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Experimental Study on Anti-Aging Effect of Asphalt Binder Liquid Anti-Aging Agent

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Abstract: During its service life, asphalt pavement is affected by environmental factors such as heat, light, oxygen and moisture. The asphalt binder ages, resulting in a decrease in the performance of the asphalt pavement. Therefore, the development and application of an asphalt anti-aging agent is of great significance. In this paper, the road performance of the developed asphalt binder liquid anti-aging agent was verified in the two scales of asphalt binder and asphalt mixture, respectively. Firstly, a simple aging test method was proposed using needle penetration as the evaluation index. The aging time of the simple aging method was determined to be 20 h. Secondly, the addition of anti-aging agents improved the low-temperature performance of the asphalt binder and had a less adverse effect on the high-temperature performance. The test values of needle penetration and the ductility of the asphalt binder increased and the values of the softening point decreased. And the road performance of the anti-aging asphalt mixture basically met the specification requirements. The addition of the anti-aging agent improved the low-temperature performance of the aged asphalt mixture by 16%, which is of great significance for improving the service life of asphalt pavement.

Keywords: asphalt binder; anti-aging agent; needle penetration; ductility values; pavement performance

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1. Introduction

Compared with other pavements, asphalt pavements have the advantages of being safe to drive on, smooth, high strength, and low noise, and they have been widely used in the construction of pavements in various countries [1,2]. The aging of asphalt binder has a great impact on the service life and service level of asphalt pavement [3], and research on the aging of asphalt binder has been a hot research topic for scholars at home and abroad. During service, asphalt pavements are affected by external environmental factors such as atmosphere, sunlight and water [4,5]. This leads to the deterioration of the asphalt binder, causing pavement distresses such as cracking, loosening and potholes [6–8]. These aspects significantly reduce the road performance and service life of the pavement. Therefore, it is necessary to carry out in-depth research on the aging law and anti-aging performance of asphalt pavement.

The aging of road asphalt binder is due to the reaction of unsaturated molecules in the asphalt binder with oxygen in the air and the gradual transformation of small-molecular-weight substances into large-molecular-weight substances, resulting in changes in the components of the asphalt binder [9,10]. The lack of small-molecular-weight substances reduces the viscosity of asphalt binder, and the asphalt binder becomes hard and brittle after aging. The most fundamental way to improve the aging resistance of asphalt binder is to optimize the oil source of the asphalt binder as well as to improve the extraction process of the asphalt binder [11,12]. But for road workers, the asphalt binder oil source and refining process cannot be changed. Engineering structural measures and the external mixing of anti-aging agents are commonly used methods to improve the anti-aging properties of asphalt binder. Anti-aging agents mainly realize anti-aging effects through physical and chemical reactions, and the commonly used types of anti-aging agent materials are polymers, antioxidants and matrixes. In practice, it is found that the cost consumption of engineering structural measures is higher, and their anti-aging effects are not obvious, which cannot solve the problem from the root. Therefore, adding an anti-aging agent has become the main method to improve the anti-aging performance of asphalt binder [13]. In order to enhance the performance of asphalt binder during the mixing, transportation and service phases, different types of anti-aging agents are often added to asphalt binder to prepare high-performance modified asphalt binder. The resistance of asphalt binder to photo-oxidative and thermo-oxidative aging was improved by adding different modifiers. [14]. Currently, anti-aging agents mainly include organic additives (antioxidants and light stabilizers) and inorganic additives (carbon black, inorganic nanoparticles, layered silicates and supramolecular UV-blocking materials) [15].

At present, anti-aging agents in asphalt binder are mainly in the powder state, which means they are complicated to prepare and have the problem of insufficient long-lasting anti-aging performance [14]. Liquid anti-aging agents have better dispersibility, so they also do not need a high temperature to achieve uniform mixing and require less energy consumption [16]. A developed liquid anti-aging agent, which was used for the anti-aging of asphalt binder in an original sample, consisted of oil antioxidant, polyphosphoric acid (PPA) and SBS-modified asphalt binder. These three components effectively inhibited the oxidation reaction of asphalt binder in service through synergistic effects [17]. An oil antioxidant mainly provides anti-aging properties, which significantly improves the low-temperature performance and fatigue anti-cracking properties of virgin asphalt binder. PPA is a commonly used chemical modifier for asphalt binder, and the addition of PPA not only reduces the adverse effect of oil antioxidants on the high-temperature performance of asphalt binder [18,19] but also provides anti-aging properties. The compounding of an oil antioxidant, PPA and SBS-modified asphalt binder can maximize the anti-aging performance of asphalt binder and minimize the adverse effects on the high-temperature performance of asphalt binders.

Aging will cause a series of chemical reactions in asphalt binder. It will lead to the occurrence of addition, polymerization, oxidative dehydrogenation and other reactions within the molecule, generating macromolecular compounds and polar functional groups. Aging will also cause the lightweight component to shift to the heavy component, and the asphalt binder will be hardened, which will lead to the deterioration of the macro-mechanical properties of the asphalt binder and decreases in the asphalt mixture's low-temperature performance, fatigue resistance, etc. [19].

The thermal oxidation process of asphalt binder is a series of free-radical chain reactions. Under the action of heat, light or oxygen, the chemical bonds of the asphalt binder molecules break down. Active free radicals and hydroperoxides are formed. Hydrogen peroxide undergoes a decomposition reaction. This also produces hydrocarbon oxygen radicals and hydroxyl radicals. These free radicals have the potential to initiate a series of free-radical chain reactions that can lead to fundamental changes in the structure and properties of the asphalt binder [14]. The principle of action of anti-aging agents is to prevent the oxidative degradation of polymers by terminating free-radical chain reactions.

Anti-aging agents can prevent a chain reaction by eliminating the newly generated free radicals or by inducing the decomposition of hydroperoxides. In polymer systems, anti-aging agents need only be present in small amounts to slow or inhibit the oxidation process of the polymer, thereby extending its service life. Anti-aging agents are themselves reducing agents, reacting first with oxygen in its presence and oxidizing themselves to protect the raw material to be protected. In addition, anti-aging agents can act by trapping free radicals or decomposing hydroperoxides. The SBS-modified asphalt binder in the anti-aging agent has a synergistic effect with the other components as well as a toughening effect.

The main objective of this paper was to verify the anti-aging effect and road performance of the developed liquid asphalt anti-aging agent to improve the service life of asphalt pavement. The road performance of the developed liquid anti-aging agent was verified from two scales of asphalt binder and mixture, and the process of a simple aging method was established with the degree of penetration and softening point as the evaluation index. Physical properties were determined; high- and low-temperature performance tests were carried out on the scale of asphalt binder; and the water stability, high-temperature rutting resistance and low-temperature cracking resistance of the aging-resistant asphalt mixture were verified on the scale of mixture.

2. Methods

2.1. The Preparation and Testing of Anti-Aging Asphalt Binders

2.1.1. Preparation of Anti-Aging Asphalt Binder

There are two types of asphalt binders, Pen.70 virgin asphalt binders (VABs) and SBS-modified asphalt binders, and their basic specifications are shown in Table 1.

Table 1. Basic properties of two kinds of asphalt binders.

Test Items	Unit	Standard Value	Pen.70 VAB Measured Value	SBS-Modified Asphalt Binder Measured Value
Penetration (25 °C, 5 s, 100 g)	0.1 mm	60~80	75	70
Ductility (10 °C is used for Pen.70 VAB, 5 °C is used for SBS-modified asphalt binder), reference to the China Code (JTJ052-2011) [20]	cm	binder	>100	38
Softening point (R&B)	°C	46	48.0	75.5
Flash point	°C	260	263	278
Dynamic viscosity	$N{\cdot}s/m^2$	-	159.1	-
Brookfield viscosity (135 °C)	Pa·s	≤3	-	1.8

The anti-aging agent was liquid. The formulations and processes of anti-aging additives were determined by central composite design response surface methodology. The oil-based antioxidant, PPA and SBS-modified asphalt binder (the mass ratio of the three was 1:0.1:0.1) were mechanically stirred at a temperature of 60 °C to 80 °C and a rotational speed of 300 r/min to 800 r/min. The mixing time was 0.5 h. The liquid anti-aging agent was produced.

The basic properties of the anti-aging agent are shown in Table 2:

Table 2. Basic properties of anti-aging agent.

Test Items	Unit	Test Value
Density (20 °C)	kg/m^3	1088
Dynamic viscosity (100 °C)	mm^2/s	16
Flash point	°C	195

(1) Un-aged asphalt binder sample preparation: A certain mass of asphalt binder in the oven was heated to the flow state (the oven temperature for the VAB was 135 °C; for the SBS-modified asphalt binder, it was 170 °C). The asphalt binder was then poured into a mold.

(2) Aging asphalt binder preparation: Standard aged asphalt binder samples were produced by short-term aging for 5 h (the mass of the sample was 50 g, and the aging temperature was 163 °C), followed by the long-term aging of PAV for 20 h (the aging temperature was 100 °C, and the pressure was 2.1 MPa). Simple aging was carried out using a large pallet; the specific operation method is described later.

(3) Two kinds of anti-aging asphalt binder were used. Firstly, a certain mass of asphalt binder was heated in an oven to a flowing state. The asphalt binder was moved into a constant-temperature oil bath at the same temperature. Liquid asphalt anti-aging agent at 5.5% of the asphalt mass was slowly added (the results of basic experiments have shown that 5.5% is the optimum level of anti-aging agent for asphalt binders). The mixture was stirred by a high-torque electric stirrer at 600 r/min for 60 min. Finally, it was left to stand for 5 min. Samples of anti-aging asphalt binder were prepared.

The asphalt binder sample types are shown in Table 3.

Table 3. Types of asphalt binder samples.

Pen.70 VAB	SBS-Modified Asphalt Binder
1#—Un-aged Pen.70 VAB	2#—Un-aged SBS-modified asphalt binder
3#—Pen.70 VAB + 20 h aging	4#—SBS-modified asphalt binder + 20 h aging
5#—Pen.70 VAB + anti-aging agent + 20 h aging	6#—SBS-modified asphalt binder + anti-aging agent + 20 h aging

2.1.2. Introduction to Test Methods for Asphalt Binder Scale

Physical Property Tests of Asphalt Binder

The penetration, softening point and ductility tests were conducted in accordance with the China Code (JTJ052-2011) [20]. For the asphalt binder penetration test, the standard test conditions of a temperature of 25 °C, load of 100 g, and penetration time of 5 s to 0.1 mm were used. The test was repeated three times. The allowable error of the test was 2 (0.1 mm). For the asphalt binder softening point test (globe method), the specimen was softened by heat and gradually fell down to come into contact with the surface of the lower layer of the substrate, and then, the temperature was read immediately, which was accurate to 0.5 °C. The same specimen was tested twice in parallel. For the asphalt binder ductility test, for Pen.70 VAB, the test temperature of 10 °C was used, and for SBS-modified asphalt binder, the test temperature of 5 °C was used. The tensile speed of 5 cm/min ± 0.25 cm/min was used. Each sample underwent no less than three parallel tests.

Multiple Stress Creep Recover (MSCR) Test

The Multiple Stress Creep Recover (MSCR) test was also performed using a dynamic shear rheometer (DSR) [21,22]. A 25 mm diameter aluminum parallel plate was selected, the spacing between the upper and lower plates was set to 1 mm, and the test temperature was 64 °C. The asphalt binder was loaded under a 0.1 kPa stress condition for 1 s, after which, no stress was applied for 9 s, and the process was repeated 10 times. The same process was then carried out under 3.2 kPa stress conditions for a total test time of 200 s. The strain response of the samples was automatically recorded by the DSR. In order to quantitatively evaluate the high-temperature performance of different asphalt binders, there are two important viscoelastic parameters, the average unrecoverable creep flexibility J_{nr} and the average creep recovery rate R, which are calculated according to Equations (1) and (2), respectively:

$$J_{\mathrm{nr}} = \frac{(\varepsilon_{\mathrm{u}} - \varepsilon_0)}{10\sigma} \tag{1}$$

$$R = \frac{(\varepsilon_{\mathrm{p}} - \varepsilon_{\mathrm{u}})}{10(\varepsilon_{\mathrm{p}} - \varepsilon_0)} \times 100\% \tag{2}$$

where ε_0 is the initial strain during creep per cycle (%); ε_{p}—the peak strain during creep per cycle (%); ε_{u}—the residual strain after the recovery of each cycle (%); $-\sigma$—the stress level applied in the test (kPa).

This test was conducted with 3 parallel samples for each condition.

Low-Temperature Performance Test (4 mm Plate Test)

The low-temperature performance of asphalt binders was evaluated using the DSR 4 mm plate [23,24]. Two parameters were measured: the strength modulus (S) of the asphalt binder, which was used to evaluate the deformation resistance of the asphalt binder at low temperatures, and the creep rate (m), which was used to evaluate the rate of change in the creep modulus of the asphalt binder under the influence of low-temperature loading. A higher m value or a lower S value indicates that an asphalt binder has better low-temperature performance. The test temperatures were −6 °C, −12 °C and −18 °C. (The test temperature was set according to the bending beam rheological (BBR) test using the asphalt binder.) This test was conducted with 3 parallel samples for each condition.

2.2. Asphalt Mixture Preparation Process and Test Methods

2.2.1. Design of Asphalt Mixture Mass Ratio of Asphalt Binder and Aggregate

The grading of the asphalt binder mixture was AC16, and the grading screening curve is shown in Figure 1. After the gradation screening, the mass ratio of the asphalt binder was determined and the aggregate verification test was carried out (the initial mass ratio of the asphalt binder and aggregate was determined to be 4.6 based on experience, and then, four variables, 4.4, 4.5, 4.7 and 4.8, were selected by interpolation). Finally, the porosity of the specimen was measured by the surface drying method, and the calculated maximum theoretical density was used to determine the optimum mass ratio of the asphalt binder and aggregate. The optimum mass ratio of the asphalt binder and aggregate in the asphalt mixture was finally determined to be 4.5, and the design porosity was 4%. The type of coarse aggregate used in the test was limestone, the fine aggregate was mechanism sand of limestone, and the filler was mineral powder of limestone. Coarse and fine aggregates were pre-mixed for 90 s. The asphalt binder was added and the mixing was continued for 90 s. Finally, a small amount of mineral powder was added and the mixing was continued for another 90 s. The mixing temperature for the SBS-modified asphalt mixture was 180 °C. The mixing temperature for the Pen.70 virgin asphalt mixture was 160 °C. The ordinary asphalt mixture was produced. The types of asphalt mixture test samples are described in Table 4.

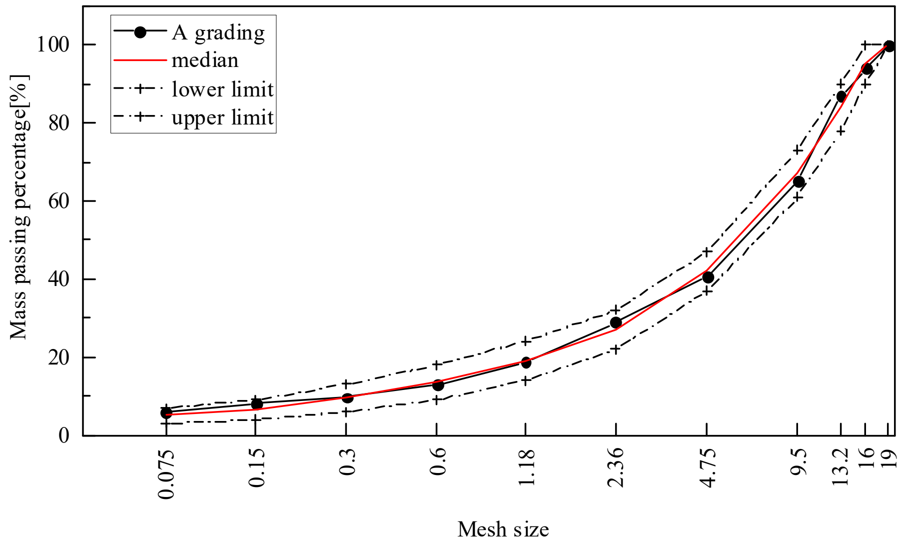

Figure 1. Grading curve.

Table 4. Types of asphalt mixture samples.

Sample Types of Pen.70 Virgin Asphalt Mixture	SBS-Modified Asphalt Mixture Sample Types
1#—Pen.70 virgin asphalt mixture	5#—SBS-modified asphalt mixture
2#—anti-aging Pen.70 virgin asphalt mixture	6#—anti-aging SBS-modified asphalt mixture
3#—Pen.70 virgin asphalt mixture + aging	7#—SBS-modified asphalt mixture + aging
4#—anti-aging Pen.70 virgin asphalt mixture + aging	8#—anti-aging SBS-modified asphalt mixture + aging
	Total of 8 types of asphalt mixture

The types asphalt binder and asphalt mixture aging are described in Table 5.

Table 5. Description of asphalt binder and asphalt mixture aging.

Type of Aging	Aging Equipment	Aging Sample Quality and Thickness Requirements	Whether or Not It Has Been Subjected to Short-Term Aging and Its Conditions	Long-Term Aging and Conditions
Standard aging	Thin-film heating oven and Pressurized Aging Vessel (PAV)	Size of asphalt binder sample placing disk: inner diameter 140 mm Sample mass per tray: 50 g ± 0.5 g	Yes: 5 h in a film heating oven at 163 °C ± 1 °C (RTFOT).	PAV aging for asphalt binder: pressure is 2.1 MPa ± 0.1 Mpa; temperature is 100 °C.
Simple pallet aging	Forced-ventilation drying ovens	Rectangular tray size for sample placement: 295 mm × 225 mm Sample mass per tray: 215 g ± 0.5 g	No.	Temperature: 160 °C; Conditions: forced ventilation; Aging time: 18 h, 20 h and 22 h.
Deterioration of asphalt mixtures	Forced-ventilation drying ovens	-	Yes: the asphalt mixture is evenly spread in an enameled pan with a loose thickness of about 21 kg/m^2~22 kg/m^2. The mixture is placed in an oven at 135 °C ± 3 °C and heated under forced ventilation for 4 h ± 5 min, and the mixture is turned over in the specimen tray with a shovel once an hour. After 4 h of heating, the mixture is removed from the oven and used for the test.	The molded specimens are placed on a specimen rack and sent into an oven at 85 °C ± 3 °C. The specimens are heated continuously under forced ventilation for 5 d (120 h ± 0.5 h). After 5 d, the oven is turned off, the oven door is opened, and the specimen is cooled to room temperature naturally (for no less than 16 h). The specimen is taken out for use in tests.

2.2.2. Test Methods for Roadworthiness of Asphalt Mixtures

All road performance test methods were based on the China Code (JTJ052-2011) [20].

Water Stability Test

The water stability of each asphalt mixture was evaluated by performing an immersion Marshall stability test and a freeze–thaw split test.

Residual stability (RS) is one of the indicators for evaluating the water stability of asphalt mixtures. A larger RS value indicates that the water stability of the asphalt mixture is better. Eight standard Marshall specimens were made for each asphalt mixture (compacted 75 times). The specimens were divided into two groups: the first group was placed in a 60 °C water bath box for 48 h, and the second group was immersed in a 60 °C water bath for 30 min. The stability of the two groups of specimens was tested using an automatic Marshall tester, and the RS was calculated by Equation (3).

$$RS = \frac{MS_1}{MS} \times 100\% \quad (3)$$

where RS is the residual stability, %; MS_1 is the stability at 48 h of immersion, kN; MS is the stability at 30 min of immersion, kN.

The freeze–thaw splitting strength ratio (TSR) is another indicator for evaluating the water stability of asphalt mixtures. The larger the TSR value is, the better the water stability of asphalt mixtures is. Each type of asphalt mixture was used to make eight standard Marshall specimens (50 times). Equation (4) was used to calculate the TSR.

$$TSR = \frac{R_{T2}}{R_{T1}} \times 100\% \quad (4)$$

where TSR is the freeze–thaw splitting strength ratio, %; R_{T1} is the splitting strength without a freeze–thaw cycle, MPa; R_{T2} is the splitting strength after a freeze–thaw cycle, MPa.

High-Temperature Rutting Test

A high-temperature rutting test was conducted to evaluate the high-temperature performance of each asphalt mixture [25,26]; the specimen size was a 300 mm × 300 mm × 50 mm plate specimen. The test temperature was 60 °C, the wheel load was 0.7 MPa, the repeat wheel time was 60 min, the creep under different loading times was recorded automatically during the test and the dynamic stability (DS) was used to evaluate the high-temperature performance of each asphalt mixture. Larger DS values indicated better rutting performances of the asphalt mixtures. The number of high-temperature rutting test specimens for each mixture was 3, and the test results were averaged.

Low-Temperature Beam Test

The low-temperature performance of each asphalt mixture was evaluated by the low-temperature beam test; the number of specimens of each asphalt mixture was 4, the specimen size was 50 mm × 30 mm × 35 mm, the span was 200 mm, the test temperature was −10 °C and the loading rate was 50 mm/min. The maximum bending and tensile strains of the asphalt mixtures were used as the evaluation indexes for the low-temperature cracking resistance of the asphalt mixtures. Higher values of maximum bending strain for asphalt mixtures indicated better low-temperature flexibility and crack resistance.

3. Experimental Results and Discussion

3.1. Analysis of Test Results for Asphalt Binder Scale

3.1.1. Simple Aging Timeline Determination

For the asphalt binder simple tray aging process, according to conversion of the rotating film oven round tray area and asphalt binder quality, the aging asphalt binder film thickness was 3.25 mm, and the aging asphalt binder film thickness was controlled to determine the quality of each tray of aging asphalt binder. The asphalt binder was aged in a forced-ventilation drying oven at a temperature of 160 °C under forced-ventilation conditions for different periods of time, such as 18, 20, 22 h, etc., and the final aging time was determined by the two indexes of the degree of penetration and the softening point, and the aged asphalt binder was stirred uniformly to carry out the subsequent tests. The needle penetration of an asphalt binder is one of the main quality indicators for evaluating asphalt binders. It can indicate the degree of asphalt softness and consistency and its ability to resist shear damage, and at the same time, it can reflect the relative viscosity of asphalt binder under certain conditions. The test error is small, and the operation is simple, so this study chose needle penetration as the evaluation index. As shown in Figure 2, taking the needle penetration as the evaluation index, the needle penetration value of the Pen.70 VAB aged for 18 h was the best match with the value after standard aging, and the needle penetration value of the SBS-modified asphalt binder aged for 20 h was the best match with the value after standard aging. And the needle penetration value of the recycled asphalt binder matched best with the 22 h aged Pen.70 VAB. Taking the softening point as the evaluation index, the softening point temperature of the Pen.70 VAB that experienced 20 h of aging best matched the standard aging. The softening point temperature of the SBS-modified asphalt binder with an aging time of 18 h best matched the value after standard aging. And the softening point temperature of the recycled asphalt binder best matched the Pen.70 VAB with an aging time of 22 h. In order to ensure the validity of the test results, it was ensured that the aged asphalt binder could reach the standard aging. It was determined that the simple pallet aging time was 20 h. In addition, it could be inferred that the recycling asphalt binder contained in the recycled asphalt pavement (RAP) used in this test was the Pen.70 VAB.

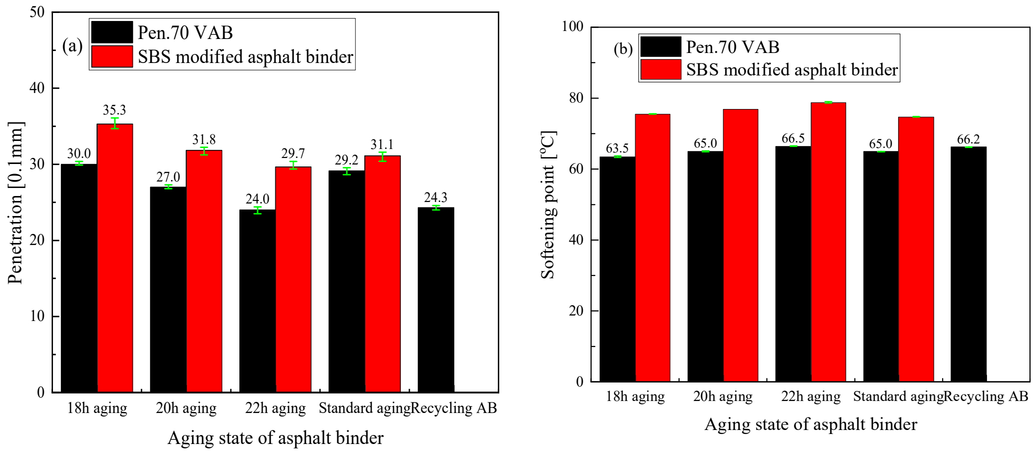

Figure 2. Needle penetration and softening point of asphalt binder at different aging states. (**a**) Needle penetration of asphalt binders, (**b**) Softening point of asphalt binders.

Note 1: The 18 h aging, 20 h aging and 22 h aging conditions are simple tray aging; the specific aging conditions are shown in Table 5. Recycled asphalt binder was obtained by the rotary evaporator method by recycling asphalt binder extraction from the RAP used in this test.

Note 2: Data points are the average value of the test, the upper limit of the error bar is the maximum value of the test and the lower limit of the error bar is the minimum value of the test; the same applies below.

3.1.2. Physical Properties of Anti-Aging Asphalt Binder and High- and Low-Temperature Performance Test

(1) Test results of physical properties of anti-aging asphalt binder

The test results of the three major indicators of two un-aged asphalt binders, aging asphalt binders and aging anti-aging are shown in Figure 3. After aging, the Pen.70 VAB and SBS-modified asphalt binders' needle penetration and ductility were significantly reduced, and the softening points increased. This indicates that the asphalt binders became hard and brittle after aging. After aging, the Pen.70 VAB's 5 °C ductility and the SBS-modified asphalt binder's 10 °C ductility were not measured, and the test was stopped. After aging, the two kinds of asphalt binders' ductility was assumed to be 10 mm. The anti-aging agent was added to delay the aging of the asphalt binder, which could be clearly seen from the ductility index. After adding the anti-aging agent, the ductility of the asphalt binder after aging under the same aging conditions was significantly increased.

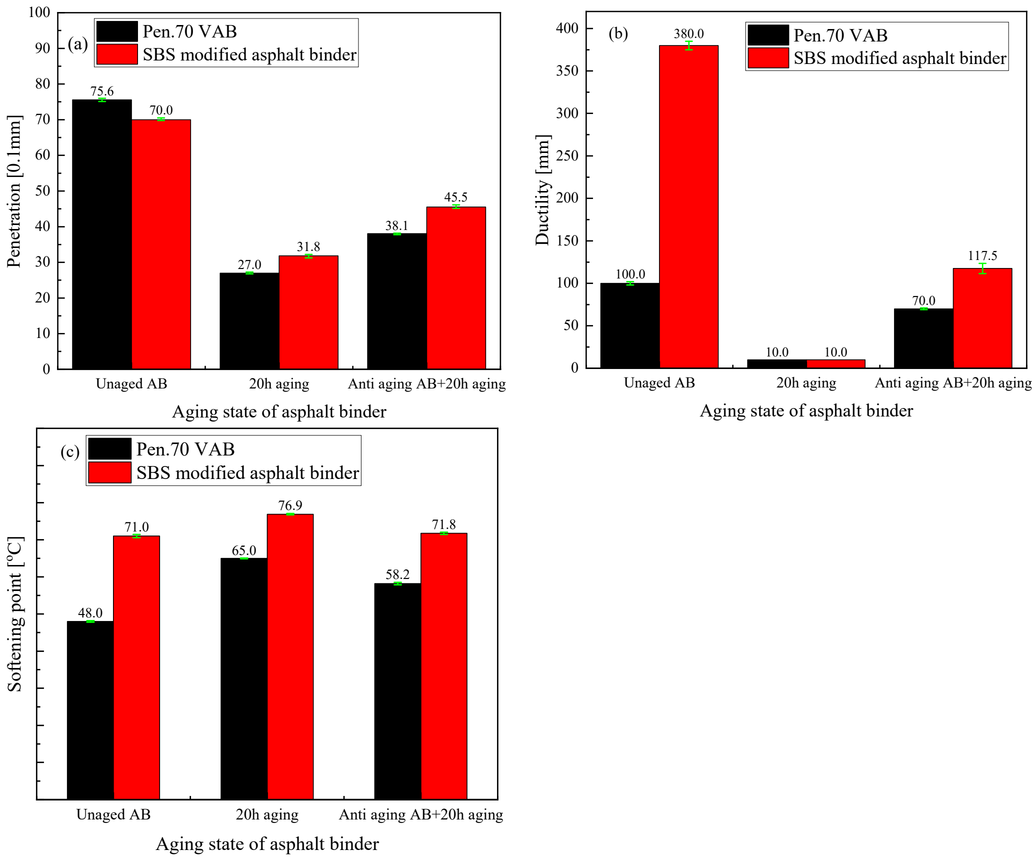

Figure 3. Comparative analysis of three major indexes of un-aged asphalt binder, aged asphalt binder and aged anti-aging asphalt binder. (**a**) Needle penetration of various asphalt binders, (**b**) Ductility of various asphalt binders, (**c**) Softening point of various asphalt binders.

(2) High-temperature performance test results of anti-aging asphalt binder

Figures 4 and 5 demonstrate the evaluated unrecoverable creep flexure and creep recovery for the aging-resistant asphalt binder types at both stresses and at 64 °C. As shown in Figure 4, the J_{nr} values of the Pen. 70 VAB and SBS-modified asphalt binder were significantly reduced at both stress levels after aging, which implies that aging enhanced the rutting resistance of both asphalt binders. The J_{nr} values of asphalt binders aged after the addition of anti-aging agents increased, both for the VAB and SBS-modified asphalt binder, which indicated that the anti-aging agent had a detrimental effect on the high-temperature rutting performance of the aged asphalt binder.

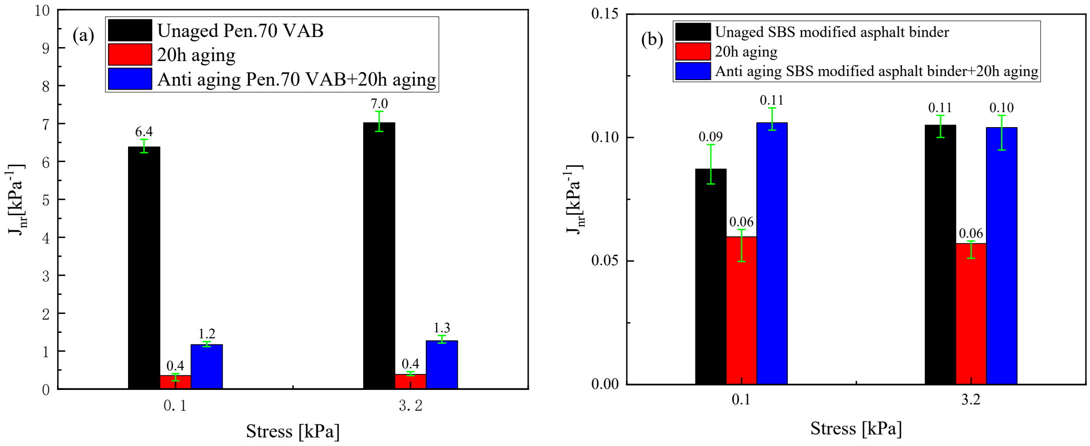

Figure 4. Irrecoverable flexibility (J_{nr}) of different types of anti-aging asphalt binders at two stress levels. (**a**) Irrecoverable flexibility of various Pen.70 VABs, (**b**) Irrecoverable flexibility of various SBS-modified asphalt binders.

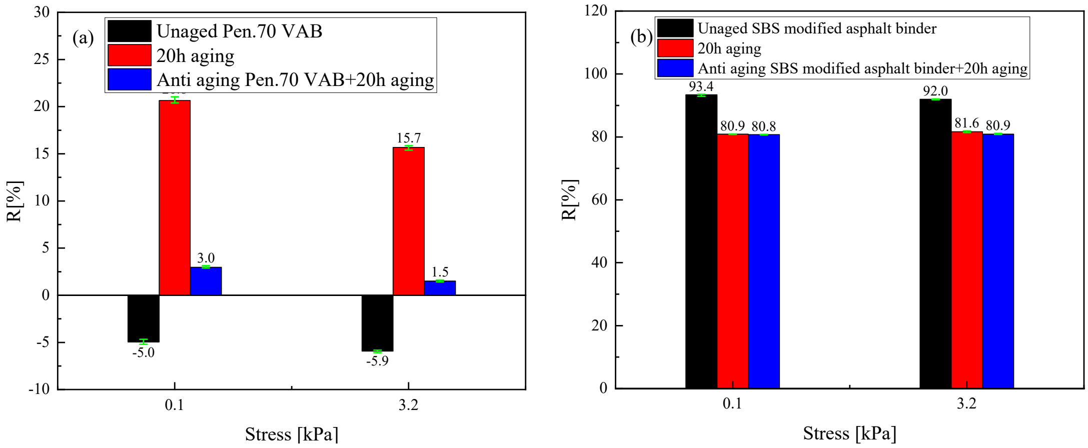

Figure 5. Creep recovery (R) of different types of anti-aging asphalt binders at two stress levels. (**a**) Creep recovery of various Pen.70 VABs, (**b**) Creep recovery of various SBS-modified asphalt binders.

As shown in Figure 5, the R-value of Pen. 70 VAB was negative at both stress levels when it was not aged. This indicates that it did not produce elastic recovery during cyclic creep and further indicates that the VAB did not have high potential for rutting resistance. For the SBS-modified asphalt binder, its creep recovery rate decreased after aging, but the addition of the aging agent had little effect on the creep recovery rate of the SBS-modified asphalt binder. This also indicates that the anti-aging agent had a less adverse effect on the high-temperature rutting performance of the aged SBS-modified asphalt binder.

(3) Test results of low-temperature performance of anti-aging asphalt binder

As can be seen in Figures 6 and 7, at the three test temperatures, the modulus of the strength *S* value of the Pen.70 VAB and SBS-modified asphalt binder after aging increased and the creep rate *m* value reduced, and the low-temperature performances decreased. Under the low-temperature condition of 18 °C, the modulus of strength of the aged SBS-modified asphalt binder exceeded 300 MPa, and the m value of the aged VAB was lower than 0.3, which did not satisfy the specification requirements. This indicates that aging reduces the flexibility of asphalt binders at low temperatures and increases the possibility of low-temperature cracking. After adding the anti-aging agent, the low-temperature performance of the asphalt binder after aging significantly improved, which indicates that the anti-aging agent had a good anti-aging effect.

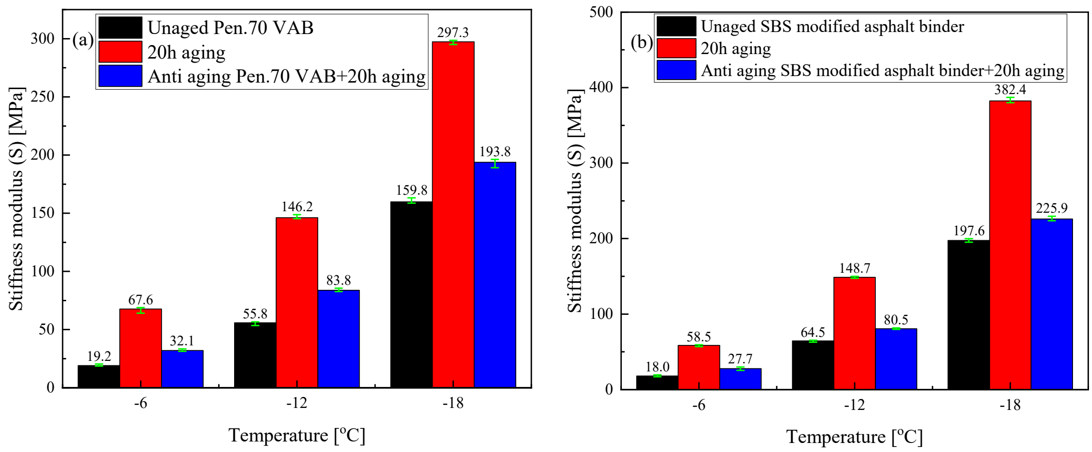

Figure 6. Values of modulus of strength (*S*) for different types of anti-aging asphalt binders. (**a**) Stiffness modulus of various Pen.70 VABs, (**b**) Stiffness modulus of various SBS-modified asphalt binders.

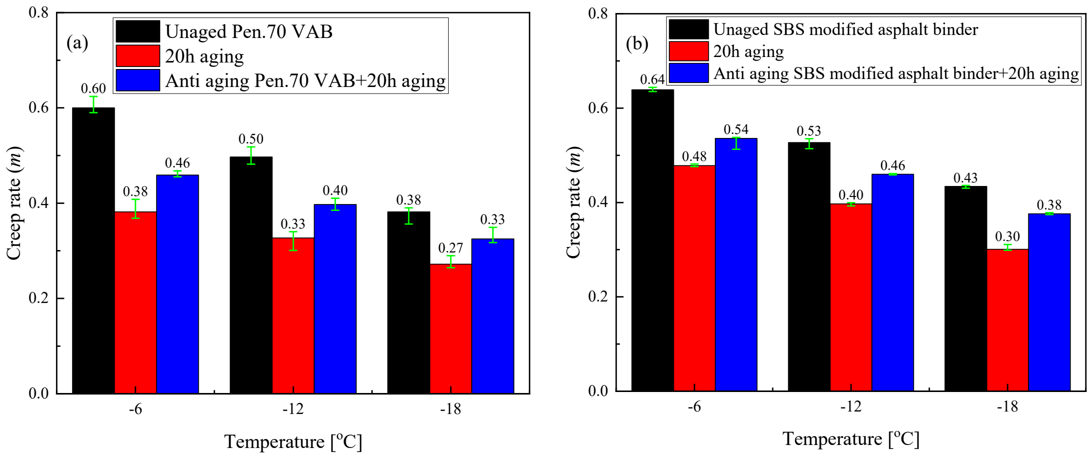

Figure 7. Creep rate (*m* values) for different types of anti-aging asphalt binders. (**a**) Creep rate of various Pen.70 VABs, (**b**) Creep rate of various SBS-modified asphalt binders.

3.2. Verification Tests on Mixture Scale

3.2.1. Results of Water Stability Test

Figure 8a shows the results of the immersion Marshall stability test before and after the aging of the normal Pen.70 virgin asphalt mixture and the anti-aging Pen.70 virgin asphalt mixture. Figure 8b shows the results of the immersion Marshall stability test before and after the aging of the SBS-modified asphalt mixture and the anti-aging SBS-modified asphalt mixture. Taking the residual stability of immersion water Marshall as the evaluation index, the addition of the anti-aging agent made the residual stability of the asphalt mixtures decrease. However, the residual stabilities of eight kinds of asphalt mixtures before and after aging were more than 88%, and the water stability met the specification requirements. The addition of the anti-aging agent had little effect on the water stability of asphalt mixtures. When the Marshall stability was the evaluation index, the addition of the anti-aging agent made the Marshall stability value of the mixture decrease. After aging, the Marshall stability value of the mixture increased.

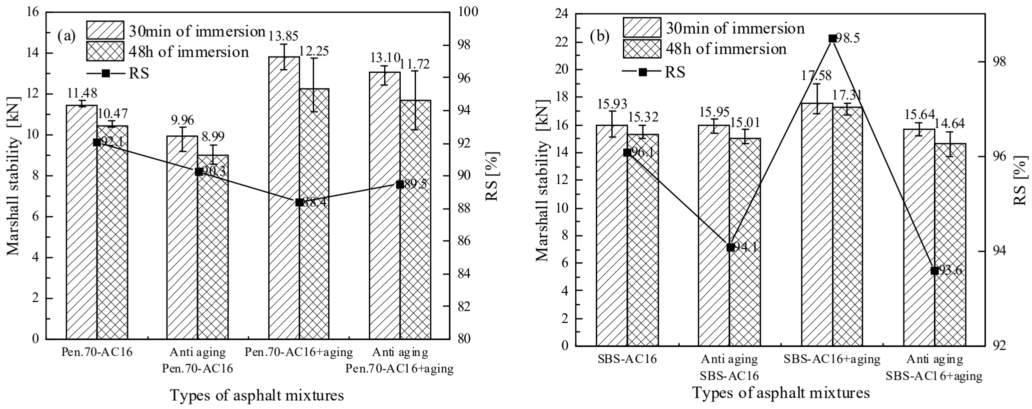

Figure 8. Comparison of two kinds of anti-aging asphalt mixtures in immersion water Marshall test results. (**a**) Various Pen.70 virgin asphalt mixtures in immersion water Marshall test, (**b**) Various SBS-modified asphalt mixtures in immersion water Marshall test.

Figure 9a shows the freeze–thaw splitting test results before and after the aging of the Pen.70 virgin asphalt mixture and the anti-aging Pen.70 virgin asphalt mixture. Figure 9b shows the freeze–thaw splitting test results of the SBS-modified asphalt mixture and the anti-aging SBS-modified asphalt mixture before and after aging. Taking the freeze–thaw splitting strength ratio (TSR) as the evaluation index, for the virgin asphalt mixture, aging reduced the water stability of the asphalt mixture, and the addition of the anti-aging agent had a small adverse effect on the asphalt mixture. After the aging of the asphalt binder, its toughness deteriorated and it became brittle, and the bonding force between aggregates and the asphalt binder also deteriorated. And due to the anti-aging effect of the anti-aging agent, the water stabilities of the anti-aging asphalt mixtures after aging were better than ordinary asphalt mixtures, and the water stabilities of all asphalt mixtures met the specification requirements.

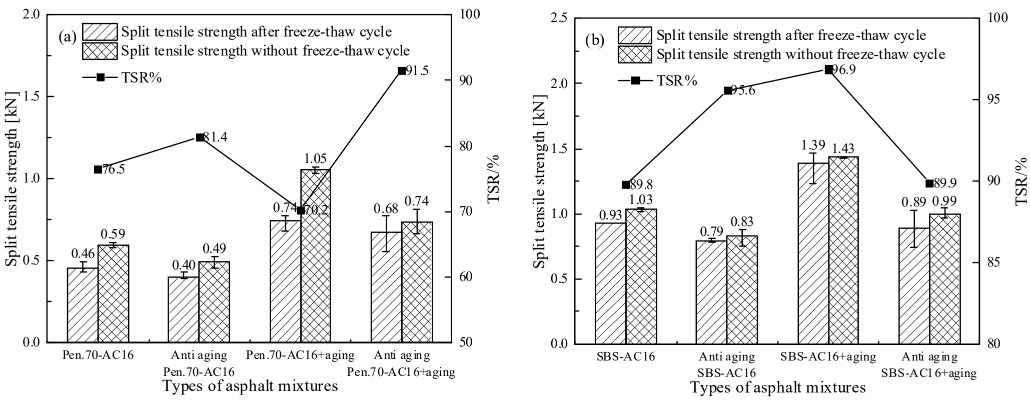

Figure 9. Comparison of the results of freeze–thaw splitting test of two kinds of aging-resistant asphalt mixtures. (**a**) Various Pen.70 virgin asphalt mixtures in the results of freeze–thaw splitting test, (**b**) Various SBS-modified asphalt mixtures in the results of freeze–thaw splitting test.

3.2.2. Analysis of High-Temperature Performance Test Results

Figure 10 shows the results of the dynamic stability test before and after the aging of the Pen.70 virgin asphalt and the SBS-modified asphalt mixture with and without the anti-aging agent. The high-temperature rutting resistance of the SBS-modified asphalt mixture was larger than that of the Pen.70 virgin asphalt mixture. The dynamic stability of the asphalt mixtures increased after aging, and the high-temperature rutting resistance increased. Adding the anti-aging agent made the dynamic stability of the asphalt mixture decrease and the high-temperature rutting resistance deteriorate. In terms of high-temperature performance, the addition of the anti-aging agent into the virgin asphalt mixture had the most significant impact, and it only met the specification of the summer heat zone

1–2 technical requirements. If an anti-aging agent is applied to improve a VAB, in order to ensure that the high-temperature rutting resistance of the anti-aging asphalt mixture meets the specification requirements, the recommended anti-aging agent dosage should be reduced; the specific dosage needs to be further studied.

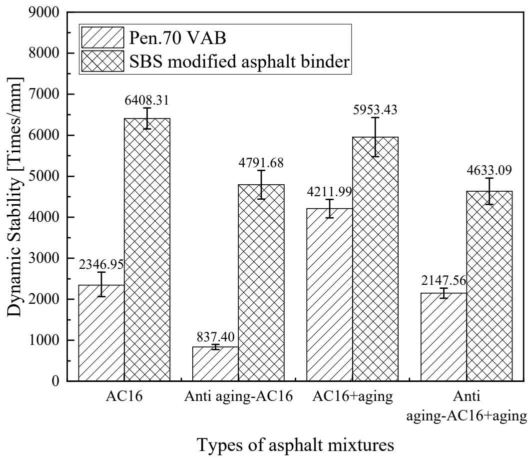

Figure 10. Comparison of dynamic stability test results of two kinds of aging-resistant asphalt mixtures.

3.2.3. Low-Temperature Performance Test Results

As can be seen from Figure 11, after the aging of the asphalt mixtures, the bending and tensile strain decreased, and the low-temperature crack resistance performance decreased. Adding an anti-aging agent can delay the aging of an asphalt mixture and improve the bending and tensile strain of an asphalt mixture; that is, it can improve the low-temperature cracking resistance of an asphalt mixture. Here, the addition of the anti-aging agent could improve the low-temperature aging performance of the asphalt mixture by 16%. The low-temperature performance of the SBS-modified asphalt mixtures was much higher than that of the Pen.70 virgin asphalt mixture for the same gradation.

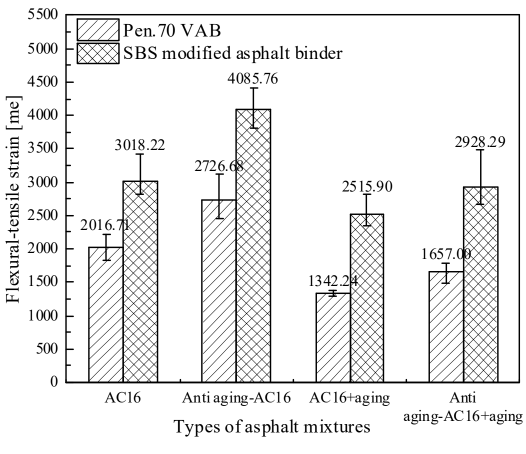

Figure 11. Comparison of bending and tensile strain test results of two kinds of aging-resistant asphalt mixtures.

4. Conclusions

Based on the analysis of the results of the asphalt anti-aging agent validation test, the following conclusions can be obtained:

(1) This paper proposed a simple aging method of asphalt binders using the aging asphalt binder needle penetration index, and the China Code (JTJ052-2011) provided the standard aging method to obtain the same results. For the aging process, according to the

conversion of the area of the circular tray of the rotating film oven and the mass of the asphalt binder, the thickness of the asphalt binder was 3.25 mm, and by controlling the thickness of the asphalt binder, we determined the mass of the asphalt binder of each tray for each aging condition. Under the condition of forced ventilation, the asphalt binder was aged in a high-temperature drying oven at 160 °C for 20 h. The advantages of this method are its simplicity and the fact that a large number of aged asphalt binder samples can be obtained in a short period of time.

(2) After aging, the needle penetration value and ductility value of the Pen.70 virgin asphalt binder and SBS-modified asphalt binder were significantly reduced, and the softening point increased, indicating that the aged asphalt binder became hard and brittle. After adding the anti-aging agent, the aged asphalt binder samples exhibited more significant increases in the values of penetration and ductility than the control group, and the softening point value decreased. The anti-aging agent had an adverse effect on the high-temperature rutting resistance of the aged asphalt binder, but the effect was small. Aging reduced the flexibility of the asphalt binder at low temperatures and increased the possibility of low-temperature cracking. After adding the anti-aging agent, the low-temperature performance of the asphalt binder before and after aging significantly improved; this shows that the anti-aging agent had a good anti-aging effect.

(3) The anti-aging asphalt mixture's road performance basically met the specification requirements. The water stability of the anti-aging asphalt mixture was slightly decreased, but the effect was good. The addition of the anti-aging agent to asphalt mixtures improved their low-temperature performance. The high-temperature rutting resistance of the asphalt mixtures had adverse effects, and in the virgin asphalt mixture, the high-temperature performance was impacted most significantly, and it only met the specification of the summer heat zone 1–2 area in terms of technical requirements. If the anti-aging agent is applied to improve a virgin asphalt binder, in order to ensure that the anti-aging asphalt mixture's high-temperature rutting resistance meets the specification requirements, it is recommended that the anti-aging agent dosage is reduced; the specific dosage needs to be further studied.

Outlook:

This paper mainly verifies the effect of an asphalt anti-aging agent from the macro scale. In the future, it will be necessary to use infrared scanning AFM and other micro means to explore the mechanism of the anti-aging agent.

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Data Availability Statement: The data presented in this study are conditionally available upon request from the corresponding author.

Conflicts of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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