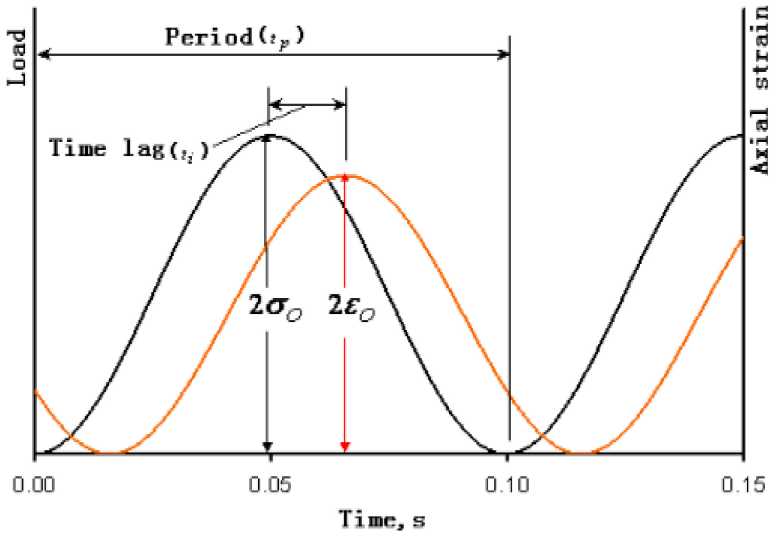


Figure 4. Loading mode of SPT uniaxial compression dynamic modulus test.

3. Test Results and Analysis

3.1. Performance Verification of High-Modulus Mixture

The performance of four types of high-modulus mixtures, EME-14 + France 15#, EME-14 + China 15#, HMAC-20 + France 15#, HMAC-20 + China 15#, under level 1 to level 4, is displayed in Table 8. The designed mixtures all meet the performance index requirements of high-modulus mixtures.

Table 8. Performance test results of level 1 to level 4.

Test Level	Test Item	Test Results				Technical Index Requirements
		China 15#		France 15#		
		EME-14	HMAC-20	EME-14	HMAC-20	
Level 1	Rotational compaction void ratio (%)	3.35	3.82	3.27	3.69	<6%
	Durex test (ITSR, %)	100.23	101.25	101.22	101.92	≥70%
Level 2	French wheel track test (30,000 times, 60 °C, deformation rate)	4.32	5.13	4.17	4.92	≤7.5%
Level 3	Complex modulus (15 °C, 10 Hz, MPa,)	16,219	14,027	16,139	14,333	≥14,000 MPa
Level 4	Two-point bending fatigue of trapezoidal beam (10 °C, 25 Hz, 130 με, times)	1,220,320	1,082,310	1,340,350	1,108,630	$\geq 10^6$

3.2. Comparative Analysis of Modulus

The CTR-2PT trapezoidal beam two-point bending complex modulus test and the SPT uniaxial compression dynamic modulus test were carried out on four kinds of high-modulus mixtures. The modulus and phase angle results of the high-modulus mixture under the two test modes at the main evaluation temperature are shown in Tables 9 and 10. The modulus decreased with the increase of temperature, and increased with the increase of loading frequency. Under the same temperature and loading frequency, the dynamic modulus was higher than the complex modulus. Taking EME-14 + China 15# as an example, the dynamic modulus is 17.6% higher than the complex modulus at 15 °C and 25 Hz loading frequency.

Table 9. Dynamic modulus results of different types of low-mark high-modulus mixtures.

Types	Void Ratio (%)	Loading Frequency (Hz)	Dynamic Modulus (MPa)			Phase Angle (°)		
			15 °C	20 °C	45 °C	15 °C	20 °C	45 °C
EME-14 + China 15#	3.76	25	22,232	18,591	5741	10.41	11.96	28.94
		20	21,631	17,998	5358	10.74	12.39	28.76
		10	19,932	16,340	4279	11.84	13.83	30.28
		5	18,258	14,707	3367	13.17	15.41	31.54
		2	15,973	12,549	2398	15.06	17.73	32.56
		1	14,240	11,009	1838	16.61	19.52	32.33
		0.5	12,570	9496	1402	18.32	21.40	31.71
		0.2	10,442	7694	985	20.66	23.99	30.6
		0.1	8934	6493	762	22.5	25.82	29.07
EME-14 + France 15#	3.82	25	20,456	18,836.5	5888.5	9.33	11.47	29.27
		20	20,117	18,355.5	5450.5	9.78	11.71	29.26
		10	18,771	16,816	4255	11.22	12.965	29.98
		5	17,273	15,267	3141.5	12.54	14.425	30.45
		2	15,254	13,230	2121.5	14.39	16.455	30.97
		1	13,669	11,631.5	1730.5	15.82	18.125	30.47
		0.5	12,116	10,194.5	1315	17.32	19.83	30.04
		0.2	10,163	8385.5	935.1	19.49	22.21	29.22
		0.1	8744	7168.5	734.1	21.12	23.94	27.24
HMAC-20 + China 15#	3.93	25	19,958	17,915	5955	10.99	11.96	28.94
		20	19,065	17,246	5139	11.24	12.18	28.76
		10	17,885	15,747	4261	12.49	13.44	30.28
		5	16,254	14,280	3285	13.86	14.99	31.54
		2	14,071	12,389	2197	15.93	16.98	32.56
		1	12,466	10,797	1597	17.58	18.67	32.33
		0.5	10,944	9445	1244	19.26	20.4	31.71
		0.2	9015	7756	862.1	21.56	22.85	30.6
		0.1	7722	6615	655.2	23.23	24.65	29.07
HMAC-20 + France 15#	3.76	25	19,675	17,374	6122	11.29	12.67	28.88
		20	18,865	16,940	5612	12.21	13.07	29.05
		10	17,227	15,382	4349	13.17	14.42	30.93
		5	15,643	13,835	3478	14.31	15.91	31.72
		2	13,552	11,906	2046	15.98	17.91	32.76
		1	12,052	10,478	1804	17.26	19.49	32.59
		0.5	10,620	9112	1386	18.57	21.16	31.16
		0.2	8829	7426	1008	20.38	23.34	30.29
		0.1	7604	6306	813	22.68	24.78	29.82

3.3. Master Curve Analysis

The master curve can fully and intuitively reflect the mechanical properties of the asphalt mixture [31–33]. When estimating the permanent deformation and fatigue life of an asphalt pavement, the modulus and phase angle of the asphalt mixture under different temperature and loading frequency conditions are usually considered. According to the data in Tables 9 and 10, the modulus master curve and phase angle master curve of four high-modulus mixtures at standard temperature, which is 15 °C for the trapezoidal beam and 20 °C for the SPT, were established by using the principle of time-temperature equivalence. The main curves of the modulus and phase angle for the trapezoidal beam complex modulus test and the SPT dynamic modulus test were shown in Figures 5 and 6, respectively.

The overall change trend of the modulus master curve obtained by the two test methods is consistent, but the frequency domain of the SPT dynamic modulus master curve is wider, which is caused by the test loading frequency range of the two. The minimum loading frequency of the SPT test was 0.01 Hz, while that of the trapezoidal beam test was 5 Hz. In contrast, the main modulus curve obtained by the trapezoidal beam does not extend to the low frequency region.

Table 10. Complex modulus results of different types of low-mark high-modulus mixtures at 15 °C.

Types	Void Ratio (%)	Loading Frequency (Hz)	Complex Modulus (MPa)	Phase Angle (°)
EME-14 + China 15#	4.12	25	18,300	9.189264
		20	17,684	9.547917
		15	16,848	10.24761
		10	16,219	10.40017
		5	15,001	11.44451
		1	12,085	11.96734
EME-14 + France 15#	3.93	25	17,226	8.582561
		20	17,064	9.387128
		15	16,550	9.942839
		10	16,139	10.0863
		5	15,010	10.78818
		1	13,124	11.56282
HMAC-20 + China 15#	4.07	25	15,956	9.218034
		20	14,842	10.34659
		15	14,329	11.08765
		10	14,027	10.79887
		5	12,929	11.81575
		1	10,284	12.015642
HMAC-20 + France 15#	4.15	25	16,228	9.977964
		20	15,725	9.873416
		15	14,835	10.23612
		10	14,333	9.987529
		5	13,255	10.85202
		1	10,990	11.36823

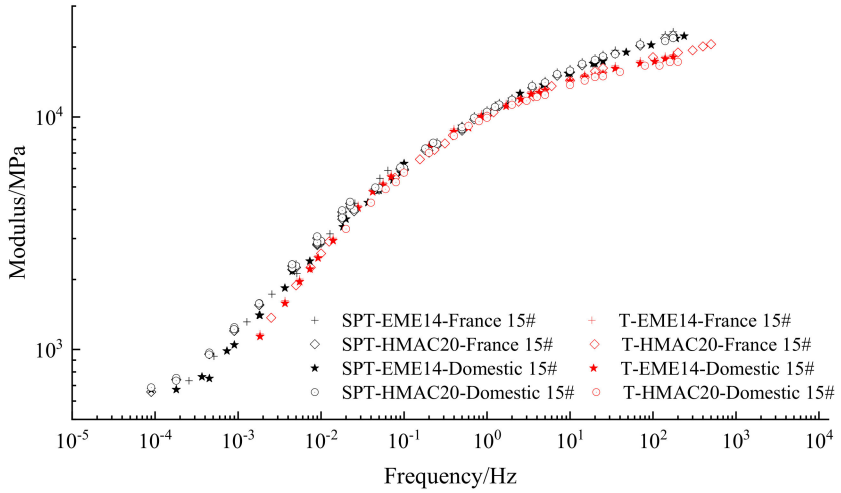


Figure 5. Modulus master curves of high-modulus mixtures with different test method.

The SPT modulus master curve established based on the respective standard temperature translation is higher than the CRT-2PT complex modulus master curve, which shows that the dynamic modulus obtained by the SPT test is greater than the complex modulus obtained by the trapezoidal beam test. It is mainly due to the fact that the compressed mode was used in the SPT test, while the bending-tension mode was used in the CRT-2PT trapezoidal beam complex modulus test.

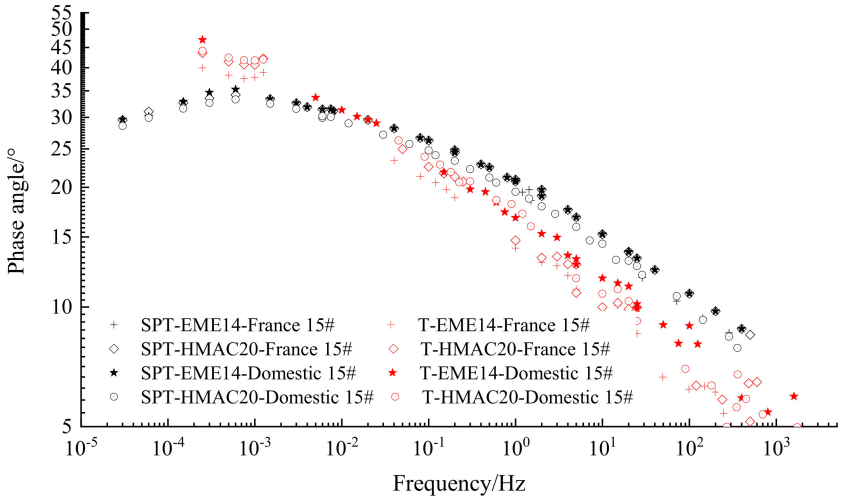


Figure 6. Phase angle master curves of high-modulus mixtures with different test method.

The specimen was continuously compacted under the load in the SPT test, and became increasingly denser without damage, causing the obtained modulus value to be too large. However, the specimen was in the state of bending-tension, and the load effect is unfavorable to the specimen, causing the measured modulus value to be too small [34–37].

Compared with the main curve of the modulus, the main curve of the phase angle of the mixture under the two loading modes is also different; however, the overall change trend is the same. The phase angle of the mixture decreases with the increase of frequency. The phase angle data is more discrete, and the main curve fitting result is not ideal. This was caused by the test equipment, the limitation of the loading frequency range of the two-point trapezoidal beam bending test machine, the molding of the test piece, and the test operation.

3.4. Conversion Relation Model between Complex Modulus and Dynamic Modulus

In the French high-modulus mixture design and evaluation system, the stiffness modulus index refers to the complex modulus of the trapezoidal beam under the conditions of 15 °C and 10 Hz. However, in the design of the Chinese high-modulus mixture, the dynamic modulus of uniaxial compression under the conditions of 15 °C and 10 Hz, 20 °C and 10 Hz, 45 °C and 10 Hz is often used for design and evaluation. Combined with the China high-modulus mixture modulus parameter conditions, under the premise that the performance index of the mixture meets the complex modulus index requirement of the French high-modulus mixture, the modulus conversion model between the complex modulus of the CRT-2PT trapezoidal beam and the dynamic modulus of the SPT uniaxial compression was established, as shown in Figures 7–10. When the complex modulus of the mixture trapezoidal beam is 14,000 MPa, the dynamic modulus value under different temperature conditions was calculated according to the conversion model. According to the calculated results, the value range of the dynamic modulus under the condition modulus parameter in China was recommended. The results are shown in Table 11.

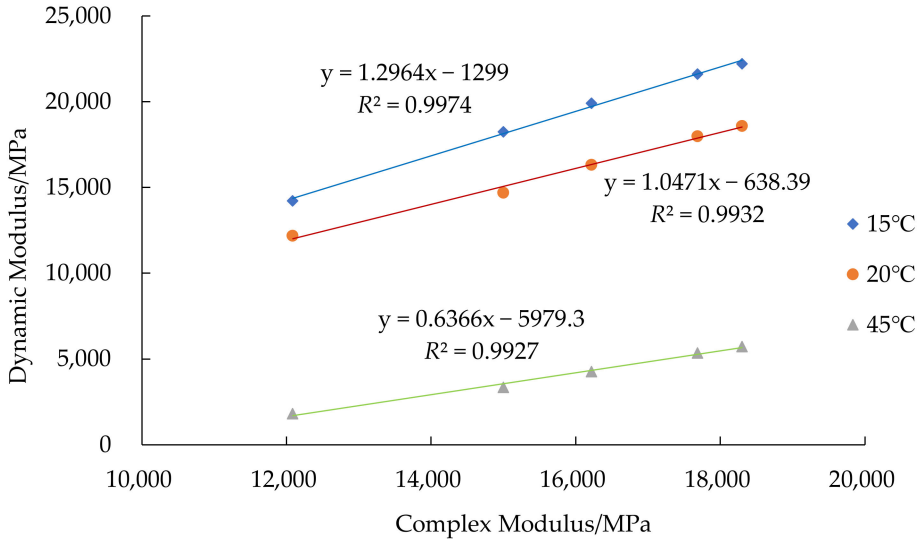


Figure 7. EME-14-China 15#.

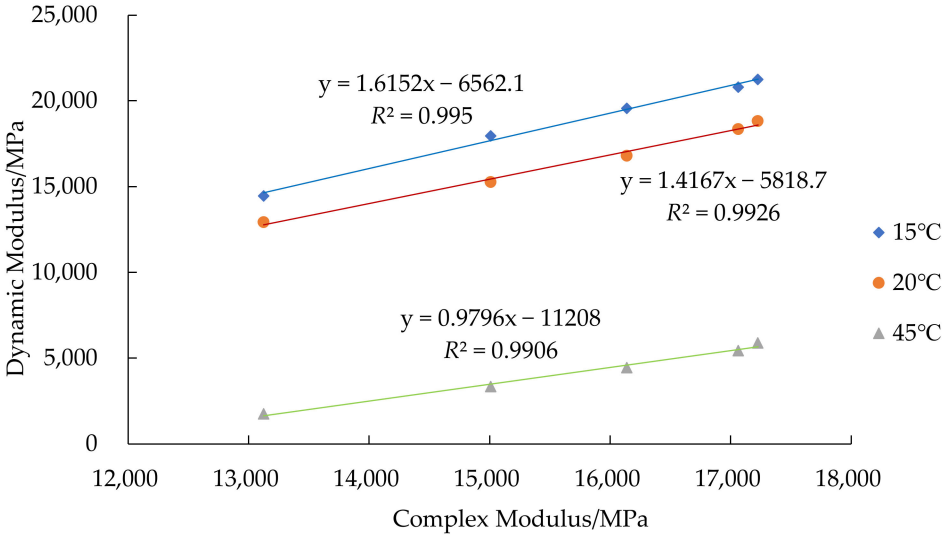


Figure 8. EME-14- France 15#.

It can be seen from Figures 5–8 that the complex modulus of different types of high-modulus mixtures was positively correlated with the dynamic modulus, and the correlation coefficients of the fitted linear equations were all above 0.99, showing a good correlation between the modulus obtained by these two test methods.

Different types of high-modulus mixtures have different dynamic modulus evaluation values according to the established conversion model.

Taking the error of the fitting formula or other factors into account, it is recommended when using the dynamic modulus parameter to evaluate high-modulus mixtures that the dynamic modulus at 15 °C and 10 Hz is not less than 16,000 MPa, the dynamic modulus at 20 °C and 10 Hz is not less than 14,000 MPa and the dynamic modulus at 45 °C and 10 Hz is not less than 2500 MPa, as shown in Table 11.

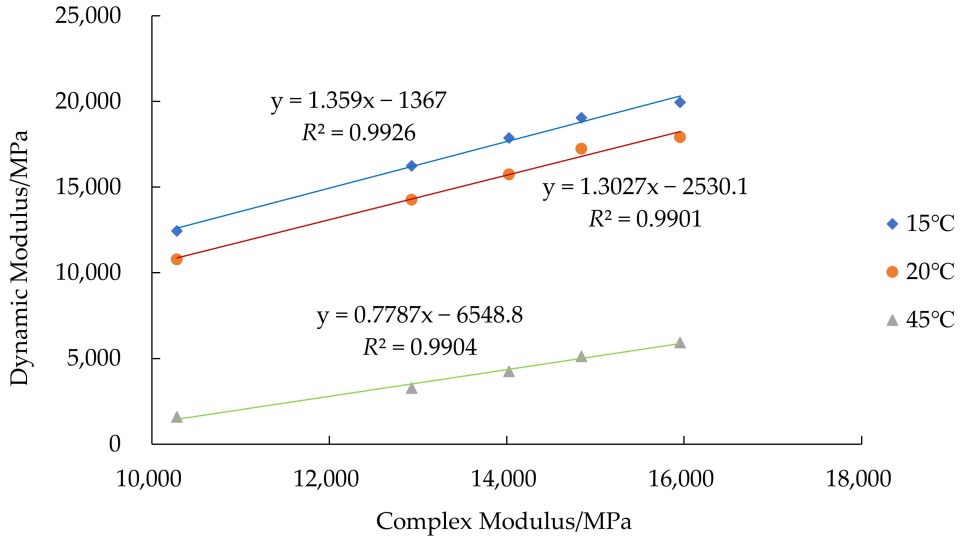


Figure 9. HMAC-20-China 15#.

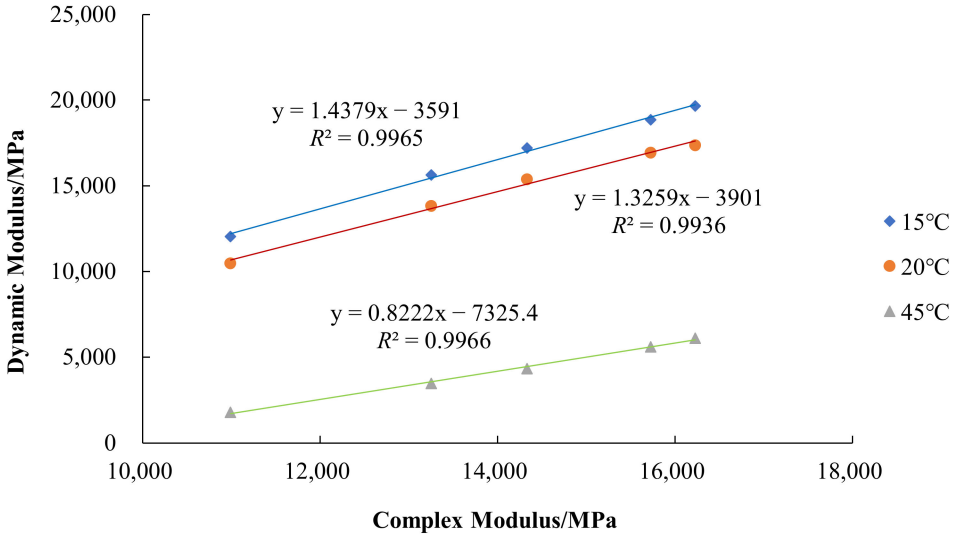


Figure 10. HMAC-20-France 15#.

3.5. Determination of Dynamic Modulus Evaluation Range of High-modulus Mixture

In order to verify the reliability of the recommended dynamic modulus evaluation value based on the modulus conversion model, 5 kinds of high-modulus mixtures used in actual road engineering, AC-20-SBS+PR MODULE, AC-20-SBS+EME high modulus modifier, AC-20-70#+PR MODULE, AC-20-70#+EME high modulus modifier and AC -20+high-modulus were carried out using the CRT-2PT trapezoidal beam two-point bending complex modulus and the SPT uniaxial compression dynamic modulus test. The relationship between the complex modulus at 15 °C,10 Hz and the corresponding uniaxial compression dynamic modulus at 15 °C, 10 Hz, 20 °C, 10 Hz and 45 °C, 10 Hz were shown in Figures 11–13.

Table 11. High-modulus mixture uniaxial compression dynamic modulus evaluation index under different temperature conditions.

Mixture Type	Test Conditions	Conversion Model	Calculated	Recommended Value
EME-14 + China 15#	15 °C, 10 Hz	y = 1.2964x − 1299	16,850	≥16,000
EME-14 + France 15#		y = 1.6152x − 6562.1	16,050	
HMAC-20 + China 15#		y = 1.359x − 1367	17,659	
HMAC-20 + France 15#		y = 1.4379x − 3591	16,539	
EME-14 + China 15#	20 °C, 10 Hz	y = 1.0471x − 638.39	14,021	≥14,000
EME-14 + France 15#		y = 1.4167x − 5818.7	14,015	
HMAC-20 + China 15#		y = 1.3027x − 2530.1	15,707	
HMAC-20 + France 15#		y = 1.3259x − 3901	14,661	
EME-14 + China 15#	45 °C, 10 Hz	y = 0.6366x − 5979.3	2933	≥2500
EME-14 + France 15#		y = 0.9796x − 11208	2506	
HMAC-20 + China 15#		y = 0.7787x − 6548.8	4353	
HMAC-20 + France 15#		y = 0.8222x − 7325.4	4185	

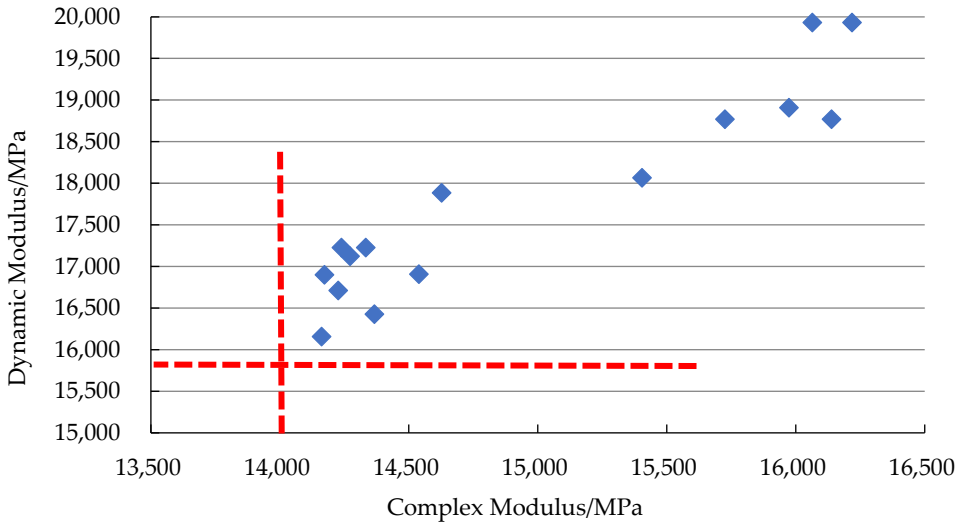


Figure 11. Corresponding relationship of modulus at 15 °C, 10 Hz.

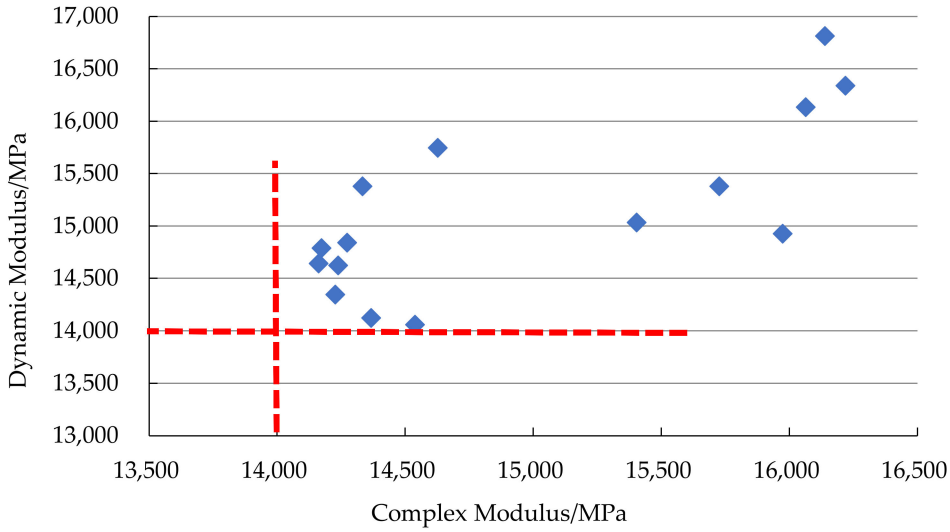


Figure 12. Corresponding relationship of modulus at 20 °C, 10 Hz.

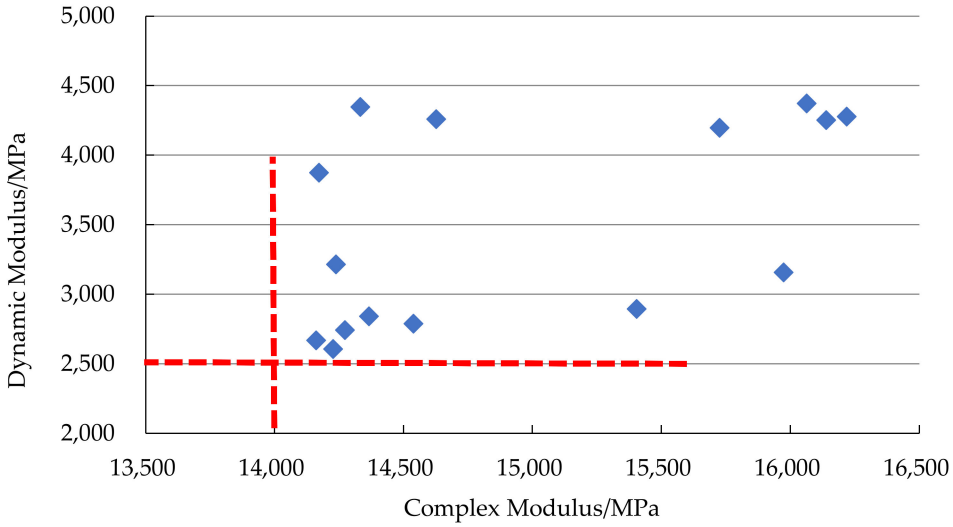


Figure 13. Corresponding relationship of modulus at 45 °C, 10 Hz.

It can be seen that, under the premise that the complex modulus of the trapezoidal beam is ≥14,000 Mpa, different types of high-modulus mixtures have a corresponding dynamic modulus ≥16,000 MPa at 15 °C,10 Hz, ≥14,000 MPa at 20 °C,10 Hz and ≥2500 Mpa. at 45 °C,10 Hz. The test results were consistent with the recommended dynamic modulus evaluation values calculated by the conversion model.

4. Conclusions

1. The performance of four types of high-modulus mixtures, EME-14 + France 15#, EME-14 + China 15#, HMAC-20 + France 15#, and HMAC-20 + China 15#, under level 1 to level 4, was verified; all met the performance index requirements of high-modulus mixtures.
2. Different loading control modes have a greater impact on the modulus and phase angle of the mixture. The frequency domain threshold of the master curve obtained by the SPT test is wider, the modulus value is larger, and the phase angle data dispersion is smaller than the CRT-2PT trapezoidal beam complex modulus test.
3. The relationship conversion model between dynamic modulus and complex modulus was established with good correlation. Based on the established correlation model, the dynamic modulus evaluation range of high-modulus mixtures under different evaluation temperature conditions was recommended.
4. Combined with the application of high-modulus mixtures in actual road engineering, the reliability of the recommended dynamic modulus range based on the calculation of the conversion model has been properly verified. The test results are all within the range of the dynamic modulus evaluation value given by the model.

Author Contributions: L.G., Q.X., W.W. and X.Z. conceived and designed the experiments. Q.X, X.Y. and J.W. performed the experiments. L.G., G.Z., W.W. and M.Z. analyzed the data. L.G., Q.X. and M.Z. contributed reagents/materials/analysis tools. Q.X. and W.W. wrote the paper. Q.X., W.W. and X.Z. revised the paper. All authors have read and agreed to the published version of the manuscript.

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