ISSN 1822-427X/eISSN 1822-4288
2024 Volume 19 Issue 3: 1–16
https://doi.org/10.7250/bjrbe.2024-19.640

THE BALTIC JOURNAL
OF ROAD
AND BRIDGE
ENGINEERING
2024/19(3)

EXPERIMENTAL STUDY ON PAVEMENT PERFORMANCE OF WARM HIGH MODULUS MIXTURE WHMM-13

SHIJUN ZHOU[1], HUI ZHANG[2*], JIAYIN JIA[1], MENGLONG ZHAO[2], QIN AI[1], LEI TONG[2]

[1]*Chongqing Zhonghuan Construction Co., Ltd., Chongqing, China*

[2]*Jiangsu Zhonglu Engineering Technology Research Institute Co., Ltd., Nanjing, Jiangsu, China*

Received 12 November 2023; accepted 11 July 2024

Abstract. In order to solve the dusting and rutting problems of hot mix asphalt mixture during construction and operation, rutting test, bending test, Marshall stability test, freeze-thaw splitting test, uniaxial compression dynamic modulus test, overlay test, and four-point bending fatigue life test are applied on WHMM-13 to study the high-temperature stability, low-temperature cracking resistance, water stability, anti-reflection crack performance and fatigue durability in comparison with HMM-13. The results show that, compared to HMM-13, the dynamic stability and dynamic modulus (45 °C, 10 Hz) of WHMM-13 are improved by 10.0% and 47% respectively, and the rutting depth is reduced by 27.3%, indicating that the high temperature stability of WHMM-13 has been greatly improved. As for low temperature cracking resistance, the bending failure strain, stiffness modulus, flexural tensile strength and rupture energy of WHMM-13 are slightly lower than those of HMM-13. As for water

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* Corresponding author. E-mail: zh@sinoroad.com

Shijun ZHOU (ORCID ID 0009-0003-5676-9265)
Hui ZHANG (ORCID ID 0000-0001-8727-7819)
Jiayin JIA (ORCID ID 0009-0007-8293-434X)
Menglong ZHAO (ORCID ID 0000-0001-8069-6500)
Qin AI (ORCID ID 0009-0007-0727-6981)
Lei TONG (ORCID ID 0009-0002-4863-3766)

stability, the residual stability of WHMM-13 in immersion Marshall test is 87.5%, and the splitting strength is 82.3%, both higher than that of HMM-13. As for anti-reflection crack performance, the total tensile rupture energy of WHMM-13 is 2.32 times that of HMM-13, with cracking resistance index (CRI) increased by 25%, which shows that WHMM-13 has better strength, can effectively prevent the crack from spreading and effectively improve the cracking resistance capacity of asphalt pavement. As for fatigue durability, the fatigue life of WHMM-13 is 5.4% lower than that of HMM-13, with bending stiffness modulus and cumulative dissipation energy reduced by 11.3% and 2.8% respectively, indicating that the fatigue durability of WHMM-13 is slightly reduced.

Keywords: anti-reflection crack performance, dynamic modulus, fatigue performance, road works, pavement performance, warm high modulus mixture.

Introduction

In recent years, due to widespread heavy loading and overloading as the result of sharp increase in traffic volume, rutting damage in asphalt pavement has become increasingly serious and has gradually become one of the most serious sources of damage in the early stage of asphalt concrete pavement (Tian et al., 2009). The rutting deformation at the wheel tracks of the pavement with rutting damage will reduce the service performance of the pavement and affect driving comfort and safety. Against this background, methods for rutting control or reduction are attracting a widespread concern in the industry. High modulus mixture (HMM), because of its high modulus and deformation resistance, can significantly reduce the strain of asphalt course under load and reduce the high-temperature plastic deformation of asphalt pavement, thus achieving the effect of rutting resistance (Ouyang et al., 2009; Wang et al., 2015). The research on HMM has made phased progress in China. HMM has been successfully applied to national and provincial trunk intersections, middle surface course of newly-built expressways and other projects. From the application situation, the pavement treatment time interval of national and provincial trunk intersections can be increased from 2a to over 5a, and the service life can be increased by more than 30% (Pan, 2006; Cortéand & Serfass, 2000; Yang, 2012).

HMM is applied by hot mixing, with a construction temperature of 170–180 °C, which gives rise to a series of problems, such as a large amount of harmful gas emission, high energy consumption, poor workability in construction and great difficulty in quality control. Against this background, domestic and foreign researchers, through continuous exploration and research, developed warm mix construction technology to reduce the construction temperature to 120–140 °C. Ding (2018) took warm asphalt mixture and hot-mix asphalt mixture as the research objects to study their fatigue performance through semi-circular bending test. Experiments showed that the anti-reflection crack performance of warm asphalt mixture was improved. Zhang et al. (2018) made a comparative study on the variation in high/low temperature performance and fatigue resistance of hot mixing AC-20 and different warm mixing AC-20 from the aspect of warm agent. Zhang (2013) investigated the energy consumption during the construction of Yunnan G108 with warm SMA-13. The results showed that warm mix process could save 33% energy compared to hot-mix process, while yielding a remarkable reduction effect on the emission of air pollutants such as SO_2, NO_x, CO_2 and dust.

At present, the research on warm mix construction technology mainly focuses on the effect of different types of warm mixing agent on the mechanical properties of binder and pavement performance of conventional asphalt mixture (AC/SMA), resulting in insufficient research on WHMM (Warm High Modulus Mixture). Against this background, this paper is intended to design a type of WHMM based on high modulus mixture, and study the WHMM through rutting test, bending test, Marshall stability test, freeze-thaw splitting test, uniaxial compression dynamic modulus test, overlay test and four-point bending fatigue life test. The ultimate goal is to meet the requirements of environment-friendly construction by reducing the construction temperature and the emission of harmful gas pollutants while maintaining the pavement performance of high modulus mixture, and to provide support for the technical research and engineering application of warm high modulus mixture.

1. Materials and test methods

1.1. Asphalt binder

The finished SBS modified asphalt is adopted in this test, where the main technical specifications of SBS modified asphalt are tested according to JTG E20 standard; the technical specifications are shown in Table 1.

Table 1. Technical specifications of SBS modified asphalt

Test item		Technical specifications	Test results
Penetration (25 °C, 100 g, 5 s)/(0.1 mm)		40–70	55.2
Softening point, °C		≥70	87.5
Ductility, cm at 5 °C		≥25	30
Rotational viscosity, Pa s at 60 °C		-	6002
Brinell rotational viscosity, Pa s at 135 °C		≤3	2.2
Rotating film heating test	Mass loss, %	−0.5~+0.5	−0.161
	Residual penetration ratio (25 °C), %	≥65	79.9
	Residual ductility (5 °C), cm	≥15	21
	Change in rotational viscosity (back/front) at 60 °C	-	0.55
	Softening point difference (back-front), °C	−10~5	−7.0
	Aging index	-	−0.02

1.2. High modulus agent

The composite high modulus agent of low-density polyethylene and natural asphalt produced by Zhonglujiaoke Technology Co., Ltd. is adopted in this test, as shown in Figure 1. It is a black ellipsoid uniform particle; the high modulus technical specifications are shown in Table 2.

Figure 1. Appearance of high modulus agent

Table 2. Technical specifications of high modulus agent

Test item	Technical specifications	Test results
Particle size/mm	≤4.75	100% passing the 4.75 mm standard sieve
Density, g/cm^3	1.0~1.1	1.056
Melting point, °C	110~150	121.3
Melt mass flow rate (140 °C, 2.16 kg, g/10 min)	≥100	103.8

1.3. Warm mixing agent

Sasobit warm mixing agent produced by Sasol-Wax in Germany is used in the test, as shown in Figure 2, where dry addition process is adopted. The technical specifications are shown in Table 3.

Figure 2. Appearance of Sasobit warm mixing agent

Table 3. Technical specifications of warm mixing agent

Test item	Technical specifications	Test results
Density (20 °C), g/cm^3	Measured	0.945
Appearance	Pale yellow solid particles	Pale yellow solid particles
Smell	Odourless	Odourless
Melting point, °C	110–120	115
Flash point, °C	≥250	260

2. Mix ratio

The ratio of HMM-13 aggregates: 1 # material (9.5–16 mm): 2 # material (4.75–9.5 mm): 3 # material (2.36–4.75 mm): 4 # material (0–2.36 mm): aggregate powder = 30%: 27%: 5%: 22%: 33.5%: 4.5%. The composite gradation is controlled based on the median of grading limit, as shown in Table 4 and Figure 3. The asphalt-aggregate ratio is 4%, the high modulus agent content is 1% of the aggregate mass, and the warm mixing agent content in WHMM-13 is 3% of the asphalt mass.

Table 4. Design gradation of high modulus mixture

Gradation type	Mass percentage, %, passing the following mesh size									
	16.0	13.2	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
Upper limit of gradation	100	100	-	60	38	-	-	-	-	8
Lower limit of gradation	100	90	-	40	25	-	-	-	-	6
Design gradation	100	97.0	72.9	43.4	32.6	24.9	18.2	12.5	9.7	6.9

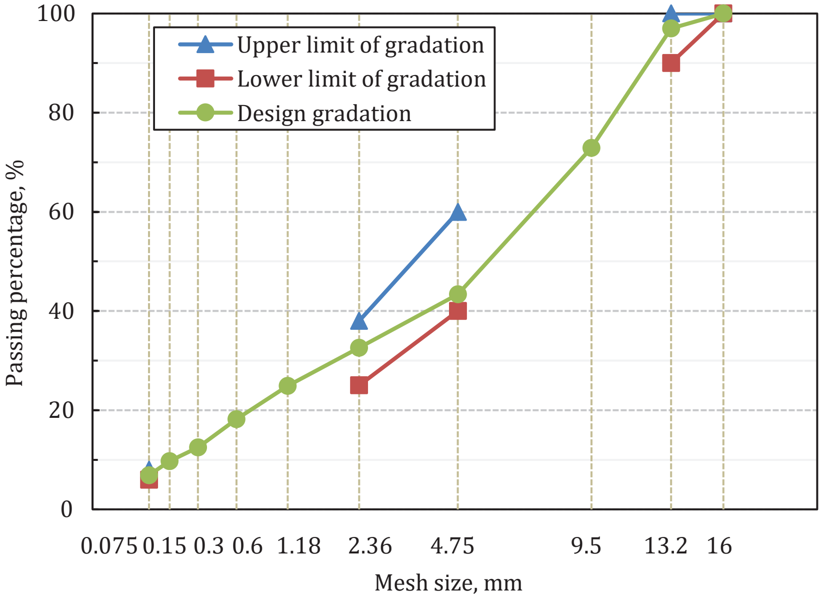


Figure 3. HMM-13 optimal gradation curve

3. Test method

3.1. Rutting test

The high-temperature stability of asphalt mixture is an important index to evaluate the durability of asphalt mixture. The test method of T0719 (JTJ E20) is adopted in this test, where a 300 mm×300 mm×50 mm plate-shaped test piece is rolled to form with a wheel rolling machine at a test temperature of 60 °C and a wheel pressure of 0.7 MPa.

3.2. Bending test

The low-temperature tensile performance of asphalt mixture is evaluated through bending test at −10 °C, where the size of the small beam test piece is 250 mm×30 mm×35 mm. Test piece is subject to the test method of T0715(JTJ E20).

3.3. Water stability test

The test methods of T0710(JTJ E20) and T0729(JTJ E20) are applied in testing the water stability of WHMM-13, which are subject to Marshall stability test and freeze-thaw splitting test, respectively.

3.4. Dynamic modulus test

The test method of T0738(JTJ E20) is applied in this test, where a Ø 100 mm×150 mm core test piece is used to test the performance of asphalt mixture with DTS asphalt mixture performance tester at test temperature of 15 °C and 45 °C, and loading frequency of 0.1 Hz, 0.5 Hz, 1.5 Hz, 10 Hz and 25 Hz, respectively. The test is carried out in a stress control mode in the order from low temperature to high temperature, and from high frequency to low frequency.

3.5. Crack propagation performance test (OT method)

The TxDOT designation method is applied for the overlay test. The size of the formed test piece is shown in Figure 4, wherein the cut test piece is glued to two drawing gadgets, with a 2 mm gap between the moulds. The test is carried out after standing the test piece for 24 h, as shown in Figure 5. The target displacement is set at 0.625 mm and the test temperature at 25±0.5 °C in the test.

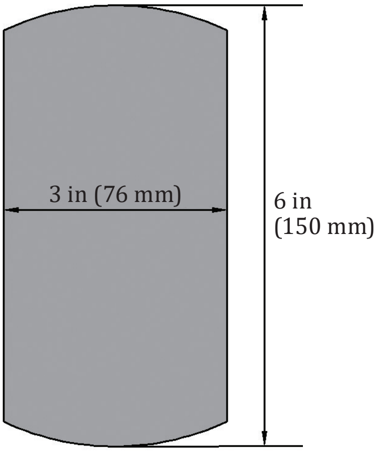


Figure 4. Test piece size in overlay test

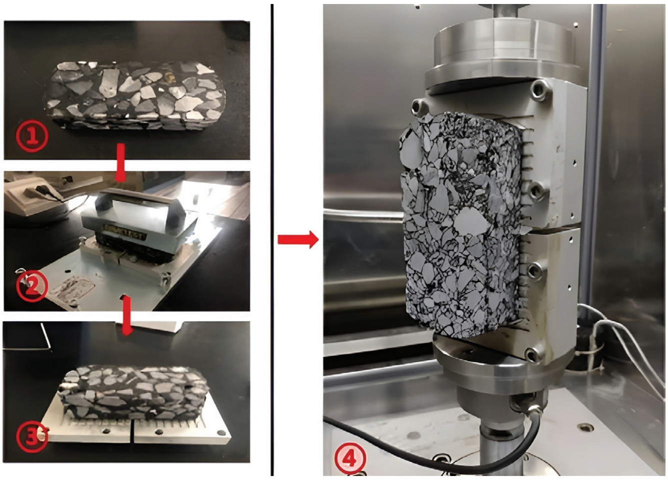


Figure 5. Overlay test process

The initial load, termination load and load loss are used as direct indices to evaluate the anti-reflection crack performance of the mixture, and the total rupture energy G_a and cracking resistance index CRI are used as indirect indices to evaluate the anti-reflection crack performance. The total rupture energy G_a is the area surrounded by the maximum load-period curve, which indicates the energy required per unit area for crack propagation. This parameter can be used to characterise the rupture resistance of the test piece in the process of crack formation. It is calculated according to Equation (1). The cracking resistance index CRI is obtained through fitting the curve of the peak load and the curve of number of loading cycles and subjecting the resultant curve to power-law equation. This index indicates the load declination required for crack propagation under the condition of OT cyclic loading test. This parameter can be used to characterise the flexibility and fatigue performance of the test piece in the crack propagation stage. It is obtained by fitting according to Equation (2).

$$G_a = \frac{W_c}{b \times h}, \tag{1}$$

where G_a is the total rupture energy, in N/m; W_c is the rupture area, in kN mm; b is the test piece width, which is 76.2 mm; and h is the test piece height, which is 38.1 mm.

$$y = a \times x^{-b}. \tag{2}$$

3.6. Four-point bending fatigue life test

The test method of T0739(JTJ E20) is applied for formation of a small beam test piece of 380 mm×50 mm×63.5 mm in this four-point bending fatigue test at a strain level of 300 με, a test temperature of 15±0.5 °C and a loading frequency of 10±0.1 Hz. The test termination condition is set at the point where the bending stiffness modulus is reduced to the number of loading cycles corresponding to 50% of initial bending stiffness modulus. Bending stiffness modulus, phase angle and cumulative dissipation energy are calculated according to the formula below.

The calculation formula of bending stiffness modulus is as follows:

$$S = \frac{\tilde{A}_t}{\mu_t}, \tag{3}$$

where S is the bending stiffness modulus, in Pa; σ_t is the maximum tensile stress, in Pa, and ε_t is the maximum tensile strain.

The calculation formula of phase angle is as follows:

$$\varphi = 360 \times f \times t, \tag{4}$$

where φ is the phase angle, in °; f is the loading frequency, in Hz; t is the time at which the strain peak lags behind the stress peak, in s.

The calculation formula for cumulative dissipation energy is as follows:

$$E_{\mathrm{CD}} = \sum_{i=1}^{n} E_{\mathrm{D}i} \tag{5}$$

where E_{CD} is the accumulated dissipation energy during fatigue test, in J/m^3; $E_{\mathrm{D}i}$ is the dissipation energy of a single cycle at i-th loading, in J/m^3.

4. Findings and discussion

4.1. High temperature stability

As shown in Figure 6, the dynamic stability of WHMM-13 is 12.161 times/mm, and the rutting depth is 1.1 mm. Compared to HMM-13, the dynamic stability is improved by 10.0%, and the rutting depth is reduced by 27.3%. This is mainly because the organic wax in Sasobit warm mixing agent is of a crystal network structure, which increases its structural stability and reduces the overall flow of the structure after being mixed with asphalt mixture, thus improving the deformation resistance of WHMM-13 under high temperature load.

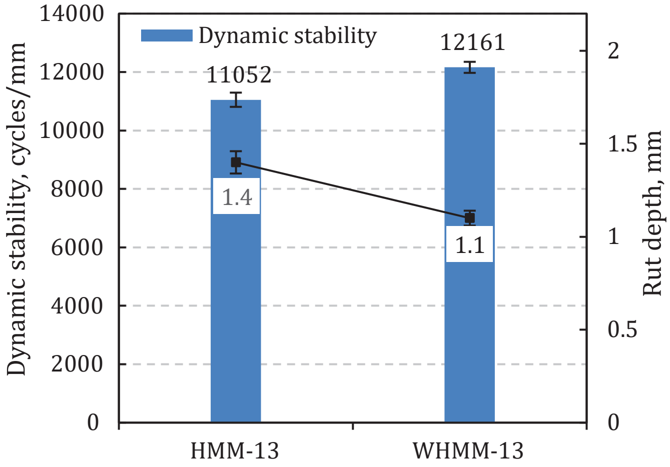
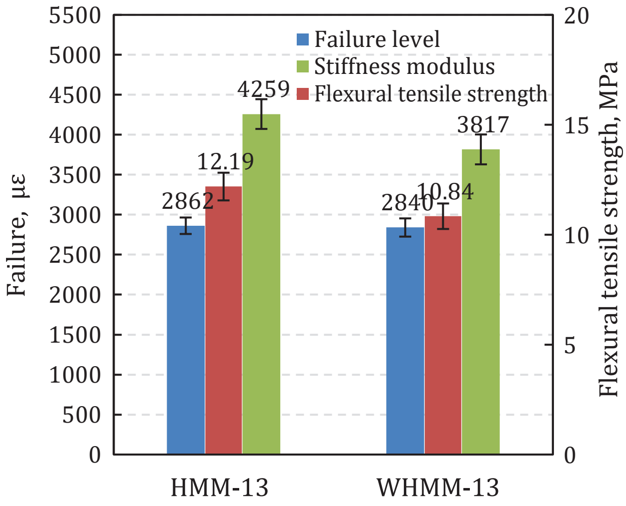


Figure 6. Rutting test results

4.2. Low temperature cracking resistance

The test results of bending failure strain, stiffness modulus and flexural tensile strength of HMM-13 are shown in Figure 7(a). The bending failure strain, stiffness modulus and flexural tensile strength of HMM-13 are 2.862 με, 4.259 Mpa and 12.19 Mpa, respectively. Compared to HMM-13, the bending failure strain, stiffness modulus and flexural

(a) Failure strain, stiffness modulus, flexural tensile strength



(b) Rupture energy

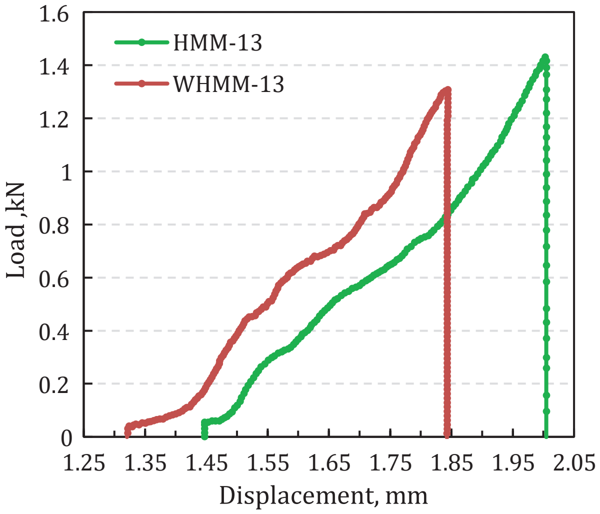


Figure 7. Low temperature bending test results

tensile strength of WHMM-13 are slightly reduced mainly due to Sasobit warm mixing agent, which has wax-like crystal structure. Its low-temperature ductility is poor, which increases the brittleness of asphalt and reduces the low temperature cracking resistance of WHMM-13. As shown in Figure 7(b), the rupture energies of HMM-13 and WHMM-13 are 0.0555 KN mm and 0.0536 KN mm, respectively, indicating that Sasobit warm mixing agent has limited effect on the low temperature cracking resistance of the mixture.

4.3. Water stability

The results of immersion Marshall stability test and freeze-thaw splitting strength ratio test are shown in Table 5. The residual stability values are 86.8% and 87.5%, respectively, and the splitting strength values are 80.8% and 82.3%, respectively, under immersion Marshall test on HMM-13 and WHMM-13. The test results meet the requirements of the test specifications. Moreover, data comparison shows that WHMM-13 has better water stability, i.e., it has stronger resistance to water damage. This entails that the water damage resistance of high modulus mixture can be improved to some extent by adding warm mixing agent.

Table 5. Results of immersion Marshall test and freeze-thaw splitting test

		Type of mixture	
		HMM-13	**WHMM-13**
Immersion Marshall test	Unconditional stability, kN	15.73	16.37
	Conditional stability, kN	13.66	14.32
	Residual stability MS0, %	86.8	87.5
	Specification requirements, %	≥85	≥85
Freeze-thaw splitting test	Unconditional splitting strength, MPa	1.480	1.602
	Conditional splitting strength, MPa	1.3195	1.319
	TSR, %	80.8	82.3
	Specification requirements, %	≥80	≥80

4.4. Dynamic modulus

The results of dynamic modulus test are shown in Figure 8. Comparison of the dynamic modulus of the mixture under different test temperatures and frequencies shows that the dynamic modulus decreases with increasing test temperature and increases with increasing test frequency. At 15 ℃ and 10 Hz, the dynamic moduli of HMM-13 and WHMM-13 are 14.661 MPa and 15.026 MPa, respectively.

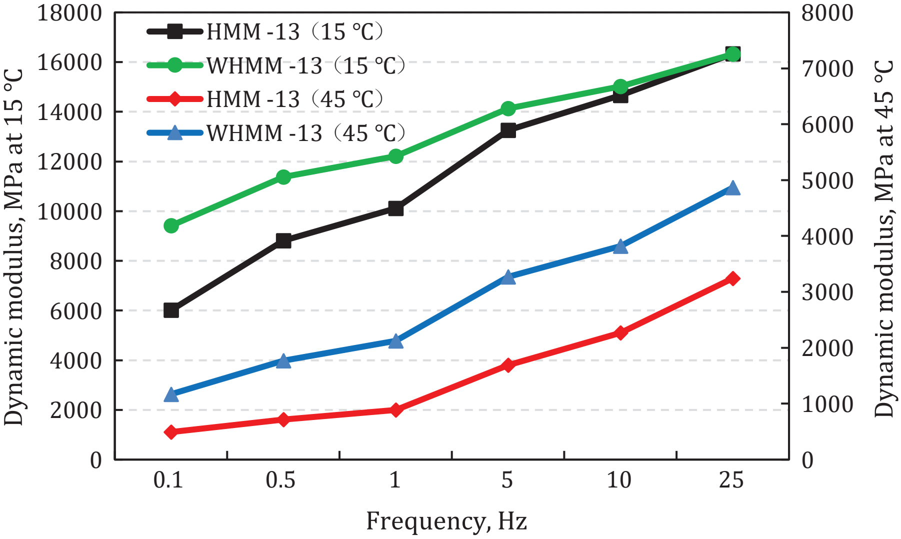


Figure 8. Dynamic modulus test results

At 45 ℃ and 10 Hz, the dynamic moduli of HMM-13 and WHMM-13 are 8.078 MPa and 4.256 MPa, respectively. This indicates that under normal temperature conditions, the stiffness and deformation resistance of WHMM-13 are basically equivalent to those of HMM-13. However, under high temperature conditions, compared to HMM-13 mixture, the stiffness and deformation resistance of WHMM-13 are increased by 47%, indicating that the addition of warm mixing agent can improve the high temperature stability of high modulus mixture to a certain extent, thus further enhancing its deformation resistance. This is consistent with the result of the high temperature dynamic stability test.

4.5. Anti-reflection crack performance

The overlay test results are shown in Figure 9. The total rupture energy Ga is calculated according to Equation (1). The initial loads on WHMM-13 and HMM-13 are 2.48 kN and 1 kN, respectively, indicating that higher load is required to stretch WHMM-13 to the set deformation for the first time, i.e., WHMM-13 is higher in strength. After 1000 cycles of loading, the termination load reaches at 0.85 kN and 0.38 kN, with load losses of 66% and 62%, respectively. This indicates that the residual strength of WHMM-13 remains higher than that of HMM-13 after being subject to equal cycles of fatigue loading. However, WHMM-13 shows a strength decay rate higher than that of HMM-13 during the test. In

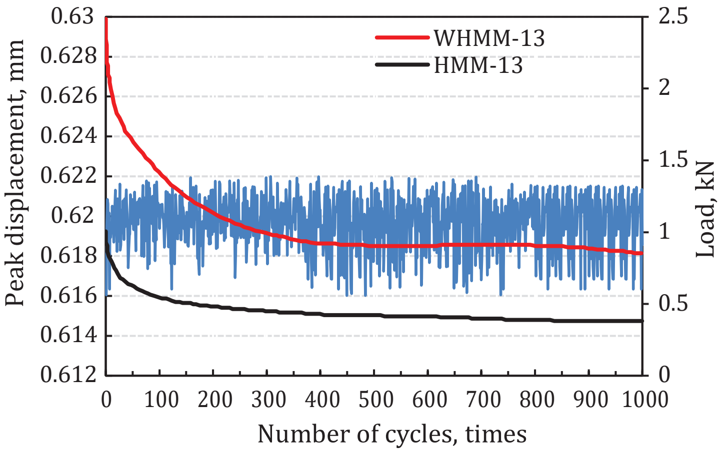


Figure 9. Maximum load–test cycle curve

Table 6. Fitting results of curve of OT maximum load-test cycle

Type of mixture	Fitting formula	R2	a	CRI
HMM-13	$Y = 1.15x - 0.16$	0.9878	1.15	0.16
WHMM-13	$Y = 3.27x - 0.20$	0.9518	1.03	0.20

terms of rupture energy index, the total rupture energy of WHMM-13 is 1.038 N/m, which is 2.32 times of that of HMM-13, indicating that WHMM-13 requires more energy for crack propagation per unit area. The curve of peak load and the curve of number of loading cycles are fitted according to Equation (2) to derive the anti-cracking resistance index CRI. As shown in Table 6, the cracking resistance index CRI of WHMM-13 is 0.20, which is 25% higher than that of HMM-13, indicating that WHMM-13 has better anti-reflection crack performance.

4.6. Fatigue durability

The results of the four-point bending fatigue test are shown in Figure 10. The bending stiffness modulus, phase angle and cumulative dissipation energy index of the mixture are calculated according to Equation (8), Equation (9) and Equation (10), respectively. As shown in Table 7, the fatigue life of WHMM-13 is 123 530 times at 300 με, which is 5.4% lower than that of HMM-13, namely, 130 170 times. The bending stiffness modulus and cumulative dissipation energy index are consistent with the results of bending fatigue life, and they are all reduced compared to HMM-13, in which the bending stiffness modulus is reduced by 11.3% and the cumulative dissipation energy by 2.8%,

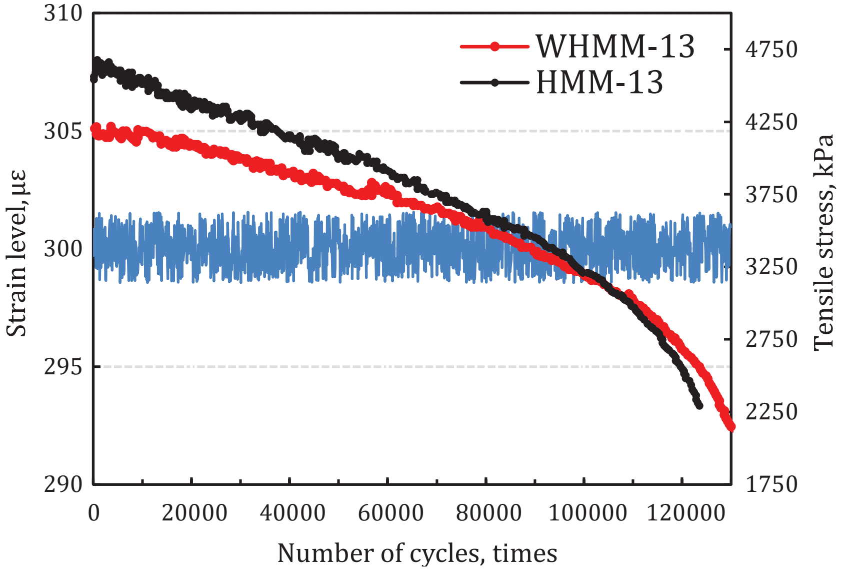


Figure 10. Curve of tensile stress–test cycle

Table 7. Fatigue performance test results

Mixture Type	Strain level, με	Average fatigue life, times	Bending stiffness modulus, MPa	Phase angle, deg	Cumulative dissipation energy, MPa
HMM-13	300	130 170	15 306	23.56	94.65
WHMM-13	300	123 530	13 568	16.42	91.96

indicating that the addition of Sasobit warm mixing agent has a small negative impact on the fatigue durability of high modulus mixture. This is mainly because Sasobit warm mixing agent improves the brittleness of asphalt and leads to the decline of fatigue resistance.

Conclusions

1. According to the results of rutting test and dynamic modulus test, compared to HMM-13, the dynamic stability and rutting depth of WHMM-13 are improved by 10.0% and 27.3%, respectively. At

15 °C and 10 Hz, the dynamic modulus of WHMM-13 is slightly improved (2.4 %). Compared to HMM-13, the dynamic stability of WHMM-13 is improved by 47% at high temperature, which shows that adding warm mixing agent can greatly improve the high temperature stability of high modulus mixture, further enhancing its high temperature deformation resistance, thus conductive to the mitigation of rutting damage to pavement.

2. The bending test results show that compared to HMM-13 and WHMM-13, the stiffness modulus, flexural tensile strength and rupture energy indices are all slightly reduced, but they still meet the technical requirements specified in the specification, indicating that Sasobit warm mixing agent has a negative but rather small impact on the flexural performance and flexural fatigue durability of high modulus mixture.
3. In the immersion Marshall test, HMM-13 and WHMM-13 have a residual stability of 86.8% and 87.5%, respectively, and a splitting strength of 80.8% and 82.3%, respectively. This indicates that adding Sasobit warm mixing agent can improve the water damage resistance of high modulus mixture to some extent.
4. According to the OT test results, the test loading times of WHMM-13 and HMM-13 have both reached 1000 times, but the load required for WHMM-13 to reach the set deformation for the first time is 2.48 times that of HMM-13, and WHMM-13 still has higher strength after the same number of fatigue loading cycles. The total rupture energy of WHMM-13 is 2.32 times that of HMM-13, and the cracking resistance index CRI is also higher than that of HMM-13, indicating that WHMM-13 has better strength and toughness, which can effectively prevent the propagation of cracks and effectively improve the cracking resistance capacity of asphalt pavement.
5. The results of four-point bending fatigue test show that the fatigue life of WHMM-13 is 5.4% lower than that of HMM-13 at 300 με. The bending stiffness modulus and cumulative dissipation energy index are consistent with the results of bending fatigue life, and they are all reduced compared to HMM-13, in which the bending stiffness modulus is reduced by 11.3% and the cumulative dissipation energy by 2.8%, indicating that the addition of Sasobit warm mixing agent has a small negative impact on the fatigue durability of high modulus mixture. This is mainly because Sasobit warm mixing agent improves the brittleness of asphalt and leads to the decline of fatigue resistance.

Acknowledgements

The authors would like to acknowledge the National Key R&D Program of China (2021YFB1600300) for its financial support in this project.

Funding

The research has been supported by the National Key R&D Program of China under Grant [2021YFB1600300].

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