Effect of Thermo-oxidative Aging on Properties of Compound High Viscosity Modified Asphalt and Mixture

Chunlei Ge[1,a*], Zhaoyang Li[1,b] and Yue Qin[2,c]

[1]Department of Civil Engineering, Guangxi Polytechnic of Construction, Nanning, Guangxi, 530007, China
[2]College of Civil Engineering and Architecture, Guangxi University, Nanning, Guangxi, 530004, China

[a*]13907811569@163.com; [b]410276132@qq.com; [c]390039465@qq.com

Abstract. The aging of asphalt is the main reason for the performance degradation of porous asphalt pavement. The purpose of this article is to investigate the aging behavior of high-viscosity agent / styrene-butadiene-styrene (SBS)-modified asphalt and asphalt mixtures. To this end, samples of asphalt and asphalt mixtures with different degrees of aging were prepared, and the rheological properties of asphalt before and after aging were evaluated using frequency scan test and Multiple Stress Creep Recovery Test (MSCR). The high-temperature performance of asphalt mixtures was analyzed using the wheel tracking test, and the water stability of asphalt mixtures was comprehensively evaluated through the immersion Marshall test, immersion Kendeberg fragmentation test, and freeze-thaw splitting test. The results show that through linear fitting of 79 sets of data, the complex modulus of asphalt has a significant dependence on the loading frequency (correlation coefficient not less than 0.98). The main curve of asphalt modulus can be constructed on a double logarithmic coordinate system, and the high viscosity agent /SBS-modified asphalt prepared is more suitable for configuration in high-speed driving areas. Aging weakens the rebound performance of asphalt and the water stability of asphalt mixtures, but the compounding effect of high viscosity agent and SBS can to a certain extent inhibit this aging effect. high viscosity agent/SBS can better meet the needs of porous asphalt pavement materials and is a better choice of asphalt material.

Keywords: Thermal oxygen aging; high viscosity agent / SBS compound modified asphalt; Rheological properties; MSCR; Water stability.

1 Introduction

With the introduction of "sponge city" construction in China, there has been increasing attention on the open-graded friction course (OGFC) pavement developed in 20th-century Western countries [1]. OGFC belongs to a skeletal porous structure, with a higher proportion of coarse aggregates to form a mineral skeleton and a lower proportion of fine aggregates to retain larger voids [2]. Therefore, this type of structure has a higher

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porosity, which enhances the pavement's skid resistance and resistance to rutting, reduces splashing and misting on the road surface, and ensures driving safety on rainy days. Additionally, due to the absorption of sound by the voids, this structure also has a good noise reduction effect [3]. Currently, this pavement structure has become the main form of highway in countries such as Japan.

Due to the large porous structure of OGFC asphalt mixtures, air, and moisture have easier access to the internal structure, which requires ensuring the durability and excellent water stability of the structure. The strength of the OGFC structure mainly relies on the asphalt bond between aggregates [4]. Therefore, the OGFC structure usually requires the use of high-viscosity modified asphalt (HVMA) for paving, to significantly enhance the resistance to water damage, high-temperature rutting performance, and low-temperature cracking resistance of OGFC pavement. Common HVMA products include TPS (TAFPACK-Super) from Japan, SINOTPS from Shenzhen Haichuan in China, and PA-T type additive (HVA) developed by the Highway Research Institute of the Ministry of Transportation, which have been widely used in numerous asphalt pavements. However, these finished high-viscosity modified asphalts (FHVMA) are often expensive, and some products still need further improvement in their road performance, thus increasing the construction cost of OGFC asphalt pavement. Therefore, scholars have been researching various cheaper and superior performance-modified asphalt materials. Cai et al. [5] prepared three different HVMA using rubber powder and recycled oil, and through pavement performance tests, it was demonstrated that the prepared HVMA exhibited good performance in terms of high and low-temperature properties and storage stability. It can be concluded that rubber powder, recycled oil, and appropriate additives contribute to the preparation of high-quality and cost-effective HVMA. Tan et al. [6] prepared a new type of HVMA using thermoplastic elastomers (TPE), styrene-butadiene-styrene (SBS) modifiers, and base asphalt. Cohesion and adhesion tests revealed that the cohesive force of HVMA was significantly superior to that of the base asphalt at different temperatures. The prepared HVMA exhibited good high-temperature stability and low-temperature flexibility, making it highly suitable for application in drainage asphalt pavements. Kiselev et al. [7] conducted composite modification of TPS and SBS modifiers and compared the two-phase mixing method with the traditional blending method. The results showed that the SBS (4%) and TPS (10%) modifiers had good applicability, improving the stability, viscosity, and consistency of the binder, and the two-phase mixing method helped improve some mechanical and functional properties of SBS/TPS modified asphalt. Zhou et al. [8] incorporated a certain amount of SBS modifier, viscosity-increasing resin, stabilizer, and plasticizer into the base asphalt to prepare a new type of HVMA. The results showed that the combination of 7% SBS modifier and 4% viscosity-increasing resin yielded the best performance, with high-temperature rutting resistance and resistance to permanent deformation comparable to FHVMA. In conclusion, scholars have explored various proportions of HVMA using SBS, recycled oil, waste rubber powder, viscosity-increasing resin, and other materials, which have played a significant role in the development of HVMA design and construction techniques. However, there is still limited research on the compounding of high-adhesive and SBS-modified asphalt.

As previously mentioned, OGFC asphalt pavement is more susceptible to air, temperature, and moisture due to its high porosity, resulting in faster aging compared to other pavement structures [9-11]. Therefore, it is necessary to study the aging mechanism and anti-aging properties of HVMA asphalt binders and mixtures. In terms of the aging of HVMA asphalt binder, Hu et al. [12] considered three factors: solar radiation, heat, and humidity, and investigated the effects of different weathering aging environments on the permanent deformation resistance and fatigue damage of HVMA. The results showed that weathering aging increased the rutting coefficient of HVMA, decreased the irreversible creep stiffness, and significantly reduced the anti-fatigue performance of HVMA during the 70°C weathering aging process, which is mainly related to the polymer structure, asphalt content, and surface microcracks. Yuan et al. [13] studied the degree and mechanism of aging of HVMA at high, medium, and low temperatures, and compared it with SBS-modified asphalt (SBSMA) and crumb rubber-modified asphalt (CRMA). They found that short-term aging had a significant effect on HVMA at high temperatures, had the greatest impact on CRMA at medium temperatures, and had a greater impact on SBSMA than the other two types of asphalt at low temperatures. In terms of the aging of HVMA mixtures, Liao et al. [14] studied the effects of aging on HVMA mixtures and found that aging helped improve the tensile strength and rutting resistance of the mixtures, but hurt tear resistance and moisture sensitivity. Jing et al. [15] conducted tests on HVMA mixtures aged in the field, analyzed the relationship between the mechanical behavior of the mixtures and aging using cyclic indirect tensile tests, and conducted dynamic shear rheological tests and Fourier transform infrared spectroscopy tests on the extracted asphalt binder. The results showed that the degree of asphalt aging in outdoor mixtures is related to space, and the stiffness of the asphalt decreases gradually with the thickness of the pavement layer. Wu et al. [16] studied the aging performance of epoxy-modified asphalt-graded mixtures for 85 days at 194°C, and found that epoxy asphalt helped improve the indirect tensile modulus of the mixtures. The higher the dosage, the better the improvement effect. In summary, current research on HVMA aging is either focused on asphalt performance or asphalt mixture performance, and there is little systematic analysis of the performance of asphalt and asphalt mixtures under equal aging conditions.

In general, research on the application of high-viscosity agents in SBS-modified asphalt is relatively limited both domestically and internationally. For OGFC asphalt pavement, high-viscosity modified asphalt is typically achieved by adding various modifying materials to the base asphalt. Research results have shown that asphalt materials without the addition of high-viscosity modifiers often struggle to meet application standards, while the use of high-viscosity modifiers alone can increase the cost of asphalt binder and impact its engineering application. Additionally, there is a lack of systematic research on the short-term and long-term aging properties of HVMA asphalt and mixtures. Therefore, this study utilized commercially available high-viscosity agents in combination with SBS-modified asphalt to prepare high-viscosity/SBS composite-modified asphalt, which was then compared with commercially available high-viscosity modified asphalt and SBS-modified asphalt. The rheological properties of the asphalt at different aging levels were comprehensively evaluated through frequency sweep tests and multiple stress creep recovery tests. Furthermore, the high-temperature stability (rutting test) and water stability (Immersion Marshall test, Immersion Kunderburg scattering test and Freeze-thaw splitting test) of the mixtures before and after aging were assessed. This study demonstrates the effectiveness of high-viscosity agents in improving the anti-aging properties, elastic recovery performance, and water stability of asphalt, providing beneficial data and theoretical support for the design and construction of HVMA.

2 Test materials and methods

2.1 Materials

The asphalt used in this study includes two types: SBS-modified asphalt and finished high-viscosity modified asphalt (FHVMA). Both types are produced by Sinopec Foshan Co., Ltd., and their basic performance characteristics are obtained through testing, as shown in Table 1.

Table 1. Basic performance of SBS and FHVMA asphalt.

Item	SBS	FHVMA
Penetration (25°C, 0.1mm)	46.9	47.8
Softening point (°C)	75.5	88.4
Viscosity (135°C, Pa·s)	1.96	2.75

The high-viscosity agent used in the experiment was provided by Tianjin Zhongyou Gaoyuan New Materials Co., Ltd., and its basic technical performance indicators are shown in Table 2.

Table 2. Basic performance of high-viscosity agent

Item	Result	Requirement
Appearances	Granular, uniform, full, no lumps, light red	Granular, uniform, full, no lumps, light red
Single particle mass (g)	0.0096	≤0.03
densities	0.958	≤1.0
Lit. melting index (g/cm^3)	2.436	≥2.0
Ash content (%)	0.76	≤1.0

The aggregates and mineral powder used in the experiment are both limestone-based, and the gradation design is based on the “Technical Specifications for Permeable Asphalt Pavement” CJJ/T190-2012 (Chinese Standard 2012). The gradation curve for OGFC-13 is shown in Fig.1.

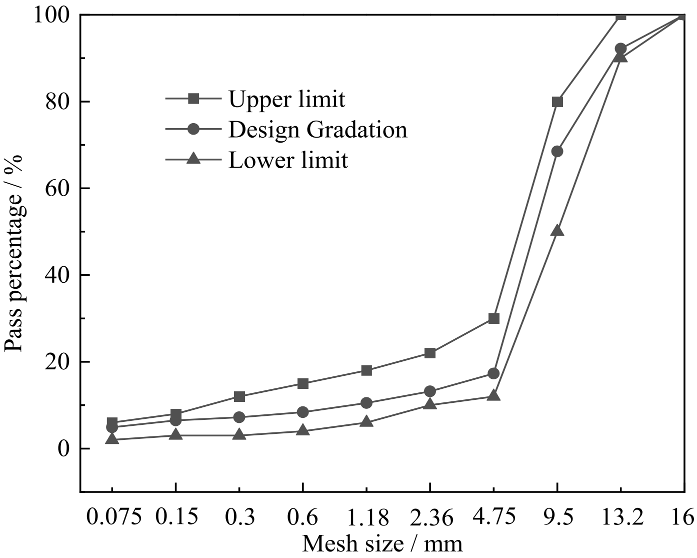


Fig. 1. The gradation curve for OGFC-13

2.2 Compound high viscosity modified asphalt preparation

The specific preparation process for compound high viscosity modified asphalt (CHVMA) is as follows: Firstly, the SBS-modified asphalt is placed in a 175°C oven and heated for at least 1 hour to achieve a fully flowable state. Secondly, the high-viscosity agent, weighing 5% of the asphalt mass, is slowly and gradually added to the SBS-modified asphalt in small portions. During this process, proper stirring is conducted using a glass rod to ensure uniform dispersion of the high-viscosity agent in the SBS-modified asphalt. Next, the dispersed asphalt is further mixed for at least 30 minutes at 160°C using a dispersion mixer. Then, at a temperature of 170°C, the mixture is subjected to shearing at a speed of 2000r/min for 30 minutes using a high-speed shear emulsifier. Subsequently, the shear speed of the high-speed shear emulsifier is increased to 5000r/min and shearing is performed for an additional 45 minutes. Finally, the sheared asphalt is placed in a 170°C oven for 1 hour to obtain the CHVMA asphalt.

2.3 Aging test of asphalt

According to JTG E20-2011 (Chinese Standard 2011), the three types of asphalts were subjected to the Rolling Thin Film Oven Test (RTFOT) and Pressurized Aging Vessel (PAV) test to obtain short-term aged asphalt and long-term aged asphalt. Therefore, SBS, FHVMA, and CHVMA each have three aging conditions: original asphalt (OA), RTFOT, and PAV. The RTFOT test can simulate the aging degree of asphalt in the mixing, transportation and paving stages, while the PAV test can simulate the aging degree of asphalt after 5 years of service. In the RTFOT test, the asphalt needs to be heated in an oven at 163 ° C for 85 min. In the PAV test, the pressure of the container was set to 2.1 MPa, the temperature was 90 °C, and the aging test was 20 h.

2.4 Aging test of asphalt mixture

According to JTG E20-2011, the asphalt mixture is uniformly spread in an enamel tray at a rate of 21-22kg/m3, and then placed in a 135°C oven for 4 hours and 5 minutes, with hourly stirring. This process is carried out to obtain short-term aged asphalt mixture, which is then used to prepare Marshall specimens and rutting specimens for testing. To simulate the effects of long-term aging, the short-term aged asphalt mixture is further used to prepare Marshall specimens and rutting specimens, which are then heated for 120 hours and 0.5 hours under forced ventilation conditions at 85°C.

2.5 Rheological property test of asphalt

The rheological tests for asphalt include frequency sweep tests and multiple stress creep recovery (MSCR) tests. The frequency sweep tests are conducted using a dynamic shear rheometer (DSR) with a temperature range of 32-82°C (with 6°C intervals) and a frequency range of 0.1Hz to 10.0Hz. The MSCR tests are performed at a temperature of 64°C, with stress levels of 0.1kPa and 3.2kPa applied for 1 second, followed by a 9-second recovery period. Each stress level is repeated 10 times.

2.6 Rutting test of asphalt mixture

According to JTG E20-2011, rutting tests were conducted on asphalt mixture specimens with different aging levels. The test temperature was set at 60°C, the rolling speed was 42 cycles per minute, and the wheel load was 0.7MPa. The duration of the test was 60 minutes.

2.7 Water stability test of asphalt mixture

The water stability test includes the immersion Marshall test, immersion Kenpau scattering test, and freeze-thaw splitting test, all based on JTG E20-2011. In the immersion Marshall test, eight Marshall specimens with different degrees of aging are first divided into two groups. The first group is immersed in a constant temperature water bath at 601 for 30 minutes, while the second group is immersed under the same conditions for 48 hours. After immersion, the Marshall stability tester is used to measure and calculate the residual stability MS0. In the immersion Kenpau scattering test, Marshall specimens with different degrees of aging are first soaked in a constant temperature water bath at 600.5 for 48 hours, then taken out and placed indoors for 24 hours, and finally tested using the Los Angeles testing machine to calculate the mass loss rate M before and after the test. In the freeze-thaw splitting test, eight Marshall specimens with different degrees of aging are first divided into two groups. One group is kept at room temperature as a control group, while the other group is used as the experimental group. Then, the experimental group is subjected to vacuum saturation for 15 minutes, placed in a freezer at -18 for 16 hours, taken out, and placed in a constant temperature water bath at 60 for 24 hours, and then placed in a constant temperature water bath at 25 for 2 hours. After completing these steps, the splitting test is conducted, and the freeze-thaw splitting strength ratio *TSR* is calculated.

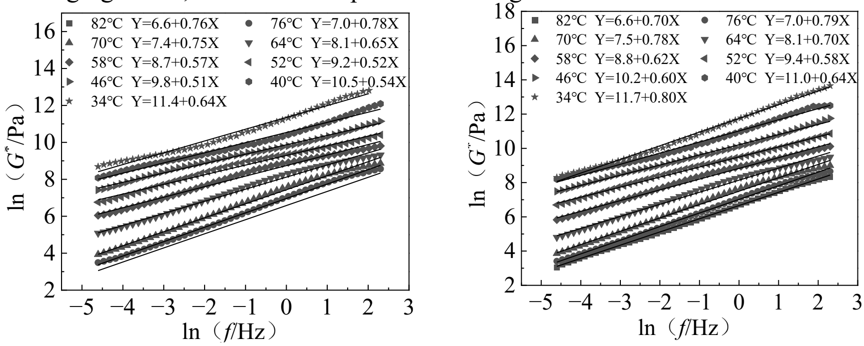
3 Results and analysis

3.1 Analysis of the dependence of asphalt complex modulus on frequency

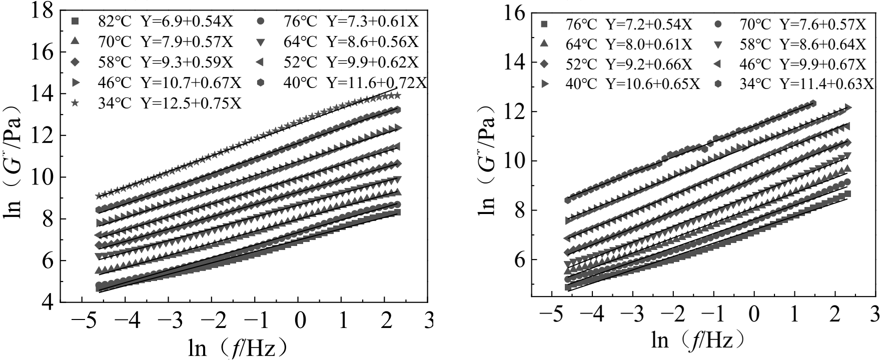
To better describe the frequency dependence of the complex modulus G^* of asphalt, a linear equation is employed to fit the relationship between G^* and the frequency f:

$$\ln(G^*) = A\ln(f) + B \tag{1}$$

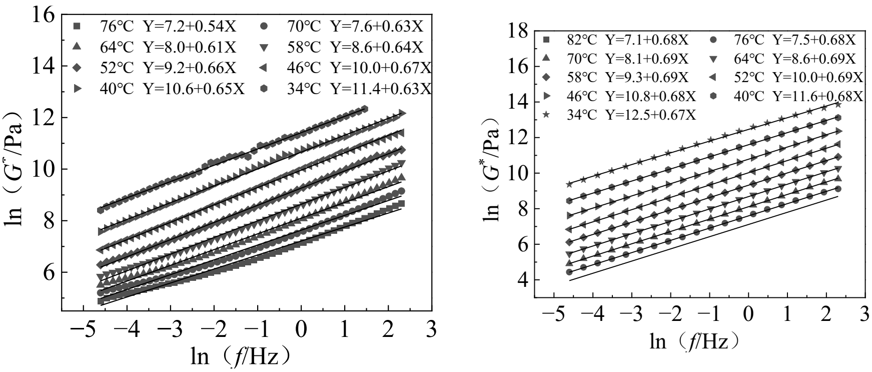
In the equation, A and B are both fitting parameters, where A reflects the sensitivity of the complex modulus to the loading frequency. A larger value of A indicates a higher sensitivity. By using equation (1) to fit the G^* and f of the three types of asphalt at different aging levels, the results are presented in Fig. 2.



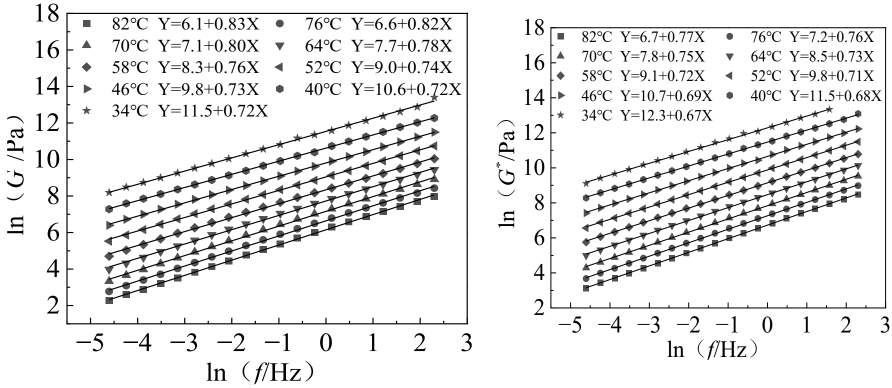
(a)OA of FHVMA (b)RTFOT of FHVMA



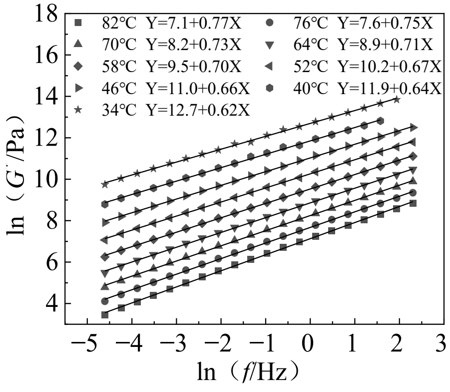
(c)PAV of FHVMA (d)OA of CHVMA



(e)RTFOT of CHVMA (f)PAV of CHVMA



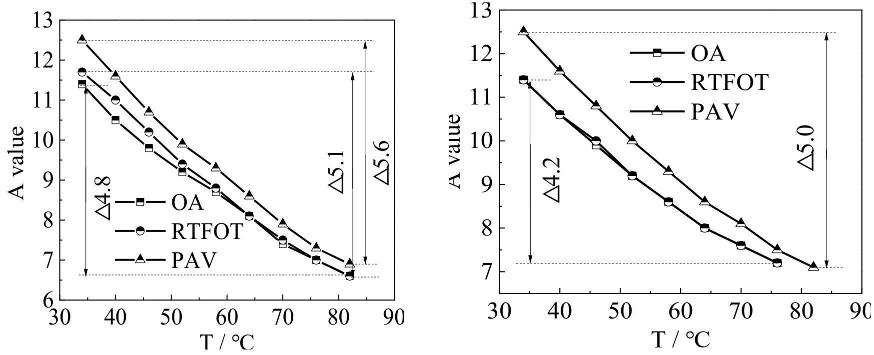
(g)OA of SBS (h)RTFOT of SBS



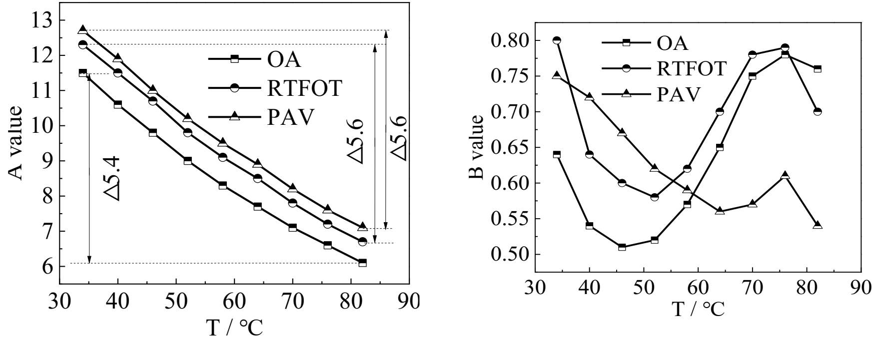
(i)PAV of SBS

Fig. 2. The relationship curve between complex modulus and frequency of asphalt under different aging degree

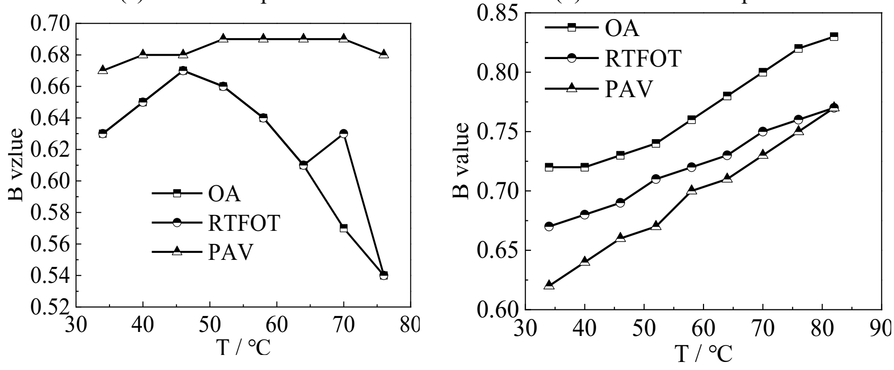
From Fig. 2, it is evident that there is a strong linear relationship between the complex modulus G^* of asphalt and the loading frequency f in a logarithmic coordinate system. This relationship holds for the three types of asphalt at three different aging levels and nine different temperatures, with a total of 79 curves (excluding two missing data sets) having fitting correlation coefficients not lower than 0.98. This indicates that the fitting results are highly reliable. By utilizing the fitting equation, it is possible to obtain the complex modulus values of asphalt under any given conditions within the experimental range, establish a dynamic viscoelastic temperature equation for asphalt, and estimate the complex modulus of highly viscous asphalt under arbitrary load and temperature conditions. Furthermore, the fitted parameters *A* and *B* are statistically analyzed, as shown in Fig. 3.



(a)*A* of FHVMA asphalt (b)*A* of CHVMA asphalt



(c)*A* of SBS asphalt (d)*B* of FHVMA asphalt



(e)*B* of CHVMA asphalt (f)*B* of SBS asphalt

Fig. 3. Asphalt *A* value and *B* value fitting results

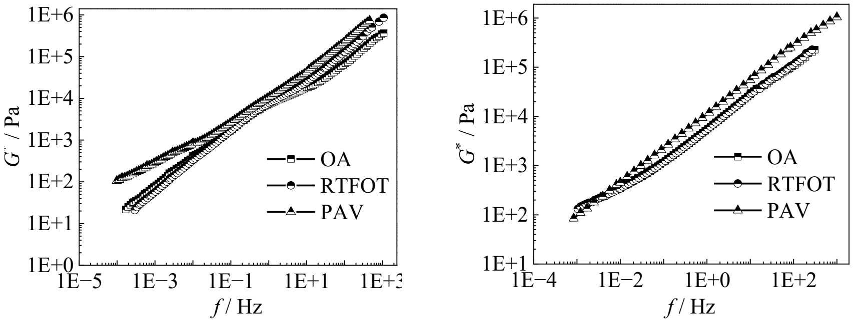
From Fig. 3(a) to Fig. 3(c), it can be observed that with increasing temperature, the *A* values of all the asphalt types show a linear decreasing trend. This indicates that the sensitivity of G^* to f decreases linearly with temperature. Additionally, it can be concluded that thermal-oxidative aging increases the sensitivity of G^* to *f*, as all three asphalt types exhibit varying degrees of increase in their *A* values after aging. It is worth mentioning that after RTFOT aging, the *A* value curve of CHVMA asphalt is almost identical to the non-aged curve, suggesting that short-term aging has minimal impact on the *A* value of CHVMA asphalt. On the other hand, after PAV aging, the increase in the *A* value for CHVMA asphalt is smaller compared to the other two asphalt types, indicating that CHVMA asphalt has better resistance to thermal-oxidative aging. Analyzing Fig. 3(d) to Fig. 3(f), it can be observed that the *B* values of different asphalts exhibit different trends with increasing temperatures. The *B* value of FHVMA asphalt shows a trend of initially decreasing, then increasing, and finally decreasing again. The *B* value of CHVMA asphalt shows a trend of initially increasing, and then decreasing. In contrast, the *B* value of SBS-modified asphalt shows a linear increasing trend. Furthermore, the effect of aging on the *B* values of different asphalts is inconsistent. With increasing temperature, the *B* values of FHVMA asphalt at different aging levels alternate. The maximum *B* value of FHVMA asphalt is observed after PAV aging, while the order of *B* values for SBS-modified asphalt is OA > RTFOT > PAV. These findings suggest that the variation in *B* values among different asphalts is significant, and may not be suitable for evaluating the sensitivity of G^* to *f*.

3.2 Master curve analysis of complex modulus of asphalt

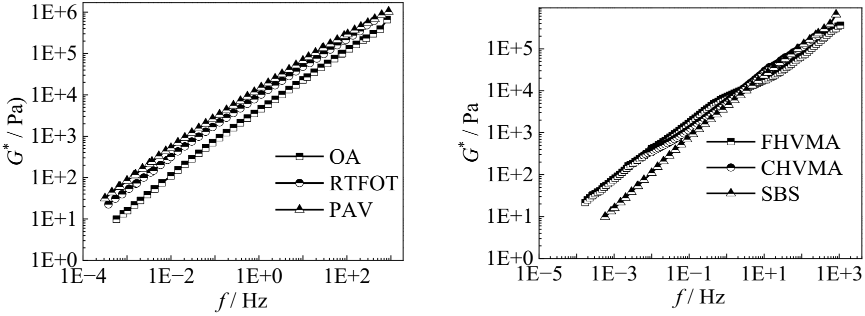
Based on the time-temperature superposition principle [17], to describe the relationship between the viscoelastic modulus and frequency of asphalt mixtures under a wider range of temperature conditions, the modulus-frequency data under different temperature test conditions can be used to shift and overlay curves. In this study, the shift factors at different temperatures are used to construct the master curve of the modulus for asphalt at 58°C. The shift factors are calculated using the William-Landel-Ferry (WLF) equation [18], as shown below:

$$\log \alpha_T(T) = -\frac{d_1(T-T_0)}{\mathrm{d}_2+(T-T_0)} \tag{2}$$

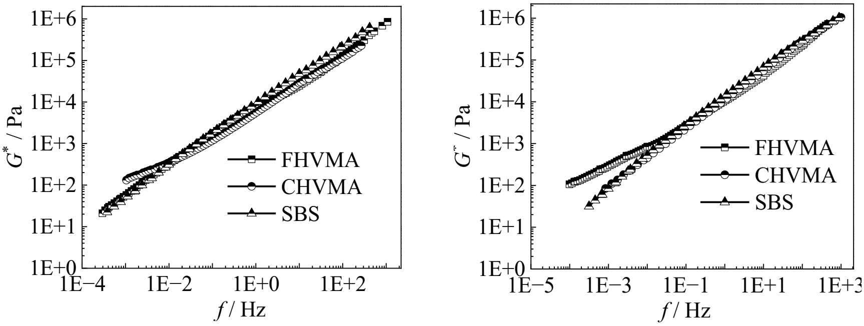
Where, α_T is the shift factor, T_0 is the reference temperature, d_1 and d_2 are the model parameters. After calculating the shift factor from different test temperatures of asphalt to the reference temperature of 58°C using equation (2), the modulus master curve at the reference temperature can be obtained by translating the corresponding modulus curve according to the shift factor, and the results are shown in Fig. 4.



(a)G^* curves of FHVMA (b)G^* curves of CHVMA



(c)G^* curves of SBS (d)G^* curves of OA



(e)G^* curves of RTFOT (f)G^* curves of PAV

Fig. 4. Comparison of asphalt complex modulus master curve results

Analyzing Fig. 4(a) to Fig. 4(c), it can be seen that the complex modulus of asphalt increases gradually with the increase of test temperature, but the rate of increase varies. For FHVMA asphalt, when the loading frequency is lower than 0.1Hz, the G^* increases slowly, and there is a small gentle slope between 0.1Hz and 10Hz, and when the frequency is greater than 10Hz, the G^* growth rate increases again. For CHVMA asphalt, when the loading frequency is lower than 0.01Hz, G^* growth is relatively slow, and after the frequency is greater than 0.1Hz, it basically shows a linear increasing trend. For SBS-modified asphalt, the growth rate of G^* was basically constant throughout the range of loading frequency. Comparison of G^* before and after aging reveals that the G^* of asphalt increases significantly after aging, which is consistent with the findings of previous studies [19-20]. This is mainly caused by the volatilization of the light component of asphalt and the oxidation of some groups after thermo-oxidative aging, which increases the proportion of heavy components and makes the asphalt hard and brittle [21]. However, for CHVMA asphalt, the modulus curve after RTFOT aging is basically duplicated with that without aging, while the modulus curve after PAV aging has the smallest spacing with that without aging, which indicates that short-term aging does not have much effect on the G^* of CHVMA asphalt and that the resistance of CHVMA asphalt to long-term aging is better than that of the other two asphalts.

From Fig. 4(d), it can be seen that the changing trend of G^* of CHVMA asphalt and SBS-modified asphalt is basically the same when not aged, but the G^* value of CHVMA asphalt is higher than that of SBS-modified asphalt as a whole after the addition of high-viscosity modifiers. The value of G^* of FHVMA asphalt is greater than that of SBS-modified asphalt in the low-frequency band (less than 5Hz), but in the high-frequency band (greater than 5Hz) it is rather smaller than SBS-modified asphalt. Therefore, in practical environments, FHVMA asphalt has better resistance to deformation in some low-speed areas (e.g., parking lots, etc.), while SBS-modified asphalt and CHVMA asphalt are more advantageous in some high-speed areas (e.g., highways, etc.). From Fig. 4(e) and Fig. 4(f), it can be found that aging improves the resistance to deformation of asphalt materials to a certain extent, especially the turning junction point of SBS-modified asphalt and FHVMA asphalt moves to a lower frequency after PAV aging, which indicates that the resistance to deformation of both of them in the low-frequency band is closer to that of the unaged one.

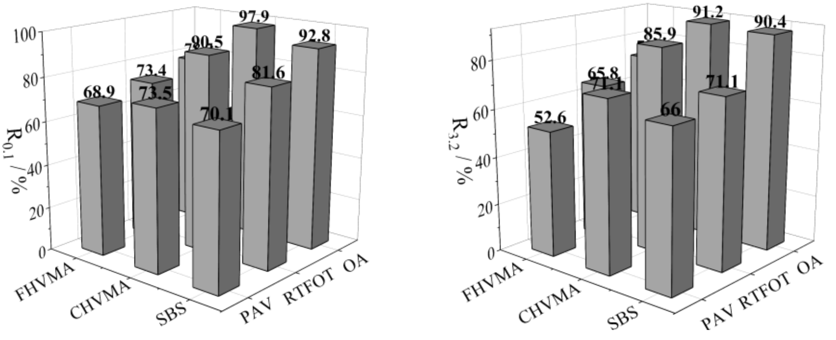
3.3 Creep recovery performance analysis of asphalt

The viscoelasticity of asphalt pavement is mainly provided by asphalt binder, so the recovery ability of asphalt pavement can be studied from the recovery ability of asphalt [22]. In this paper, the recovery rate and unrecoverable flexibility are used to evaluate the creep recovery performance of three kinds of asphalt under different aging degrees. The specific calculation formulas are as follows :

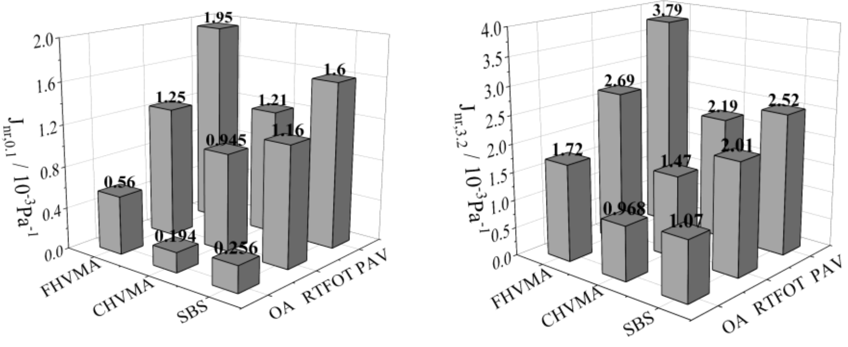
$$R_\delta = \frac{\varepsilon_\mathrm{p} - \varepsilon_u}{\varepsilon_\mathrm{p}} \times 100\% \tag{3}$$

$$J_{nr,\,\delta} = \varepsilon_u / \delta \tag{4}$$

In the formula, R_δ and $J_{nr,\,\delta}$ are the recovery rate and the unrecoverable compliance under the δ stress level, respectively; δ for the stress level, take 0.1kPa or 3.2kPa; ε_p and ε_u are peak strain and unrecovered strain, respectively. Formula (3) and Formula (4) are used to calculate the MSCR test data, and the results are shown in Fig.5.



(a)$R_{0.1}$ (b)$R_{3.2}$



(c)$J_{nr,0.1}$ (d)$J_{nr,3.2}$

Fig. 5. Comparison of asphalt recovery rate and unrecoverable flexibility results

It can be seen from Fig. 5 that the recovery rate of unaged SBS-modified asphalt is higher than that of FHVMA at different stress levels, indicating that the elastic recovery performance of SBS-modified asphalt is higher than that of FHVMA. Compared with the recovery rate of SBS-modified asphalt at 0.1kPa and 3.2kPa stress levels, CHVMA asphalt increased by 5.5% and 1.0%, respectively, indicating that the high viscosity agent can further improve the recovery ability of SBS-modified asphalt. This is because the high-viscosity agent is synthesized by a certain proportion of thermoplastic rubber and other components [23]. The thermoplastic rubber itself has better elastic recovery ability. After blending with SBS-modified asphalt, a more stable elastic combination is formed, which further improves the recovery performance of CHVMA asphalt. After aging, the recovery rate of all asphalts decreased to varying degrees, but due to the dual modification of SBS modifier and high viscosity agent, the decrease of CHVMA asphalt was smaller than that of the other two asphalts.

Under the condition of no aging, the order of the Jnr index of different stress levels of asphalt is opposite to that of the R index, which is shown as: CHVMA < SBS < FHVMA. Compared with SBS-modified asphalt, the Jnr values of CHVMA asphalt at 0.1kPa and 3.2kPa decreased by 24% and 10%, respectively. This shows that under the compound modification of high viscosity agent and SBS modifier, asphalt has a better ability to resist external force deformation. After thermo-oxidative aging, the Jnr index of all asphalts increases, because aging weakens the recovery performance of asphalt.

Under the repeated action of the same load, the cumulative unrecoverable deformation increases continuously, and the Jnr index increases continuously.

3.4 High-temperature performance analysis of asphalt mixture

For a permeable asphalt mixture, due to the small amount of fine aggregate and large porosity, it is easier to deform in a high-temperature environment. Therefore, high-temperature stability is usually a key index for the design of a permeable asphalt mixture. In this paper, according to JTG E20-2011, dynamic stability (DS) is used to evaluate the high-temperature stability of different kinds of asphalt mixtures. The results are shown in Fig. 6.

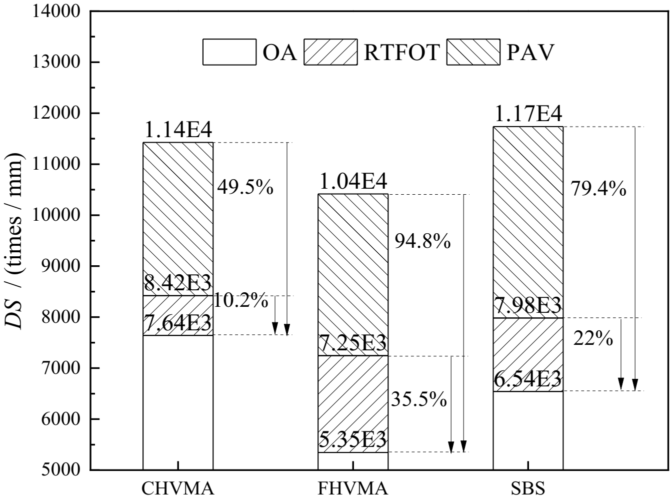
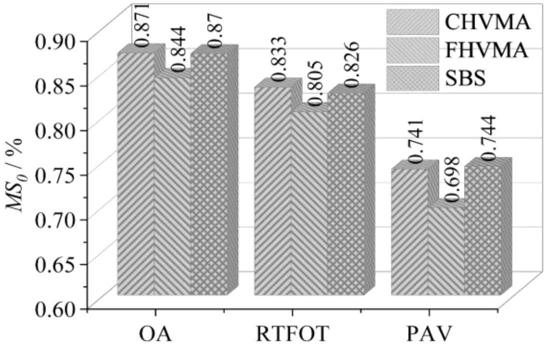


Fig. 6. Rutting test results of asphalt mixture

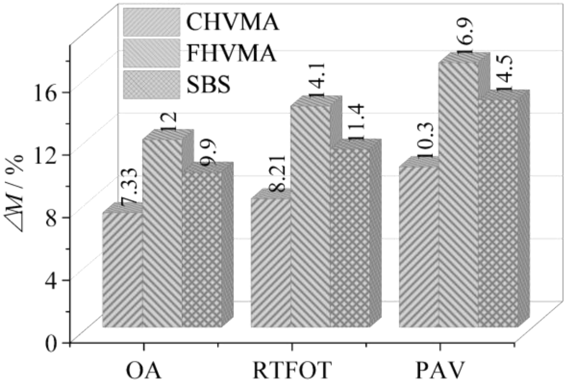
It is not difficult to find that for the unaged asphalt mixture, the *DS* of all samples is greater than 3500 times/mm, which meets the specified technical requirements. The *DS* of CHVMA asphalt mixture is the largest, followed by SBS modified asphalt mixture, and FHVMA asphalt mixture is the worst. This means that the compound modification of high viscosity agent and SBS modifier can significantly improve the high-temperature performance of asphalt mixture and make it have higher anti-rutting ability. Further analysis shows that after aging, the *DS* of three different asphalt concretes has increased to varying degrees, which is consistent with the previous research conclusions [24-25]. The reason is that during the aging process, the light components in the asphalt are continuously volatilized with heat, and the small molecular groups of the asphalt are oxidized with oxygen in the air to form more asphaltenes, resulting in a decrease in the content of aromatics and resins. The change in composition means a change in composition : the saturates are transformed into colloids and then into asphaltenes [26]. As a result, the viscosity of the asphalt increases, the stiffness becomes larger, and the overall modulus of the asphalt mixture becomes larger. At the macro level, the deformation decreases and the high-temperature stability increases. In addition, it can be seen that whether it is short-term aging or long-term aging, the *DS* increase of FHVMA asphalt mixture is smaller than that of the SBS modified asphalt mixture. This is because the cross-linking modification of high viscosity modifier and SBS modifier delay the hardening trend of asphalt binder.

3.5 Analysis of water stability of asphalt mixture

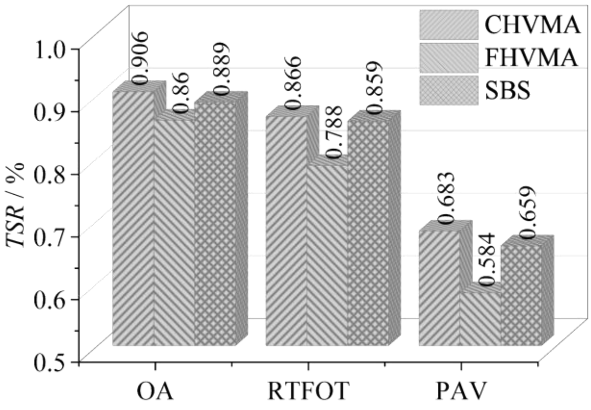
Water stability is the most important index of permeable asphalt pavement. Because of its special macro pore structure, water can easily enter the interior of the pavement structure through the gap, eroding the interface between asphalt and aggregate, which leads to diseases such as spalling, looseness and pits on the pavement, which seriously affects the durability and performance of the pavement. In this paper, the water stability of three different asphalt mixtures before and after aging was compared and evaluated by the Immersion Marshall test, Immersion Kunderburg scattering test and Freeze-thaw splitting test. The results are shown in Fig.7.



(a) Immersion Marshall test



(b) Immersion Kunderburg scattering test



(c) Freeze-thaw splitting test

Fig. 7. Water stability results of asphalt mixture before and after aging

As shown in Fig. 7 (a), the residual stability *MS₀* of the three asphalt mixtures showed a downward trend with the deepening of aging. After RTFOT and PAV, the MS_0 of FHVMA asphalt mixture decreased the fastest, by 4.5% and 17.3% respectively, while the MS_0 of CHVMA asphalt mixture decreased by 4.4% and 15.0% respectively, which was the slowest decline among the three asphalt mixtures. During different aging processes, the stability and residual stability of CHVMA asphalt mixture are always the highest, which indicates that the sensitivity of the mixture to temperature is lower than that of the other two mixtures.

As shown in Fig. 7 (b), the mass loss rate $\triangle M$ increases linearly with the increase of aging degree, which is opposite to the change trend of residual stability MS_0. Whether it is short-term aging or long-term aging, the $\triangle M$ of CHVMA asphalt mixture and SBS modified asphalt mixture is less than 15%, which still meets the technical requirements of less than 15% in CJJ/190-2012 specification. However, after long-term aging of FHVMA asphalt mixture, $\triangle M$ reached 16.9%, which exceeded the technical requirements of CJJ/T190-2012. Under RTFOT and PAV aging, the increase of $\triangle M$ of CHVMA asphalt mixture is the lowest, which is 12.1% and 40.0% respectively. Therefore, from the perspective of dispersion loss rate, it can also be concluded that the anti-aging performance of CHVMA asphalt is better than that of the other two asphalt binders.

As shown in Fig.7 (c), the strength ratio *TSR* decreases with the deepening of aging. Under the same aging degree, the *TSR* of asphalt mixture in 3 is ranked as follows: CHVMA asphalt > FHVMA asphalt > SBS modified asphalt. During the long-term aging process, the *TSR* of CHVMA asphalt mixture decreased by 24.6%, which was the slowest among the three mixtures. The *TSR* of FHVMA asphalt mixture decreased by 32%, which was the fastest in the three mixtures. It should be noted that after short-term aging, the *TSR* of FHVMA asphalt mixture has dropped to 0.788, which does not meet the technical requirements of not less than 85% in the CJJ/T190-2012 specification, while the *TSR* of the other two mixtures is greater than 85%, which is still within the specified technical range. However, after long-term aging, the *TSR* of all asphalt mixtures has dropped below 85%, which does not meet the requirements of the specification.

In summary, the water stability of asphalt mixture decreases with the deepening of aging. The main reason for this phenomenon is that during the aging process, asphalt will produce substances such as ketones and surfactants [27]. These substances have strong hydrophilicity, which will lead to easier dissolution of asphalt molecules in water, thereby weakening the adhesion between the mixture and causing internal damage to the mixture. At the same time, the long-term effect of high temperature and oxygen leads to the volatilization of the lightweight combination in the asphalt, and oxidation and polymerization reactions occur [28]. The asphalt gradually transitions from the sol-gel type to the gel type. The asphalt becomes hard and brittle, and the fluidity decreases, thereby reducing the cohesion of the mixture. Among all asphalt mixtures, CHVMA asphalt mixture has stronger anti-aging and water damage resistance. This is because the compound high viscosity modified asphalt combines the excellent properties of SBS and high viscosity agent, forms a more stable spatial network structure, and increases the adhesion between asphalt and aggregate.

4 Conclusions

(1) The complex modulus of asphalt has a significant dependence on the loading frequency. By fitting 79 groups of curves, it is found that there is a good linear relationship between the complex modulus and the loading frequency in the double logarithmic coordinates (the correlation coefficient is not less than 0.98).

(2) Under the double logarithmic coordinates, the modulus master curve of asphalt can be well constructed. Through the analysis of the main curve of different frequency bands, it is found that the high-viscosity / SBS compound-modified asphalt is more suitable for high-speed driving areas.

(3) The MSCR test shows that the creep recovery rate of asphalt increases and the unrecoverable compliance decreases significantly under the composite modification of high viscosity agent and SBS, indicating that high viscosity agent is helpful to improve the elastic recovery ability and deformation resistance of SBS modified asphalt.

(4) Thermo-oxidative aging weakens the adhesion between asphalt and aggregate and damages the water stability of asphalt mixture, but the combination of high viscosity agent and SBS modifier can effectively slow down this aging effect. High viscosity agent/SBS compound modified asphalt can be recommended as porous asphalt pavement material.

This study comprehensively reveals the thermo-oxidative aging behavior of High viscosity agent/SBS compound modified asphalt and mixture, and provides certain data and theoretical support for the material selection and design of High viscosity agent/SBS compound modified asphalt pavement.

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