coatings

Article

Comparative Study on Road Performance of Low-Grade Hard Asphalt and Mixture in China and France

Guodong Zeng [1], Wenjuan Wu [2,*], Juechi Li [1], Qinsheng Xu [2], Xianghang Li [1], Xiangpeng Yan [2,*], Ye Han [2] and Jincheng Wei [2]

[1] Foshan Transportation Science and Technology Co., Ltd., Foshan 528315, China; wutongshuxi_a@163.com (G.Z.); ljc20211013@163.com (J.L.); dfy8307@163.com (X.L.)
[2] Shandong Transportation Institute, Jinan 250031, China; 15966652536@163.com (Q.X.); hanye@sdjtky.cn (Y.H.); weijincheng@sdjtky.cn (J.W.)
* Correspondence: wuwenjuan@sdjtky.cn (W.W.); yanxiangpeng@sdjtky.cn (X.Y.)

Abstract: The high-modulus asphalt mixture produced by hard asphalt has played a good role in reducing asphalt pavement rutting and improving pavement durability. It was widely used in the construction of various levels of road engineering in Europe. However, low-grade hard asphalt was rarely used in road engineering in China, and the use of hard asphalt for the design and construction of high modulus asphalt mixtures lacks sufficient engineering experience. Considering the above issues, comparative research on the performance of Chinese and French low-grade hard asphalt and mixture was carried out. In this paper, the performance of French 15# hard asphalt commonly used for EME (Enrobés à Module Elevé Class) high modulus asphalt mixture and China 15# hard asphalt was analyzed comparatively, where six typical high modulus asphalt mixtures corresponding to two low-grade hard asphalts were designed referring to the design requirements of French high modulus asphalt mixtures. The road performance of a high-modulus asphalt mixture was evaluated to verify the feasibility of its application in engineering. The research results show that the performance indicators of both Chinese and French asphalts meet the requirements of binder materials used in high modulus asphalt mixtures, and the performance of their corresponding mixtures of the two asphalts also meet the specifications of high modulus asphalt mixtures. However, the two asphalts and the performance of their corresponding mixture are slightly different. The high modulus asphalt mixture of Chinese low-grade hard bitumen can be used well in road engineering applications in China. It can strongly promote the wide application of high modulus asphalt mixture in China.

Keywords: low-grade asphalt; high-modulus asphalt mixture; road performance; road engineering application

check for updates

Citation: Zeng, G.; Wu, W.; Li, J.; Xu, Q.; Li, X.; Yan, X.; Han, Y.; Wei, J. Comparative Study on Road Performance of Low-Grade Hard Asphalt and Mixture in China and France. *Coatings* **2022**, *12*, 270. https://doi.org/10.3390/coatings12020270

Academic Editor: Valeria Vignali

Received: 25 January 2022
Accepted: 15 February 2022
Published: 17 February 2022

1. Introduction

High modulus asphalt mixture refers to an asphalt mixture with a complex modulus ≥14,000 Mpa under the conditions of 15 °C and 10 Hz, which is derived from the French high modulus asphalt mixture EME (Enrobés à Module Elevé Class) and the high modulus asphalt mixture HMAC (High Modulus Asphalt Concrete) of the middle surface layer in the concept of permanent pavement (in the USA) [1–3]. Its core is to improve the modulus and high-temperature stability of asphalt concrete and reduce the strain of asphalt concrete under load to achieve the purpose of improving the anti-rutting ability of the pavement, reducing the thickness of the pavement and improving the durability of the pavement. High modulus asphalt mixture has become a research hotspot due to its excellent high-temperature stability, strong resistance to water damage and good fatigue resistance [4–7]. Some Chinese researchers have carried out research on high modulus asphalt mixture from different angles. However, most of the existing high-modulus asphalt mixtures in China have a completely different technical approach to production from French high-modulus mixtures. The production of high modulus asphalt mixtures in France has two main technical methods: one is to use low-grade asphalt, mainly using 15# hard asphalt, that is, non-modified asphalt with a penetration of 10–20 (0.1 mm) at 25 °C; the other is the use of high modulus additives. The former accounted for about 70%, and the latter accounted for about 30%. However, in China, the exploration of high modulus asphalt mixtures is more inclined to the contribution of high modulus modifiers to its performance. French road workers [8–15] applied hard asphalt with a penetration of 151/10 mm to the high-modulus concrete EME structure of the bottom layer and increased the amount of asphalt to the same level as the surface layer at the same time and the results showed that the permanent deformation resistance of the high-modulus asphalt mixture produced by the hard asphalt with a degree of 151/10 mm is better than that of the SBS modified asphalt mixture, and the fatigue life is 30% longer than that of the original subsurface mixture. Newcombet al. [16] used low-grade hard asphalt and modified asphalt on the same road, respectively, and conducted a comparative test study. The test results show that low-grade hard asphalt has better road performance than modified asphalt. De Backer C [17] gave a detailed introduction to the use of hard asphalt in high-modulus asphalt concrete in Belgium at the European Transport Association. The test results show that the hard asphalt has good road performance. Visscher [18] and Backer [19] introduced the research progress of high-modulus asphalt concrete in Europe at the 4th European Conference on Asphalt and Asphalt Mixtures and clearly expressed the importance of using hard asphalt for high-modulus concrete. Rohde [20] found that the high-modulus asphalt concrete containing hard bitumen has good resistance to permanent deformation and good low-temperature performance by comparing and analyzing different types of high-modulus asphalt concrete. In China, Liaoning Transportation Research Institute Co., Ltd. carried out research on the application technology of high modulus asphalt concrete and adopted the method of adding high modulus admixtures to improve the high-temperature dynamic modulus of asphalt mixtures [2]. Linquan Guo et al. [21] carried out research on the application of high modulus asphalt concrete in road rutting treatment and studied the relationship between the modulus of asphalt mixture and rutting from the aspects of molecular weight and modification mechanism of SBS (styrene–butadiene–styrene block copolymer) modified asphalt. Qing Huazhou et al. [5] carried out a series of high modulus asphalt mixture performance tests and road engineering application research from the aspect of mixture admixtures. They used French PR series high modulus modifiers to increase the mixture modulus and adopted an SK-70 asphalt +High modulus modifier to produce AC (Asphalt Concrete)-20, AC-25, SUP-20, SUP(Superpave)5, EME-14, EME-20 and other gradation type mixtures for performance test research, and the test roads were paved. Although some progress has been made in the research of high modulus asphalt mixtures, the application of low-grade hard asphalt has been neglected, resulting in the high cost of high-modulus asphalt mixtures, which restricts its large-scale application in engineering [22].

Hard asphalt was first produced and used in France, mainly used in high modulus asphalt mixture EME. After nearly two decades of development, it has been widely used in European countries and was promoted in Australia, South Africa and other countries. Chinese road workers have also carried out some research on hard asphalt and its mixtures based on foreign experience. Zhaohui Liu et al. [5] found that 30# hard asphalt has good resistance to deformation at high temperatures through experimental research and road paving tests. Yuming Dong et al. [23] conducted dynamic shear rheological tests on 30# hard asphalt produced in China, finding that it exhibited good high-temperature performance. Chunyu Liang [24] and Weihong Xiong [25] conducted comparative experiments on the performance of low-grade asphalt with a penetration of 20–30, 70# asphalt, SBS modified asphalt and rubber asphalt and found that the low-grade hard asphalt mixture has excellent high-temperature performance and its dynamic stability is more than five times higher than that of 70# asphalt under the same test conditions. Zhao Lei et al. [26] carried out research on the application of hard asphalt mixture in rutting treatment engineering of trunk highways and found that the mixture has good compactability, and applying it to the lower layer of trunk highways can significantly improve the anti-rutting performance of the road surface. Some research has been performed on hard asphalt and its high modulus asphalt mixtures, but most of the hard asphalt performance studies simply evaluated whether it meets the requirements of the specifications and have not compared the performance of the 15# hard asphalt commonly used in France EME2. In the design and evaluation of high modulus asphalt mixtures, there is no systematic study in accordance with the French high modulus asphalt mixture EME system. Most studies only discuss the high-temperature anti-deformation ability and stiffness modulus of hard asphalt mixtures, without comprehensive analysis of its low-temperature anti-cracking performance, water stability, fatigue resistance and durability. Moreover, there are few engineering applications for low-grade hard asphalt, and there is little experience in the design and application of high-modulus asphalt mixtures based on low-grade hard asphalt.

In this paper, two kinds of low-grade hard asphalt from China and France were used, and three kinds of high modulus asphalt mixture, including EME-14 continuous, EME-14 discontinuous and HMAC-20, which are typical and commonly used in the middle and lower layers, were selected. The performance difference of the two low-grade hard asphalts from China and France was analyzed, and the road performance and mechanical properties of three typical high modulus asphalt mixtures based on the China and France hard asphalt were systematically evaluated. It is verified whether the performance of hard asphalt high modulus asphalt mixture produced in China based on limestone meets the requirements, and the feasibility of its application in road engineering was analyzed, which provides a reference for the application of hard asphalt high-modulus asphalt mixture in China.

2. Materials and Experimental

2.1. Materials

The crushed limestone and its ground ore powder were used as aggregates and filler, and the technical indicators meet the requirements of standard JTG-F40-2004 [27], 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 asphalt mixture. One is the hard asphalt with the label of 10/20, namely France 15# hard asphalt, the other is China 15# hard asphalt produced in China, which has similar performance to France 15#. The technical indicators of the two types of hard bitumen meet the requirements of standard EN 13924 [28], and the test results are shown in Table 2.

Table 2. Asphalt conventional technical indicators.

Pilot Projects		China 15#	France 15#	EN 13924
Penetration (100 g, 5 s, 25 °C)/0.1 mm		16.5	16.8	10–20
Softening Point (5 °C)/°C		64.25	66.6	58–78
Ductility (5 cm/min, 15 °C)		Brittle	Brittle	-
Solubility/%		99.6	99.78	≥99
density (15 °C)/g/cm^3		1.029	1.033	-
Flash point/°C		280	344	≥245
dynamic viscosity/Pa·s		6076	7219	≥700
RTFOT	Quality change/%	−0.31	0.051	≤0.5
	Residual penetration ratio/%	78	71.6	≥55

2.2. Mix Design

EME-14 (continuous and intermittent) and AC-20, three types of typical high modulus asphalt 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 designed composite gradation is shown in Table 3 and the gradation curve is shown in Figure 1.

Table 3. Synthetic gradation design of high modulus asphalt mixture.

Sieve Size (mm)	26.5	19	16	13.2	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
EME-14 continuous	100	100	100	97	90.1	48.7	33.1	25.7	16.1	10.6	7.9	5.7
EME-14 intermittent	100	100	100	88.6	63.7	47.1	33.9	26.4	16.4	10.7	7.7	5.8
HMAC-20	100	96.2	86.2	75.4	56.2	34.6	24.3	19.3	12.6	8.9	7.1	5.7
Design upper limit	100	100	-	-	82.0	64.0	43.0	-	-	-	-	8.0
Design lower limit	100	90.0	-	-	66.0	41.0	28.0	-	-	-	-	6.0
Design median	100	95.0	-	-	74.0	52.5	35.5	-	-	-	-	7.0

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 [29]. K has nothing to do with the density of gravel. According to LCPC (Laboratoire Central des Ponts et Chaussées) 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 asphalt mixture was calculated according to Equations (1)–(3), as shown in Table 4.

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

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

$$100 \sum = 0.25G + 2.3S + 12s + 150f \tag{2}$$

$$\alpha = \frac{2.65}{\rho G}. \tag{3}$$

where:

TL_{ext} is the percentage of admixture (whetstone ratio), %;
K is the 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 0.25~0.63 mm, %;
s is the aggregate ratio with a particle size of 0.063~0.25 mm, %;
f is the ratio of aggregates with a particle size of less than 0.063 mm, %;
a is the correlation coefficient related to aggregate density;
ρG is the density of aggregate, g/cm^3;

2.3. Test Methods

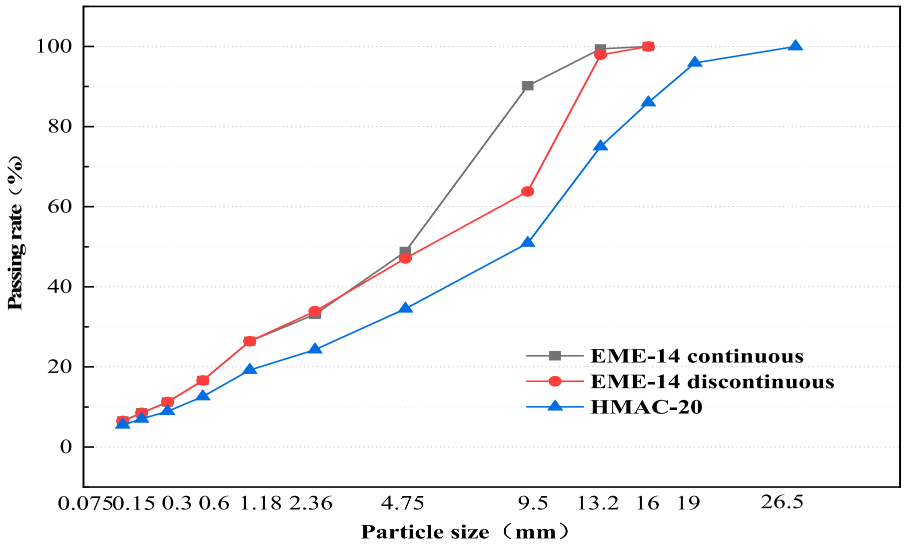


Figure 1. Synthetic gradation curves of three typical high modulus asphalt mixtures.

Table 4. Abundance coefficient calculation table.

Mixture Type	G(%)	S(%)	s(%)	f(%)	ρG	Oil–Stone Ratio/%	Abundance Coefficient
EME-14 (continuous and intermittent)	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

2.3.1. Asphalt Binder Performance Test

1. High-temperature rheological properties test

The dynamic shear rheometer DSR (Dynamic Shear Rheometer) is usually used to evaluate the high-temperature stability of an asphalt binder. According to Chinese standard JTG E20-2011 [30], a fully automatic dynamic shear rheometer was used to determine the dynamic shear modulus and phase angle of asphalt.

2. Low-temperature rheological properties test

A Bending Beam Rheometer (BBR) is usually used to evaluate the low-temperature performance of asphalt materials. According to Chinese standard JTG E20-2011 [30], a fully automatic bending beam rheological tester was used to measure the flexural creep stiffness modulus S and creep rate m.

3. Pneumatic rheological rebound test

The maximum creep deformation when loaded and the ability to recover from deformation when unloaded are unique properties of each thermoplastic material. The LTI-210 asphalt quality rapid testing equipment can quickly evaluate the mechanical response and road performance of asphalt materials at a certain temperature, which mainly used nitrogen loading technology to measure the creep and creep recovery capacity of asphalt under single stress or multi-stress conditions.

2.3.2. High Modulus Asphalt Mixture Performance Test

Referring to the design concept of the French high modulus asphalt mixture EME2, the performance of six kinds of high modulus asphalt mixtures, EME-14 continuous + France 15#, EME-14 continuous + China 15#, EME-14 intermittent + France 15#, EME-14 intermittent + China 15#, HMAC-20 + France 15#, HMAC-20 + China 15#, under the test level 1 to 4 was evaluated according to LPC Bituminous Mixtures Design Guide [31]. The test methods are shown in Table 5. Moreover, the low-temperature crack resistance was also evaluated according to JTG E20-2011 [30].

Table 5. High modulus asphalt mixture performance index verification test plan.

Test Level	Test Item	Test Methods
Level 1	Rotational compaction void ratio (%)	EN 12697-31 [32]
	Water stability: Durize test (Compressive strength ratio, %)	EN 12697-12 (Method B) [33]
Level 2	High-temperature stability: French wheel rutting test (30,000 times, 60 °C)	EN 12697-22 [34]
Level 3	Stiffness modulus: complex modulus (MPa, 15 °C, 10 Hz/0.02 s)	EN 12697-26 [35]
Level 4	Fatigue life: two-point bending fatigue of trapezoidal beam (10 °C, 25 Hz, 106 cycles, 130 $\mu\varepsilon$)	EN 12697-24 [36]

3. Performance Evaluation of Asphalt Binder

3.1. Penetration, Softening Point, Dynamic Viscosity and Residual Penetration

The data comparison of the penetration, softening point, dynamic viscosity and residual penetration of China 15# and France 15# hard asphalt are shown in Table 2, respectively. The penetration, softening point and dynamic viscosity at 60 °C of France 15# hard asphalt are slightly higher than those of China 15#, indicating that the high-temperature stability of France 15# is relatively better. After short-term RTFOT aging, the residual penetration of China 15# is 8% higher than that of France 15#, indicating that the anti-aging performance of Chinese hard asphalt is better.

3.2. High-Temperature Rheological Properties of Asphalt Binder

The dynamic shear rheometer DSR (Dynamic Shear Rheometer) can be used to evaluate the high-temperature stability of the asphalt binder, and the viscoelastic properties of asphalt materials can be characterized by measuring the complex modulus G^* and phase angle δ of asphalt under different temperature and load conditions [5]. The rutting factor $G^*/\sin\delta$ is used as an index to evaluate the high-temperature rutting resistance of asphalt materials.

G^* represents the rutting resistance of the asphalt material, and δ represents the viscoelasticity of the asphalt material. The larger G^*, the smaller the δ, the better the resistance of the asphalt material to deformation under load. Figure 2 shows the variation of complex modulus G^* and phase angle δ with temperature. It can be seen that the complex modulus G^* and the phase angle δ of the two kinds of hard asphalts have the same trend of change with temperature, but the change range is slightly different. When the temperature is low, the two asphalts have higher complex modulus and smaller phase angle, the asphalt tends to be elastic, and its ability to resist deformation is better; with the increase in temperature, the complex modulus G^* decreases, the phase angle δ increases rapidly, the asphalt tends to be more viscous, and its ability to resist deformation becomes weaker. The complex modulus of France 15# hard asphalt is slightly higher than that of China 15#, and the phase angle is relatively small, indicating that the high-temperature stability of France 15# is better than that of China 15#.

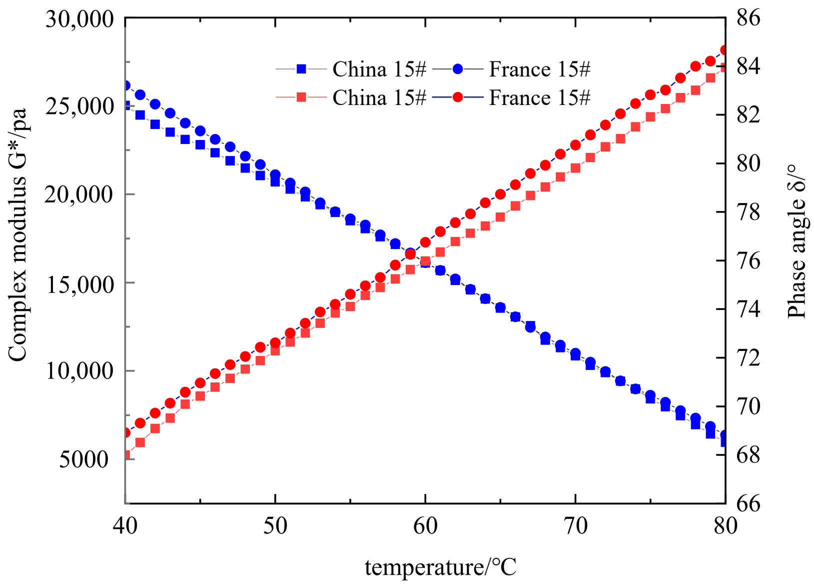


Figure 2. The complex modulus G* and phase angle δ.

Figure 3 shows the variation trend of the rutting factor with temperature. Studies have shown that the greater the anti-rutting factor G*/sinδ, the stronger the anti-rutting ability of the asphalt material and the better its high-temperature stability. It can be seen from the figure that the anti-rutting factor of the two low-grade hard asphalts has the same trend of change, and both gradually decrease with the increase in temperature. The G*/sinδ of the France 15# hard asphalt is larger, indicating that the rutting resistance of France 15# hard asphalt is better than that of China 15# hard asphalt.

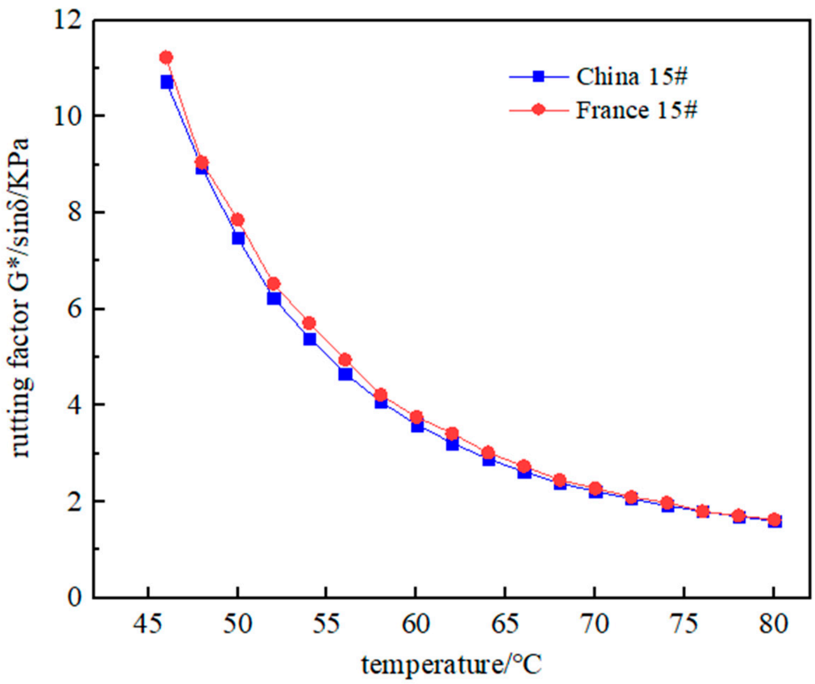


Figure 3. The rutting factor G*/sinδ.

3.3. Low-Temperature Rheological Properties of Asphalt Binder

The Bending Beam Rheometer (BBR) can evaluate the low-temperature performance of asphalt materials. Since most of the low-temperature cracking of asphalt pavement in China occurs in the early stage, the low-temperature rheological performance of asphalt materials after short-term RTFOT aging was analyzed [25,26]. By measuring the flexural creep stiffness modulus S and creep rate m of the two low-grade hard asphalt, the low-temperature crack resistance performance was evaluated. The larger the modulus of stiffness, the smaller the creep rate, and the easier it is to fracture for asphalt material when it is stretched at low temperature.

The deflection changes of the two hard asphalts with loading time are shown in Figure 4. The stiffness modulus and creep rate results are given respectively in Table 6. It can be seen that the stiffness modulus S of China 15# is slightly lower than that of France 15#, and the creep rate is lower than that of France 15#, indicating the crack resistance and stress relaxation performance of the French low-grade asphalt in the low-temperature environment are better than China 15# hard asphalt.

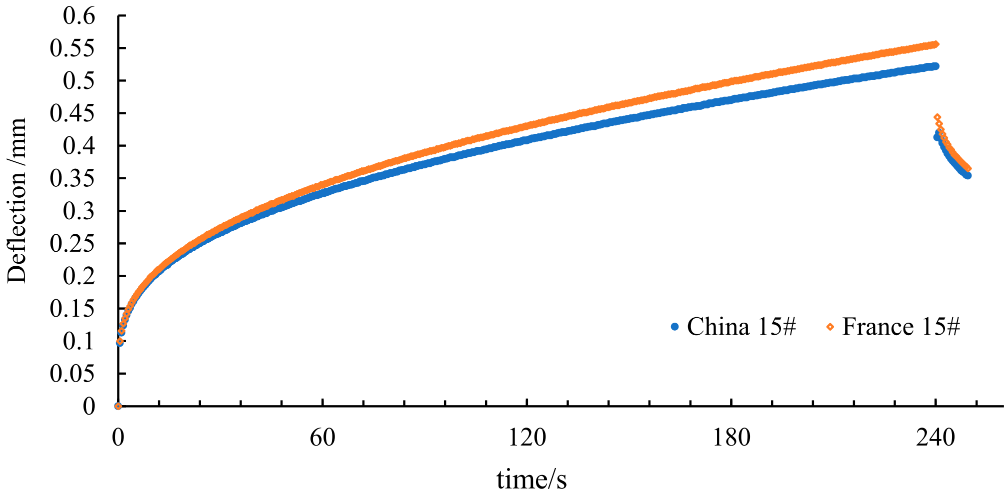


Figure 4. Deflection change of two hard bitumen with loading time.

Table 6. The values of creep stiffness modulus S and creep rate m of two hard bitumen.

Asphalt Type	Creep Stiffness Modulus S/−6 °C (Average Value)	Standard Deviation	Creep Rate m/−6 °C (Average Value)	Standard Deviation
France 15#	256	1.63	0.365	0.021
China 15#	264	2.06	0.36	0.016

3.4. Pneumatic Rheological Rebound Performance

The data from the rebound test of asphalt rheological properties in Figure 5 and Table 7 shows that the change trends of the two low-grade hard asphalts in China and France are the same, but under different stress conditions, the maximum deformation and the degree of deformation recovery when unloading are different. Under the standard conditions of 9.75 Psi, the maximum creep deflection of China 15# hard asphalt is small, and the deformation recovery rate when unloading is high, indicating that Chinese low-grade hard asphalt has high hardness (high modulus) and better viscoelasticity. However, as the pressure increases to 20 Psi, the maximum creep deflection of France 15# hard asphalt is smaller and the deformation recovery rate is higher than China 15#, indicating that the French low-grade hard asphalt is less sensitive to changes in stress levels.

Table 7. Maximum deformation and elastic recovery rate.

Asphalt Material	9.75 Psi		20 Psi	
	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

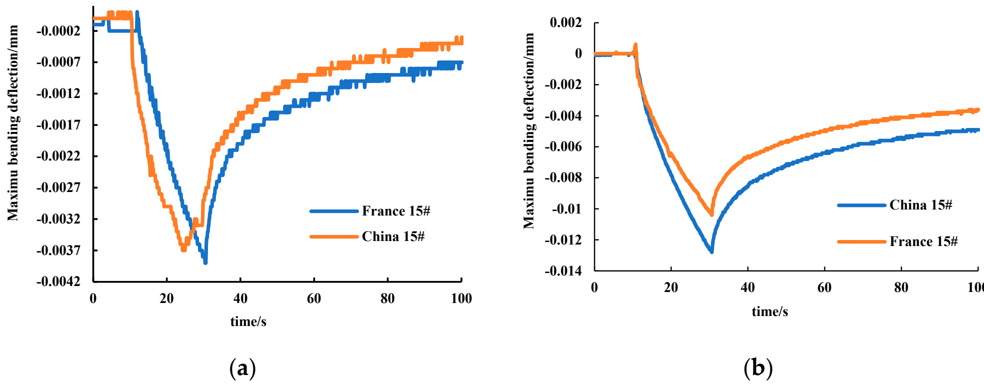


Figure 5. The deformation and deformation recovery corresponding to (**a**) 9.75 and (**b**) 20 Psi.

4. Analysis and Evaluation of High Modulus Asphalt Mixture Performance

4.1. Porosity Verification and Water Sensitivity Evaluation

According to the French high modulus asphalt mixture design guide LCPC level 1 performance requirements [31], the PCG rotary compaction test and Durize test were carried out on the six designed high modulus asphalt mixtures, and the porosity and water sensitivity of the two low-grade high modulus asphalt mixtures of China and France were analyzed. The results of the void ratio and water sensitivity are shown in Tables 8 and 9, respectively.

Table 8. Porosity of different types of high modulus asphalt mixtures.

Gradation Type	Void Ratio/%	Standard Deviation
EME-14 continuous-France 15#	3.65	0.033
EME-14 discontinuous-France 15#	3.48	0.012
HMAC-20-France 15#	3.58	0.024
EME-14 continuous-China 15#	3.57	0.012
EME-14 discontinuous-China 15#	3.52	0.021
HMAC-20-China 15#	3.63	0.016

Table 9. The compressive strength ratio of different types of high modulus asphalt mixtures.

Gradation Type	Specimen of Immersion Group (Average Value)		Test Pieces of the Comparison Group (Average Value)		Compressive Strength Ratio	Standard Deviation
	Void Ratio (%)	Strength (MPa)	Void Ratio (%)	Strength (MPa)		
EME-14 continuous-France 15#	3.98	15.13	3.88	14.95	101.2	1.29
EME-14 discontinuous-France 15#	2.96	18.53	3.12	18.16	102.04	2.09
HMAC-20-France 15#	3.78	17.38	3.56	17.05	101.94	1.32
EME-14 continuous-China 15#	4.07	14.8	4.16	14.75	100.34	2.16
EME-14 discontinuous-China 15#	3.1	17.41	2.52	17.12	101.69	1.28
HMAC-20-China 15#	4.01	16.15	3.76	15.95	101.25	1.51

It can be seen from Table 8 that the porosity of asphalt mixture specimens of different gradation types obtained by the PCG rotary shear compaction all meet the design index requirements (<6%) of French high modulus asphalt mixture, indicating that the asphalt dosage determined by the calculation of the abundance coefficient formula meets the design requirements. In Table 9, the compressive strength ratios of these six kinds of high modulus asphalt mixtures are greater than 75%, and all meet the control threshold requirements of the level 1 test index. Moreover, the compressive strength ratio of the two low-grade asphalt mixture for the same gradation type is close to 1(1.01:1), indicating that the water stability of the high-modulus asphalt mixtures based on France 15# and China 15# low-grade asphalts is not very different.

4.2. High-Temperature Performanc

Referring to LCPC level 2 rutting performance requirements [34], the French large-scale rutting test was carried out on six kinds of high modulus asphalt mixture under 60 °C to analyze the high-temperature performance. Figure 6 shows the variation of the rutting deformation rate with the increase in rolling times. The rutting deformation rate curve of the six types of mixture has the same changing trend with the increase in the rolling times. In the initial stage, the rutting deformation rate increases rapidly, and with the increase in the rolling times, the rutting deformation rate increases smoothly. As specified in CSN EN 12697-22 [34] and Chinese standard DB 37/T 3564-2019 [37], the rutting deformation rate of the high modulus asphalt mixture should be less than 7.5% under the condition of 60 °C and 30,000 rolling times. It can be seen in Figure 5 that the rutting deformation rates of different types of high modulus asphalt mixtures are all less than 7.5% under the specified 30,000 rolling times, which meets the high modulus asphalt mixture level 2 test performance requirements.

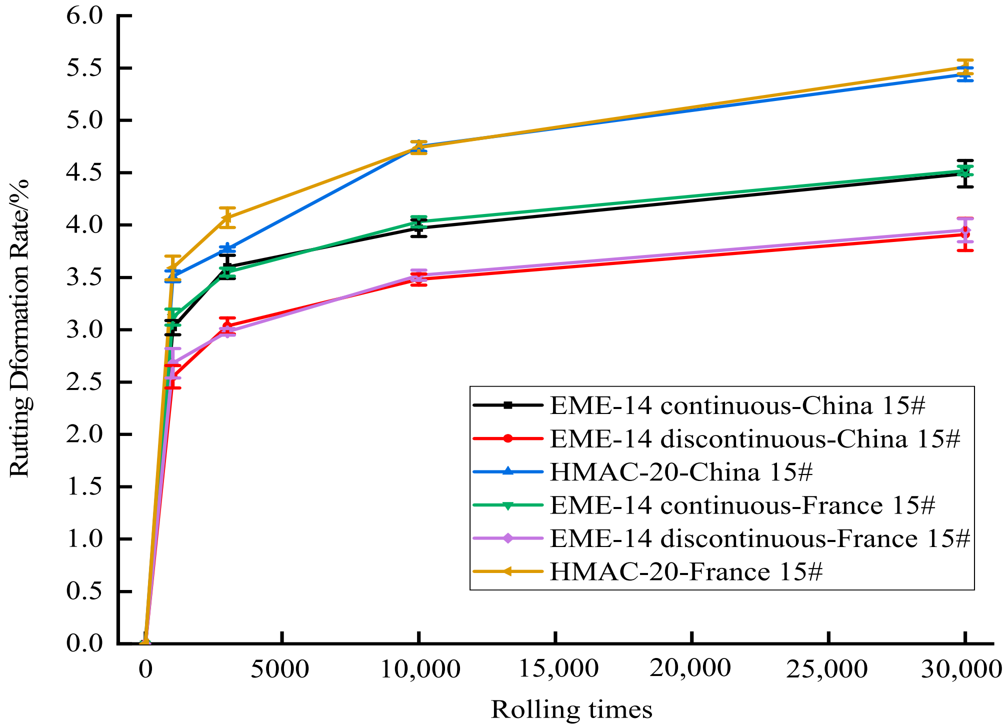


Figure 6. The rutting deformation rate curve of different types of high modulus asphalt mixtures.

According to the test results, the relationship between rutting deformation rate Pi and rolling number N was exported in the double logarithmic coordinate system, as shown in Figure 7, and the fitting curve relationship was exhibited in Table 10. Under the same test conditions, the rutting deformation rate of the three high modulus asphalt mixtures corresponding to China 15# asphalt is smaller than that of France 15# asphalt mixtures, and the rutting deformation rate curve parameter b values for China 15# asphalt mixtures are also smaller. It shows that the high-modulus asphalt mixture corresponding to the Chinese low-grade asphalt has stronger resistance to high-temperature deformation than French, and the high-temperature performance of the mixture is better. As to the rutting deformation rate slope, the values of curve parameter a for France 15# hard asphalt mixtures are smaller than those of China 15# hard asphalt mixtures, which indicated that the high modulus asphalt mixture based on the French low-grade asphalt is less sensitive to load changes.

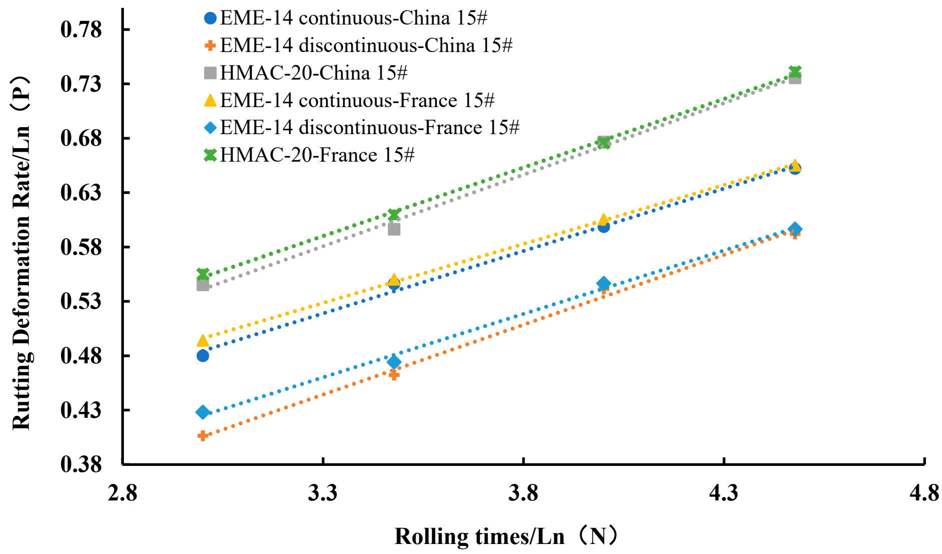


Figure 7. The relationship between rutting deformation rate Pi and rolling number N in the double logarithmic coordinate system.

Table 10. Rutting deformation rate curve.

Mixture Type	a	b	Curve Equation	R^2
EME 14 continuous-France 15#	0.1086	0.1703	Ln(Pi) = 0.1086 × Ln(N) + 0.1703	0.9992
EME 14 continuous-China 15#	0.1148	0.1402	Ln(Pi) = 0.1148 × Ln(N) + 0.1402	0.9955
EME 14 discontinuous-France 15#	0.1168	0.0749	Ln(Pi) = 0.1168 × Ln(N) + 0.0749	0.9955
EME 14 discontinuous-China 15#	0.1285	0.0201	Ln(Pi) = 0.1285 × Ln(N) + 0.0201	0.9957
HMAC 20-France 15#	0.126	0.1742	Ln(Pi) = 0.126 × Ln(N) + 0.1742	0.9985
HMAC 20-China 15#	0.1316	0.1465	Ln(Pi) = 0.1316 × Ln(N) + 0.1465	0.9958

4.3. Low-Temperature Performance

According to Chinese standard JTG E20-2011 [30], the low-temperature bending tests were conducted on six designed EME-14 (continuous and intermittent) and AC-20 asphalt mixtures to evaluate the low-temperature crack resistance performance of the two low-grade high-modulus asphalt mixtures. The maximum flexural strain was taken as the mixture low-temperature performance evaluation index in this paper and the result is shown in Figure 8. As seen from Figure 8, the strain values of the EME-14 continuous, EME-14 discontinuous and AC-20 high modulus asphalt mixtures based on the two low-grade asphalts of China and France are all greater than 2000 MPa and all meet the requirements of bending and tensile strain specified in Chinese standard GB/T36143-2018 [38]. The flexural strain values of France 15# asphalt mixture are about 10% larger than that of China 15#, which showed that the low-temperature crack resistance of high modulus asphalt mixture based on the French low-grade hard asphalt is better.

4.4. Stiffness Modulus

Through the complex modulus test of the CRT-2PT two-point trapezoidal beam, the result of the complex modulus at 15 °C and 10 Hz was exhibited in Figure 9, and the main curves of modulus and phase angle were established, as shown in Figure 10a,b, respectively.

At 15 °C and 10 Hz, the complex modulus values of high-modulus asphalt mixtures based on Chinese and French low-grade asphalt are > 14,000 MPa, which all meet the requirements of the level 3 modulus index (≥14,000 MPa). When the gradation types are the same, the ratios of the modulus values of the two low-grade hard asphalt mixtures are chosen to be 1, indicating that the complex modulus indexes of Chinese and French low-grade hard asphalt mixtures are almost equivalent.

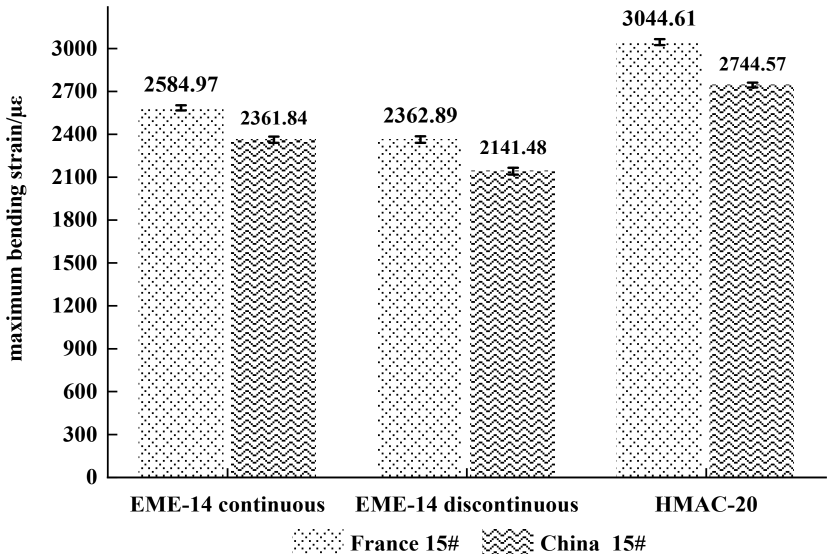


Figure 8. Flexural strain of different types of high modulus asphalt mixtures.

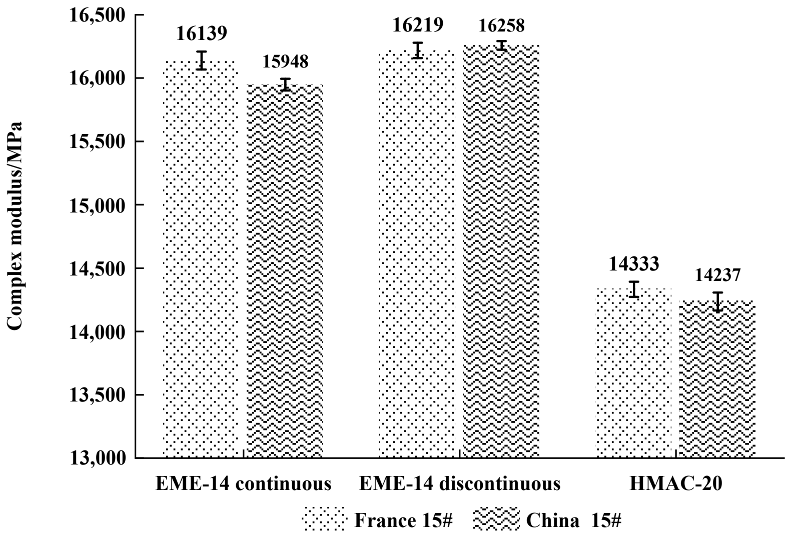
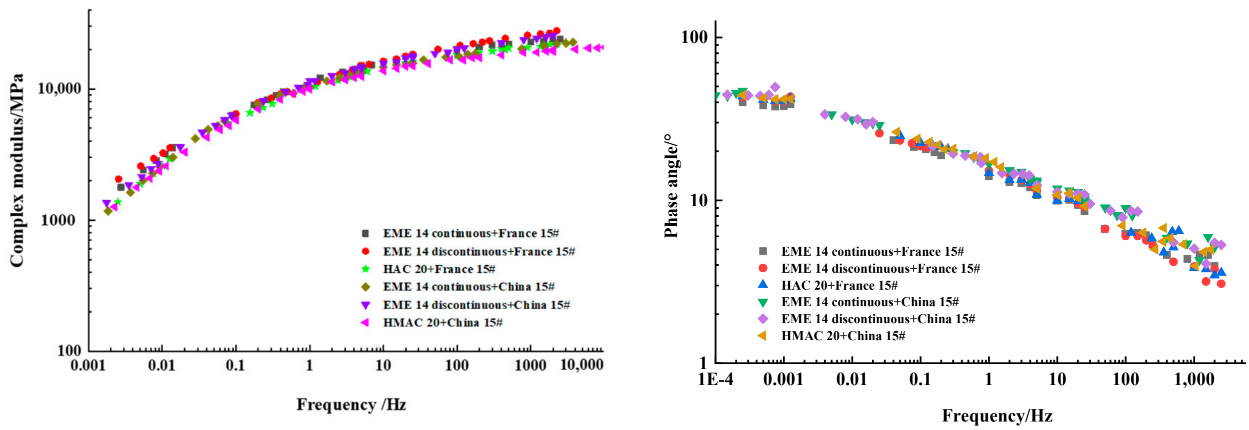


Figure 9. The complex modulus of high modulus asphalt mixtures.



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

Figure 10. Modulus and phase angle master curves of high modulus asphalt mixtures: (**a**) Modulus; (**b**) Phase angle.

The research on the high and low-temperature performance of the asphalt mixture can also be realized by fitting the master curve. The modulus and phase angle main curve of the mixtures at different temperatures fitted with 15 °C as the reference temperature in Figure 10 shows that the modulus and phase angle of different types of high modulus asphalt mixtures change with the loading frequency in the same trend. As the frequency increased, the modulus of the mixture increased and the phase angle decreased. On the whole, the modulus and phase angle master curves of these two low-grade hard asphalt mixtures are close to overlap, indicating that the mixture modulus and phase angle are similar.

4.5. Fatigue Life

The fatigue test was performed on the designed low-grade high-modulus asphalt mixture referring to CRT-2PT two-point trapezoidal beam fatigue test. The test result is shown in Table 11, and the fatigue curve was drawn according to the test results, as shown in Figure 11.

Table 11. Fatigue life of low-grade high-modulus asphalt mixtures with different grading types.

Gradation Type	Average Void Ratio (%)	Strain Level (με)	Average Fatigue Life (Time)	Standard Deviation
EME-14 Continuous + France 15#	2.22	110	4,422,308	11,746.56
		130	1,390,390	4874.22
		150	617,943	2153.63
		200	147,639	912.68
EME-14 Discontinuous + France 15#	2.02	110	3,765,624	16,056.46
		130	1,129,163	5384.39
		150	570,676	2062.17
		200	130,954	852.25
HMAC-20 France + 15#	2.92	110	2,349,959	10,545.53
		130	1,098,623	4472.47
		150	482,917	1357.56
		200	114,285	519.04
EME-14 Continuous + China 15#	2.46	110	4,638,924	10,318.48
		130	1,490,490	3135.88
		150	605,541	2196.78
		200	142,573	889.59
EME-14 Discontinuous + China 15#	2.30	110	4,054,673	11,574.17
		130	1,242,715	3633.73
		150	563,702	1838.54
		200	128,627	800.34
HMAC-20 + China 15#	3.01	110	2,674,851	10,018.67
		130	1,181,271	4154.14
		150	472,865	2398.79
		200	101,752	838.11

According to the data in Table 8, under the specified test conditions of 10 °C and 25 Hz, the fatigue life of EME-14 continuous + China 15# is 1,490,490 times, the fatigue life of EME-14 discontinuous + China 15# is 1,242,715 times, and the fatigue life of HMAC-20 + China 15# is 1,181,271 times. The fatigue life of EME-14 continuous + France 15# is 1,390,390 times, the fatigue life of EME-14 discontinuous + France 15# is 1,129,163 times, and the fatigue life of HMAC-20 + France 15# is 1,098,623 times. The fatigue times of the above six low-grade high-modulus asphalt mixtures are $\geq 10^6$ times under the conditions of 10 °C, 25 Hz and 130 με, indicating that the fatigue performance of the mixture meets the fatigue performance index requirements of high-modulus asphalt mixtures under French standards.

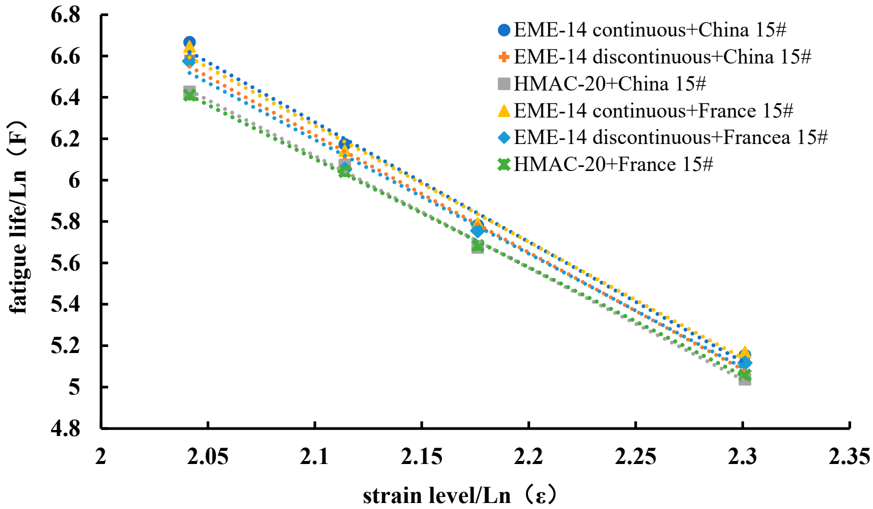


Figure 11. Fatigue curves of high modulus asphalt mixture.

It can be seen from Figure 11 that the fatigue life of different gradation types of high modulus asphalt mixtures based on the two low-grade asphalts of China and France have the same change trend. The fatigue life of the mixture decreases with the increase in strain level, but the degree of fatigue life decrease for different asphalt mixtures is different with the increase in strain.

According to Figure 11, the fatigue model Ln(N) = a + (1/b) × Ln(ε) of fatigue life N and strain level ε was established, and the fatigue parameters a and 1/b are shown in Table 12. The larger the value of a, the better the fatigue resistance of the mixture, and the larger the absolute value of 1/b, the more sensitive the fatigue life of the mixture is to changes in strain levels. When the gradation type is the same, the parameter a value of Chinese low-grade high modulus asphalt mixture is slightly larger than that of French low-grade high modulus asphalt mixture. It indicated that Chinese low-grade high-modulus asphalt mixtures showed greater fatigue life and better fatigue performance. As to the parameter 1/b, its absolute value of French low-grade high modulus asphalt mixture is slightly smaller than that of Chinese low-grade high-modulus asphalt mixture, showing that the fatigue performance of the French low-grade high-modulus asphalt mixture is less sensitive to strain changes.

Table 12. Fatigue equation parameters.

Mixture Type	a	1/b	Curve Equation	R^2
EME 14 continuous + France 15#	18.068	−5.6211	Ln(N) = −5.6211 × Ln(ε) + 18.068	0.9932
EME 14 continuous + China 15#	18.436	−5.7886	Ln(N) = −5.7886 × Ln(ε) + 18.436	0.9938
EME 14 discontinuous + France 15#	17.764	−5.5089	Ln(N) = −5.5089 × Ln(ε) + 17.764	0.992
EME 14 discontinuous + China 15#	18.111	−5.6639	Ln(N) = −5.6639 × Ln(ε) + 18.111	0.9945
HMAC 20 + France 15#	17.09	−5.232	Ln(N) = −5.232 × Ln(ε) + 17.09	0.9994
HMAC 20 + China 15#	17.476	−5.4089	Ln(N) = −5.4089 × Ln(ε) + 17.476	0.9981

5. Conclusions

This research assessed the mechanical performance of low-grade hard asphalt in China and France comparatively. The high and low-temperature performance, water stability, two-point bending complex modulus test and bending fatigue of trapezoidal test were performed to evaluate the road performance of high-modulus asphalt mixtures for Chinese and French hard asphalt, respectively. The following conclusions were given based on the results in this study:

1. The performance indicators of the China 15# hard asphalt meet the requirements of the binder used in the high modulus asphalt mixture. China 15# and France 15# hard

bitumen are similar in performance but slightly different. The French low-grade hard asphalt showed better high-temperature stability and less sensitivity to changes in the level of change, while the Chinese low-grade hard asphalt had better anti-aging performance and viscoelastic properties.

2. The high and low-temperature performance, water stability, stiffness modulus and fatigue life of the high-modulus asphalt mixture based on China 15# hard asphalt all meet the specification requirements, indicating that the application of the high modulus asphalt mixture of Chinese low-grade hard bitumen can be carried out in China.
3. The road performance of the Chinese and French 15# hard asphalt mixtures is similar but slightly different. Chinese low-grade hard asphalt mixtures showed better high-temperature performance and fatigue performance. The French 15# hard asphalt mixture was less sensitive to changes in load times and strain levels and performed better at low temperature, which can increase the low-temperature performance by about 10%. There is not much difference in water stability and stiffness modulus for the two low-grade hard asphalts mixtures.

The results of this study helped to evaluate whether the Chinese hard asphalt mixture can meet the performance index requirements of French high modulus asphalt mixture and verified the feasibility of the application of Chinese hard asphalt in road engineering. The results will also guide the construction of hard bitumen high modulus asphalt mixture pavement of the highway in China, promoting the wide application of high modulus asphalt mixture in China.

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

Funding: This research was funded by the National Key R&D Program of China, grant No.2018YFB1600103, the National Natural Science Foundation of China, grant No. 42107213, Shandong Provincial Natural Science and Foundation, grant No. ZR2020QE271 and Shandong Provincial Key Research and Development Program, grant No. 2019GSF109020.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data sharing is not applicable to this article.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. *NF P98-141*; Asphalt Mixture-Wearing Course and Base Course: High Modulus Asphalt Mixture-Definition-Classification-Characteristics-Production and Construction. French Standardization Association: Paris, France, 1999.
2. Xia, X.P.; Zhang, R.N.; Fu, H.W. Characteristics and new development of high modulus asphalt mixture. *Chin. For. Highw.* **2005**, *2*, 123–127.
3. Serfass, P.; Bense, P.; Pellevoisin, P. Properties and New Developments of High Modulus Asphalt Concrete. In Proceedings of the Lecture Series 8th International Conference on Asphalt Pavements, Seattle, WA, USA, 10–14 August 1997.
4. Jean, F.C. *Development and Uses of Hard-Grade Asphalt and of High-Modulus Asphalt Mixes in France*; Transportation Research Board: Washington, DC, USA, 2001; pp. 12–31.
5. Zhou, Q.H.; Sha, A.M.; Yang, Q. Experimental study on mechanical properties of high modulus asphalt concrete. *J. Zhengzhou Univ.* **2008**, *3*, 128–131.
6. Witczak, M. *Simple Performance Tests: Summary of Recommended Methods and Database*; NCHRP-547; Transportation Research Board: Washington, DC, USA, 2005; pp. 2–7.
7. Montanelli, E.F. Fiber/Polymeric Compound for High Modulus Polymer Modified Asphalt (PMA). *Procedia-Soc. Behav. Sci.* **2013**, *104*, 39–48. [CrossRef]
8. Gottam, S.R.; Adepu, R.; Vijayapuri, V.R.; Ramu, P. Laboratory evaluation of hard grade bitumen produced with PPA addition. *Int. J. Pavement Res. Technol.* **2020**, *14*, 505–512.

9. Maupin, G.W.; Diefenderfer, B.K. Design of a High-Binder-High-Modulus Asphalt Mixture. Virginia Transportation Research Council: Charlottesville, VA, USA, 2006; pp. 1–30.
10. Silvino, D.C.; Luis, P.S. Assessing permanent deformation resistance of high modulus asphalt mixtures. *J. Transp. Eng.* **2006**, *132*, 394–401.
11. Didier, D.; Philippe, G.; Patrice, O. Comparative experiment for PMB and hard bitumen on a thin anti rutting maintenance treatment. In Proceedings of the Vienna: 3rd Eurasphalt & Eurobitume Congress, Vienna, Australia, 12–14 May 2004.
12. Serfass, J.P.; Bauduin, A.; Garnier, J.F. High modulus asphalt mixes laboratory evaluation, practical aspects and structural design. In Proceedings of the 7th International Conference on Asphalt Pavements, Nottingham, UK, 16–20 August 1992; Volume 1, pp. 275–288.
13. Lee, H.J.; Lee, J.H.; Park, H.M. Performance evaluation of high modulus asphalt mixtures for long life asphalt pavements. *Constr. Build. Mater.* **2007**, *21*, 1079–1087.
14. Yang, J. Study on low temperature performance of gussasphalt on steel decks with hard bitumen. *J. Southeast Univ.* **2003**, *19*, 160–164.
15. Corte, J.F. Development and uses of hard grade asphalt and of high modulus asphalt mixes in France. *Transp. Res. Circ.* **2003**, *503*, 12–31.
16. Newcomb, D.E.; Buncher, M.; Huddleston, I.J. *Concepts of Perpetual Pavements*; Transportation Research Board: Washington, DC, USA, 2001; pp. 4–11.
17. Claude, B.; Joëlle, V.; Lieve, G.; Ann, V.; Stefan, V.; Lucien, H. A Comparative High-modulus Asphalt Experiment in Belgium. *Transp. Res. Arena Eur.* **2008**, *32*, 22–38.
18. De Visscher, J.; Vansteenkiste, S.; Vanelstraete, A. Test sections in high-modulus asphalt: Mix design and laboratory performance testing. In Proceedings of the 4th Eurasphalt and Eurpbitume Congress, Copenhagen, Denmark, 21–23 May 2008; pp. 1–11.
19. De Backer, C.; Glorie, L.; Reynaert, R. Test sections in high-modulus asphalt:a comparative experiment with ten variants. In Proceedings of the 4th Eurasphalt and Eurpbitume Congress, Copenhagen, Denmark, 21–23 May 2008; pp. 1–11.
20. Rohde, L.; Ceratti, J.A.P.; Nunez, W.P.; Vitorello, T. Using APT and laboratory testing to evaluate the performance of high modulus asphalt concrete for base courses in Brazil. In Proceedings of the Third International Conference Centro de Estudios y Experimentación de Obras Públicas (CEDEX) Transportation Research Board, Madrid, Spain, 1–3 October 2008.
21. Guo, Q.; Tan, J. Application of High Modulus Asphalt Concrete in Pavement Rutting Treatment. *J. Highw. Transp. Res. Dev.* **2006**, *7*, 59–62.
22. Han, C. Design and Application Research of Durable High Modulus Asphalt Mixture Based on Hard Asphalt. Master's Thesis, Southeast University, Nanjing, China, 2018.
23. Dong, Y.; Tan, Y. Research on high temperature performance of hard grade asphalt based on repeated shear creep test. *High* **2015**, *2*, 160–164.
24. Liang, C.; Liu, F. Research on properties of 30# hard asphalt and asphalt mixture. *J. China Foreign Highw.* **2006**, *6*, 185–188.
25. Xiong, W. Experimental study on road performance of low-grade asphalt mixture. *Highw. Automot. Appl.* **2008**, *1*, 80–82.
26. Zhao, L.; Han, C.; Zheng, G.; An, F.; Dong, S. Application of Domestic Hard Asphalt in Rutting Treatment Project of Trunk Highway. *Shanghai Highw.* **2019**, *4*, 6–8+64+3.
27. *JTG F40-2004*; Technical Specifications for Construction of Highway Asphalt Pavements. People's Communications Press: Beijing, China, 2005.
28. *BS EN 13924*; Bitumen and Bituminous Binders-Specifications for Hard Paving Grade Bitumens. British standard: London, UK, 2006.
29. Corté, J.-F.; Serfass, J.-P. The French approach to asphalt mixtures design: A performance-related system of specifications. *Assoc. Asph. Paving Technol.* **2000**, *69*, 794–834.
30. *JTG E20-2011*; Standard Test Methods of Bitumen and Bitumen Mixtures for Highway Engineering. People's Communications Press: Beijing, China, 2011.
31. France, R.S.T.; "Asphalt Mixture Design" Working Group. *LPC Bituminous Mixtures Design Guide*; Laboratoire Central des Ponts et Chaussées: Paris, France, 2010.
32. *CSN EN 12697-31*; Bituminous Mixtures-Test Methods for Hot Mix Asphalt-Part 31: Specimen Preparation by Gyratory Compactor. The Commonwealth Standards Network: London, UK, 2007.
33. *CSN EN 12697-12*; Bituminous Mixtures-Test Methods for Hot Mix Asphalt Part 12: Determination of the Water Sensitivity of Bituminous Specimens. The Commonwealth Standards Network: London, UK, 2008.
34. *CSN EN 12697-22*; Bituminous Mixtures-Test Methods for Hot Mix Asphalt-Part 22: Wheel Tracking. The Commonwealth Standards Network: London, UK, 2020.
35. *CSN EN 12697-26*; Bituminous Mixtures-Test Methods for Hot Mix Asphalt-Part 26: Stiffness. The Commonwealth Standards Network: London, UK, 2003.
36. *CSN EN 12697-24*; Bituminous Mixtures-Test Methods for Hot Mix Asphalt Part 24: Resistance to Fatigue. The Commonwealth Standards Network: London, UK, 2012.
37. *DB 37/T 3564-2019*; Anti-Rutting and Anti-Fatigue High Modulus Asphalt Mixture Design and Construction Technical Specifications. Shandong Provincial Market Supervision Administration: Jinan, China, 2019.
38. *GB/T 36143-2018*; High Modulus Anti-Fatigue Asphalt Mixture for Road. People's Communications Press: Beijing, China, 2018.