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Study on Components Determination and Performance Evaluation of LS Pre-Maintenance Agent

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Featured Application: Aimed at the serious aging problem of asphalt pavement in strong UV regions, developed the LS pre-maintenance agent, provided a new material and technical guidance for pre-maintenance engineering in special areas.

Abstract: Adequate maintenance and taking active preventive measures can effectively prevent the early disease of asphalt pavements before significant damage occurs. By developing a light screening preventive maintenance agent (LS pre-maintenance agent) for strong ultraviolet (UV) radiation areas, based on the asphalt aging and regeneration mechanism, we analyzed the function and basic components and determined the optimum components ratio based on the best proportion of penetrant and solvent oil for solubility. The optimum ratio for quick-drying and long-term storage ability is the mass ratio of rock asphalt, reducing agent, penetrant, and solvent oil, which is 30:20:20:30. The light-shield agent is 5% of the total mass of the rock asphalt, reducing agent, penetrant, and solvent oil, and the dispersant is 0.4%. Digital image technology was used to provide an accurate measurement of the LS pre-maintenance agent penetration depth, evaluate its permeability and reasonable amount. We then used the rolling thin film oven test (RTFOT) to analyze its effect on aged asphalt and evaluated the restoration performance. Using the strong UV radiation aging test, we analyzed its anti-light aging performance. The results showed that pavement must be closed at least 2 h after the brushing LS pre-maintenance agent has been applied and this can be extended to upwards of 8 h time permitting. A dosage of 0.5 kg/m^2 can ensure sufficient penetration depth and curing effect. Furthermore, the agent shows excellent restorative and anti-light aging abilities, which can effectively improve the low-temperature performance of aged asphalt and meet the pre-maintenance requirements for asphalt pavement, especially in strong UV radiation areas.

Keywords: highway engineering; light screening preventive maintenance agent; optimum proportion; permeability; restore performance; light aging resistance

1. Introduction

Asphalt pavement is affected by traffic load and other environmental factors during its service period. Its performance gradually declines, as shown in Figure 1, and therefore taking active pre-maintenance before significant damage can occur effectively prevents the early disease of asphalt pavement and improves road conditions [1,2]. How to choose the targeted maintenance schedule means understanding the right time, and has been the focus of maintenance engineering research over many years. Specifically, high altitude areas, strong ultraviolet (UV) radiation, and thin asphalt surface cause serious damage and can significantly age asphalt. The UV aging range typically reaches 20–25% thickness of the surface layer, which means higher requirements for maintenance materials and technology [3]. Although some progress has been made, such as micro-surfacing and fog sealing, the application effect of existing technology is limited. Research into asphalt pavement pre-maintenance materials in strong UV radiation areas is relatively scarce [4,5]. Thus this study explores existing scarce research and develops a novel treatment schedule.

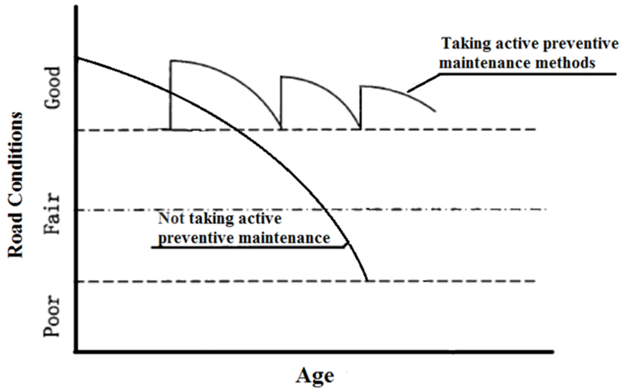


Figure 1. Road conditions under taking/not taking pre-maintenance work.

Existing studies have conducted research on aging and regenerating of asphalt. X.H. Lu used the thin film oven test (TFOT) and rolling thin film oven test (RTFOT) tests to simulate the aging process of asphalt. They studied the chemical and rheological properties of aging asphalt by infrared spectroscopy, chromatography, and dynamic mechanical analysis, then compared the effects of the different aging methods [6]. M. Naskarton compared the effects of the RTFOT and UV aging tests on the thermal stability and adhesion of aged asphalt, using kinetic information to predict the service life of modified asphalt [7]. H.L. Zhang used X-ray diffraction to analyze the micro-structural changes in UV aging of SBS by adding organic montmorillonite (OMMT), analyzing the light aging resistance of the OMMT/SBS asphalt [8]. W.B. Zeng used a dynamic shear rheometer (DSR) and FTIR (Fourier transform infrared spectroscopy) to analyze the temperature effect on the asphalt UV aging process, comparing the significance of temperature in an aging test [9]. Z.Q. Zhang combined component tests, combined with conventional and Superpave indicators to analyze asphalt change as a result of the RTFOT and pressure aging vessel (PAV) tests, comparing asphalt composition changes and anti-aging properties during the aging process [10]. The above research provides a multi-angle analysis on asphalt rheological properties and chemical changes in thermal oxygen aging and UV aging methods. The research outlined above of asphalt UV aging is closely related to this study.

For asphalt regeneration, the essence is to add new asphalt and an aromatics reducing agent into the aged asphalt to restore its original performance. P.L. Cong simulated a long-term light and heat aging process of an asphalt pavement, establishing a standard aging test model that analyzed the anti-aging and storage stability of antioxidants and UV absorbers [11]. Michal Varaus evaluated the restorative effects of different reducing agents on aged asphalt by bending beam rheometer (BBR) and DSR, especially on asphalt viscoelastic and low temperature performance [12]. A.Q. Chen used AFM (Atomic Force Microscopy) to study the mechanism of asphalt aging and regeneration, analyzing the change in asphalt composition from the micro-structure [13]. The above research above provides a solid theoretical basis and the experimental ideas guiding this study.

From the viewpoint of maintenance time, scientifically determining the maintenance time can effectively reduce the cost, prolong road life, and improve surface conditions; however, this requires a matched monitoring, data collecting, and analyzing system [14]. Q.Z. Wang summarized the effectiveness and applicability of common pre-maintenance measures, such as fog seal, slurry seal, thin cover and micro-surfacing. Established pavement preventive evaluation systems provided the decision-making basis [15]. C.H. Wang focused on the suitability of pre-maintenance, established an optimization model for timing and countermeasures based on the DEA (Data envelopment analysis) method, and provided a more reliable decision-making solution [16].

Asphalt pavement pre-maintenance material is mainly made up of asphalt, penetrant, and functional components, which are able to close surface micro-cracks, supply and activate aged asphalt, solidify loose aggregates, and delay disease development [17]. Among them, the Rhinophalt agent developed by the Britain's ASI Company, the ERA-C agent used by the United States, and the HAP agent developed by China have a wide range of applications [18–20]. C. Zhang established the evaluation methods and indicators for different pre-maintenance materials and provided a reasonable evaluation standard for pre-maintenance materials performance [21]. However, existing materials still have an application limitation for pavement in strong UV radiation areas with severe light-aging damage.

Therefore, this paper aims at the serious aging problem of asphalt pavement in strong UV regions by developing a LS pre-maintenance agent. We analyze and determine the raw materials and optimum composition ratio by contrast test. Using digital imaging methods, we evaluate the LS pre-maintenance agent's infiltration effect and its reasonable dosage. Using the RTFOT test, we evaluate the LS pre-maintenance agent' restorative effects on aged asphalt, contrasting the softening point of 25 °C penetration and the 15 °C ductility changes of aged asphalt after adding the LS pre-maintenance agent and Rhinophalt. Using an artificial UV aging test to accelerate the simulate natural UV aging process, we analyze the anti-light aging performance by calculating the UV aging mass loss rate of the LS pre-maintenance agent. Through the above research, we hope to provide new material and technical guidance for asphalt pavement pre-maintenance engineering in special areas.

2. Materials

According to asphalt pavement maintenance requirements, the LS pre-maintenance agent requires good penetration and bonding performance, which will ensure the penetration effect after spraying. By restoring and activating the aged asphalt by supplying lightweight components, this improves the asphalt's performance. Strong light screening abilities are able to inhibit the light aging damage in strong UV areas. Quick-drying and long-term storage stability reduces traffic closure time and meets the storage requirements for large-scale maintenance engineering. Finally, the construction economy, convenience, safety, and environmental protection must be guaranteed. In summary, the raw materials of the LS pre-maintenance agent include:

1. Asphalt with low viscosity and consistency, high penetration, and ductility to ensure permeability.
2. Organic reducing agent with a high light component content and low viscosity to impregnate the asphalt layer.
3. Penetrant to balance the solute and solvent molecular weight and ensure the long-term stability.
4. Solvent oil to speed up the evaporation and curing process.
5. Dispersant to reduce the asphaltene precipitation and extend material storage time.
6. Light-shield agent (LS agent) with high dispersibility, hiding power, and UV shielding capabilities.

2.1. Reducing Agent

We selected five commmonly used reducing agent materials (A–E). Agent A was produced by the Xi'an Xianyang Guolin Asphalt factory (Xi'an, China). B and C were produced by the Xi'an Yujian Petrochemical Co., Ltd (Xi'an, China). D and E were produced by the Shanghai Mingzhi Industrial Co., Ltd (Shanghai, China). According to the «Highway Engineering Asphalt and Asphalt Mixture Test Rules» (JTG E20-2011) [22], which measured their component proportions, including 25 °C penetration, the softening point, 5 °C ductility, 60 °C Brookfield viscosity, and other indexes. The results are shown in Table 1.

Table 1. The components and indexes of the reducing agent.

Indexes	A	B	C	D	E
Saturated fragrance/%	41.2	46.2	82.7	88.5	84
Aromatics/%	48.1	47.8	13.2	8.1	11.5
Colloid/%	3.5	2.1	0.5	0.2	0.1
Asphaltene/%	7.2	3.9	3.6	3.2	4.4
Penetration/0.1 mm (25 °C,100 g, 5 s)	140.7	141.3	165	185.3	201.3
Softening point/°C	44.8	44.7	42.2	40.9	40.3
Ductility/cm (5 °C)	71.1	71.9	83.7	85.5	96
Viscosity/Pa·s (60 °C)	1.105	1.085	0.875	0.755	0.685
Mass loss/% (RTFOT)	−0.15	−0.24	−0.46	−0.27	−0.15
Residual penetration ratio/%	81	80.5	71.2	79.1	82.1
Residual softening point value/°C	1.7	1.9	4.5	1.3	1.2
Residual ductility/cm (5 °C)	46.1	47.5	46.7	120.5	106.2
Residual viscosity ratio	1.13	1.21	1.56	1.3	1.08

From Table 1, agents D and E had the highest penetration and ductility and smallest viscosity before and after the RTFOT test, which were more satisfied with the requirements of the reducing agent, but their price is often higher than the others. The indexes of C decreased significantly after aging; residual penetration ratio and ductility reduced by 71.2% and 44.2% compared with the data before aging, showing a poor anti-aging ability, and therefore was not suitable to use. The indexes between A and B were close, but A had a higher content of light components, which made it easier to form a stable system. It also had a stronger dissolving ability to disperse and dissolve the aging asphaltene with low viscosity and strong penetration to meet the needs of the mixing and spraying work. The mass loss and viscosity of A were relatively small after the RTFOT test.

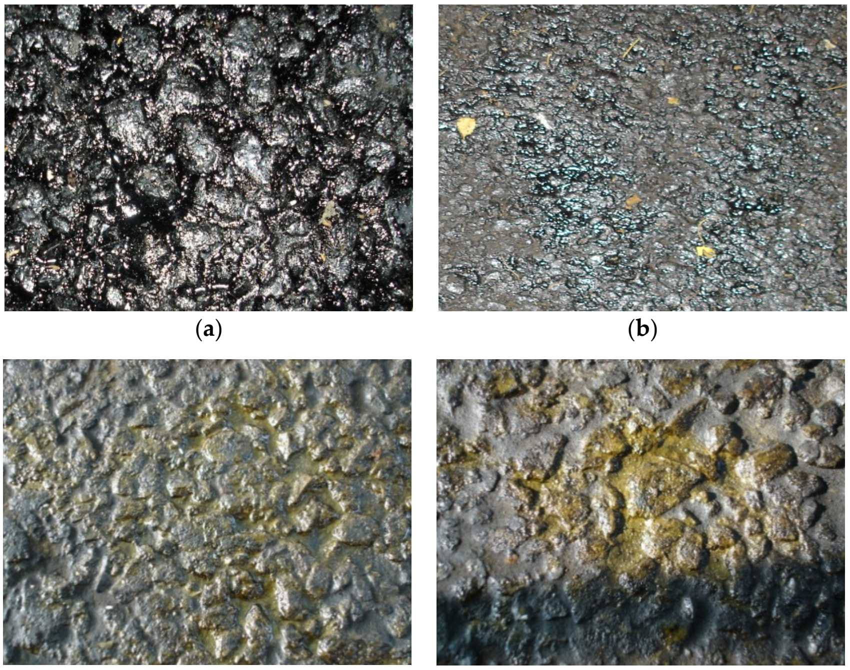
The road spraying test was given to A, B, D, E, respectively. Agents A, B, D and E were sprayed on asphalt pavement then left for 48 h. The appearance was observed and the results are showed in Figure 2. The pavement appeared yellowing and bleeding 48 h after the D and E spray application. It turned slightly green after spraying B; however, it was still black and shiny after spraying A, which showed the overall best effect during the spraying test. In summary, A was selected as the reducing agent of the LS pre-maintenance agent.

2.2. Penetrant

Three penetrant agents (A, B, C) were selected. Each were colorless and transparent liquids with strong penetrating ability. Their densities are 0.89, 0.88, and 0.95 g/cm^2; their molecular weights are 178.3, 220.4, and 221.3 g/mol; and their boiling points are 143, 190, and 220 °C. During the heating test, A volatilized rapidly and produced a strong irritating odor after heating. B quickly condensed and became filamentous, losing its permeability. C was stable and maintained permeability after heating; its small molecular structure could penetrate the surface of the cemented material into the asphalt layer and react with the water molecules in the air to form a waterproof layer. It is characterized by stable macromolecules and as a result built a better bonding between the asphalt and aggregate. C was significantly better than A and B, so C was selected as the penetrant of the LS pre-maintenance agent.

2.3. Solvent Oil

Selected No.6 solvent oil, which is a colorless transparent liquid with a relative density of 0.65–0.701, a *N*-hexane content of about 30%, and 2,4-dimethylpentane and 2,3-dimethylbutane each about 20%. It is a mixture of various lower alkanes. The recent extraction process of No. 6 solvent oil can effectively reduce its harmful ingredient content, which means very low toxicity. It can be dissolved in benzene, chlorine, acetone and other organic solvents yet is insoluble in water, which is a basic organic chemical of raw materials.



(**a**) (**b**) (**c**) (**d**)

Figure 2. The comparison of the road spraying test. (**a**) Agent A (black and shiny); (**b**) Agent B (green and bleeding); (**c**) Agent D (yellowing and bleeding); (**d**) Agent E (yellowing and bleeding).

2.4. Matrix Asphalt

$110^{\#}$ road asphalt, $SK90^{\#}$ asphalt, and ordinary rock asphalt were selected for the test. Among them, rock asphalt occurs in nature. Its physical properties tend to be coal while its main components are asphaltene, colloidal, and mineral asphalt matrix. The softening point can reach to 160–175 °C with good high temperature stability. Its high nitrogen content can acquire large viscosity and better anti-oxidation ability, respectively mixing them with solvent oil and penetrant can provide long-term precipitation observation. The results showed that the mixture prepared by $110^{\#}$ and $SK90^{\#}$ resulted in significant precipitation, which was caused by the large molecular weight difference between the asphalt and solvent oil. This can easily break the steady state after mixing and the asphalt continued to sink until precipitation. By contrast, there was less precipitation in the rock asphalt and it showed better quick-drying performance through the pavement spraying test. The drying time was much shorter than the $110^{\#}$ and $SK90^{\#}$ asphalt mixture. In summary, rock asphalt was selected as the matrix asphalt of the LS pre-maintenance agent.

2.5. Dispersant and LS Agent

The materials and adding dosage of the dispersant and LS agent are determined in Section 3.4, after the optimum ratio determination of the rock asphalt, reducing agent, penetrant, and solvent oil.

3. Optimum Composition Ratios

The dissolution degree of the rock asphalt to the penetrant and solvent oil mixture reflects the permeability and solubility, which determines the optimum range of the penetrant and solvent oil. The tratio with quick-drying properties is determined by a consolidation test that analyzes the percentage of the remaining mixture after air drying and that viscosity changes that occur after long-term storage. This determines the optimum proportion of the four main components. Finally, use consolidation and the UV aging test determine the dispersant and LS agent.

3.1. Optimum Ratio of Penetrant and Solvent Oil

We ground solid rock asphalt into fine powder and then mixed rock asphalt powder and penetrant (Agent C) by cutting and stirring, then added solvent oil under the premise of no precipitation, tilted the container, and observed the bottom precipitation after standing. To analyze the solubility of the mixture on rock asphalt, the asphalt dosage must not be too little; the penetrant mass must be maintained as 100 g and the limited rock asphalt minimum mass by 10% of the penetrant. The results are shown in Table 2.

Table 2. Proportions and solubility results.

Components	Proportions						
Rock asphalt/g	50	30	20	20	10	10	10
Penetrant/g	100	100	100	100	100	100	100
Solvent oil/g	<50	50	100	>100	100	200	>200
Precipitation/YES/NO	Yes	Yes	No	Yes	No	No	Yes

According to Table 2, when the ratio of penetrant to solvent oil was 1:1-1:2, there was no precipitation; the solution had good solubility to the rock asphalt. The results were similar to the solubility of the penetrant and solvent oil on the reducing agent, and the solubility degree was greater. After comprehensively comparing the results, the optimum ratio rage of penetrant to solvent oil should be 1:1-1:2.

3.2. The Composition Ratio Based on Quick-Drying Test

3.2.1. The Proportion of Rock Asphalt and Reducing Agent

Considering that the penetrant is expensive and produces a slightly irritating odor when it is heated, its hydrolysis reaction with water will affect road beauty, thus its dosage must be controlled. The initial penetrant proportion must be set as 20% of the four components. The mixtures were made according to different ratios and brushed on the road and penetration condition was observed. The results showed that when the rock asphalt and reducing agent mass was above 60%, the solution viscosity was too high. As shown in Figure 3, a thin film formed on the pavement, which hindered the penetration and volatilization process. The film edge tilted and fell off after solidifying, which means a poor maintenance effect and material waste. When the mass was less than 30% the solvent oil dosage was too high, resulting in an excessive volatilization rate that had a negative effect upon maintenance. In summary, the optimum ratio of the rock asphalt and reducing agent should be 30–60%.

Figure 3. Thin film on the pavement.

3.2.2. Quick-Drying Test Analysis

We set 11 proportion samples and performed a quick-drying test by putting them into an empty disk and recorded how quickly their surface dried and the full consolidation time. The results are shown in Table 3.

Table 3. 11 proportions and quick-drying test results.

Components	Proportions										
Number	1	2	3	4	5	6	7	8	9	10	11
Rock asphalt/%	40	40	30	30	30	25	20	15	20	35	40
Reducing agent/%	20	15	15	10	20	25	30	35	40	15	10
Penetrant/%	20	20	20	20	20	20	20	20	20	20	20
Solvent oil/%	20	25	35	40	30	30	30	30	20	20	20
Surface dried/h	2	2	1.5	1.5	1.5	2.5	2.5	3.5	>5	2.5	1
Fully consolidation/h	4	5	2.5	2.5	2.5	4.5	4.5	5	>5	3	2.5

From Table 3, the consolidation speed was accelerated with the increase of the rock asphalt and solvent oil, when the mass of penetrant and solvent oil varied within 40–50%. Quick-drying performance was enhanced with the increase of rock asphalt. The main reason for this is because rock asphalt is solid at normal temperatures. Once the solvent evaporates, the precipitated rock asphalt immediately condenses into solid. Quick-drying performance was also affected by the reducing agent. No. 8 and 9 showed that when the reducing agents' mass were above 30%, drying time was obviously higher than the others and not conducive to maintenance. From No. 3–5, when the rock asphalt and reducing agent mass was less than 50%, or when the reducing agent was less than 20%, the drying speeds were relatively fast, which is beneficial for maintenance. In summary, by setting the mass ratio of the penetrant as 20% when the total mass of the rock asphalt and reducing agent was 40–50% and the reducing agent was less than 20%, the material could acquire a good quick-drying ability.

3.3. Optimum Proportion Based on Storage Stability

3.3.1. Air-Drying Test Analysis

To compare the effective retention rate after air-drying, we prepared 5 samples within the range of the ratio determined in Section 3.2, put them into an empty disk and then tested their percentage of remaining (*POR*) after 24 h air-drying using Rhinophalt as the contrast group. The calculation method is shown in Equation (1) and the *POR* results are shown in Table 4.

$$POR = \frac{G_2 - G_P}{G_1 - G_P} \times 100\% \tag{1}$$

POR—Percentage of remaining after air-drying, %;
G_P—The weight of the plate, g;
G_1—The weight of plate and wet material, g;
G_2—The weight of plate and dry material, g.

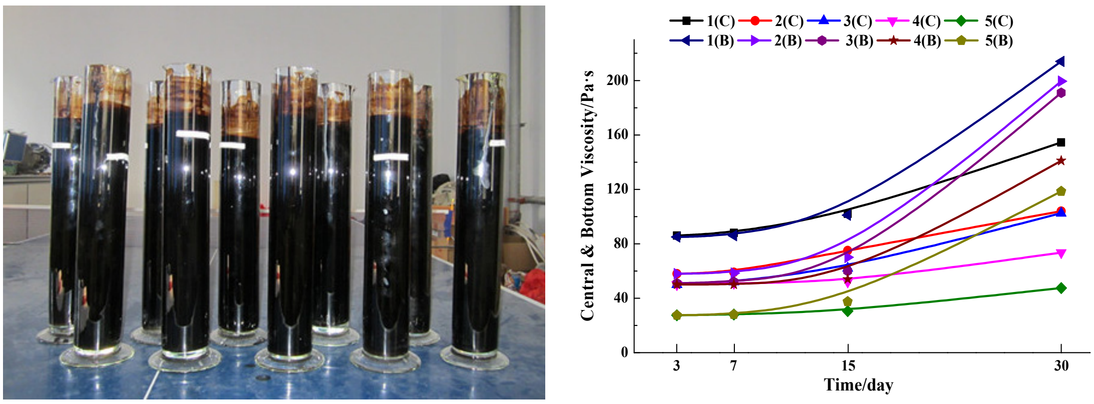
From Table 4, the 5 samples' *POR* results were all larger than Rhinophalt. The highest *POR* is No.1, which was 1.5 times than Rhinophalt. The *POR* values of No. 1–5 were all greater than the total ratio of the rock asphalt, reducing agent and penetrant, proving that the three components were all remaining after the air-drying. It showed that the proportion based on the quick-drying analysis was reasonable; in this range the agent had good quick-drying and storage performance.

Table 4. *POR* test results in 5 proportions.

Samples	Rock Asphalt/%	Reducing Agent/%	Penetrant/%	Solvent Oil/%	Plate/g	Plate & Wet Material/g	Plate & Dry Material/g	*POR*/%
1	30	20	20	30	37.3	47.4	44.7	73.3
2	30	15	20	35	48.5	55.4	53.2	68.1
3	30	10	20	40	52.6	61.8	58.5	64.1
4	25	25	20	30	51.9	57.6	55.9	71.9
5	20	30	20	30	51.5	61.8	58.5	70.1
Rhinophalt	\	\	\	\	37.1	47.4	41.9	47.7

3.3.2. Storage Stability Analysis

Storage stability is mainly reflected as the viscosity changes during long-term storage. The 5 samples above were stored in a cylinder where the tube mouth was tightened. A BROOKFIELD viscometer was used to periodically measure the viscosity change at room temperature. Since the solution is very volatile, the volatilization during the sampling interferes with the accuracy of the data in the upper cylinder, so only the data in the central (C) and bottom (B) part were recorded. The results are shown in Figure 4.



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

Figure 4. Storage stability contrast test. (**a**) Storage stability samples; (**b**) Viscosity contrast results.

From Figure 4, after 3 and 7 days, the viscosity between the central and bottom were relatively small. The samples were stable, with slight changes mainly caused by temperature change. After 15 and 30 days, the viscosity showed a rapid increase because of the stratification; the viscosity gap between the central and bottom increased gradually. Comparing the 5 samples, the central and bottom viscosity difference of No. 1 and 4 were relatively small compared with 2, 3, and 5. Also No. 1 and 4 had less precipitation at the bottom, which was a controlled rock asphalt and reducing agent ratio between 30:20 and 25:25 with a penetrant and solvent oil ratio of 20:30, which resulted in better long-term storage stability and also less degradation and precipitation.

In summary, based on Sections 3.1–3.3, the optimum components ratio was determined as, rock asphalt: reducing agent: penetrant: solvent oil = 30:20:20:30.

3.4. Dispersant and LS Agent

3.4.1. Dispersant

We chose three dispersant materials (A, B, C). According to Figure 5, A was a white powder and commonly used as an asphaltene precipitation dispersant. B was a paraffin-like solid, used as a leveling agent with good dispersion and emulsification. C was a white ultrafine powder, used in the rubber industry with good lubricity and light stability.

(a) (b) (c)

Figure 5. Dispersant appearance contrast. (**a**) Dispersant A; (**b**) Dispersant B; (**c**) Dispersant C.

The petroleum industry shows that a controlled dispersant dosage within 1% can significantly improve the stability of asphaltene in crude oil [23]; therefore, A, B, C were added into a pre-maintenance agent prepared at the optimum ratio. The adding amounts were 0.2, 0.4, 0.6, 0.8, and 1% of the mass of the pre-maintenance agent prepared according to the optimum ratio. The samples were sealed in glass bottles, and their consolidation condition was observed and recorded in cool, dark environment. The results are shown in Table 5.

Table 5. The Consolidation results of three dispersants.

Consolidation Time/day	Dispersant Amount/%					
	0	0.2	0.4	0.6	0.8	1
A	45	40	30	30	20	20
B	45	45	40	40	30	30
C	45	60	>85	70	55	50

From Table 5, the consolidation time without any adding dispersant was 45 days. After adding A and B, the consolidation time gradually reduced with the increasing dispersant. The main reason was that adding the dispersant increases the proportion of small and medium substances, breaks the original stable state, and affects stability. The consolidation time of C was longer than A and B, and higher than 45 days in all dosages. The sample with 0.4% was not consolidated after 85 days. The storage stability of C was significantly better than A and B. From the molecular structure, A and B were short single-chain structures. C contained a positively charged and highly dispersed inorganic nuclei and two linear long hydrocarbon chains. The charged end can be wrapped in the asphaltene structure, preventing asphaltene flocculation and extending material storage time. In summary, we selected C as the dispersant agent; the dosage was 0.4% of pre-maintenance agent mass.

3.4.2. LS Agent

The LS agent selected was Nano-grade black powder. The main component is carbon black. We mixed it into SBRII-C modified asphalt (commonly used in high altitude strong UV regions), according to the dosage range determined by the existing studies of asphalt anti-UV aging additives [3]. The dosage was determined as 3, 5, and 7% of the asphalt mass and stirred for 10 min to ensure it dispersed evenly. The 25 °C penetration, softening point, and 5 °C ductility were measured before and after adding the LS agent. UV aging was performed for 12 h with a self-developed artificial UV aging device to measure the asphalt indexes again. The results are shown in Table 6.

Table 6. Asphalt indexes results.

Indexes	25 °C Penetration/0.1 mm	Softening Point/°C	5 °C Ductility/cm
SBRII-C	77.3	53.5	54.7
SBR + 3% LS agent	77.9	52.8	44.1
SBR + 5% LS agent	79.3	51.4	42.9
SBR + 7% LS agent	80.1	50.9	42.1
Aged SBRII-C	54.7	59.1	34
Aged SBR + 3% LS agent	56.3	56.9	26.1
Aged SBR + 5% LS agent	60.1	53.3	24.9
Aged SBR + 7% LS agent	60.9	53.2	23.8

From Table 6, the 25 °C penetration and softening point change were relatively small before UV aging. After aging, the penetration increased and the softening point decreased with the increase of the LS agent, of which the effect of 3% was limited, the effect of 5% and 7% were better and close to each other, proving that the LS agent can improve asphalt low temperature anti-cracking performance after UV aging. 5 °C ductility before and after aging were both reduced. The addition of the LS agent had a negative effect on asphalt ductility, the reason being the LS agent is a powdered solid, which will impact the plastic deformability of asphalt, thus its dosage should be controlled in order to reduce the negative effect to the asphalt while ensuring the anti-UV aging ability. Considering the significant degree of LS agent to asphalt, the effect of the LS agent in 5% and 7% were close, showing that a good anti-aging effect can be achieved in the 5–7% dosage. In order to reduce the adverse effects of the additive on asphalt rheology while controlling material costs, the dosage was determined as 5%.

4. Road Performance Test Plan

4.1. Penetration Test

An insufficient penetration depth of the curing agent will not achieve the maintenance effect. Too much will cause material waste and affect the reasonable internal porosity of the pavement. We provide an accurate measurement of the LS pre-maintenance agent penetration depth with digital image technology following this method: we quantitatively painted a LS pre-maintenance agent on asphalt mixture specimens then used a camera to shoot the infiltration interface, adjusted the brightness and contrast by Photoshop, outlined the penetration range and fill with color, performed image scale calibration with IPP software, converted the pixel into length, separated the permeable region and measured its area and width, and then divided them to achieve the average penetration depth.

The actual dense gradation asphalt pavement porosity is about 6–7%, which gradually compacts to 3%. We prepared dense graded asphalt mixture specimens by the static pressure method, controlled the porosity under 3, 4, 5, 6, and 7%, then evenly brushed 0.5 and 1 kg/m^2 LS pre-maintenance agent and measured the average permeation depth after 0.5, 2, 8, and 24 h. Then we analyzed the relationship of the penetration depth, brushing amount, and penetration time, the digital image method is shown in Figure 6.

4.2. Restore Performance Test

The restore effect of the LS pre-maintenance agent is determined by the recovery degree of the aged asphalt. Ordinary road petroleum asphalt was used as the matrix asphalt, based on the «Highway Engineering Asphalt and Asphalt Mixture Test Rules» (JTG E20-2011) [22], the sample was prepared and assayed according to the softening point, 25 °C penetration, and 15 °C ductility, then the asphalt was aged for 3 h by RTFOT and equal amounts of LS pre-maintenance agent and Rhinophalt agent were added. In the current maintenance project, the adding amount of the reducing agent is about 5–10% of the asphalt mass [24]. The selected reducing agent amount is 5, 7, and 9%, and the equivalent to the LS pre-maintenance agent is 25, 35, and 45% of the asphalt mass. Melted state aging asphalt is added into LS and Rhinophalt agent and for stirred 15 min. The data is compared to evaluate the restorative effects.

Figure 6. Infiltration interface and digital image analysis.

4.3. Light Aging Resistance Test

The impact of UV radiation on asphalt pavement is more serious than thermal aging, especially in high altitude areas with strong UV radiation [7,25]; however, natural light aging is a long process, which is not conducive to analyze, therefore, an indoor aging test that simulated and accelerated the natural process was used. By irradiating asphalt specimens with strong UV radiation uninterruptedly and observing the appearance change, we can calculate and compare the UV aging mass loss rate. A self-developed artificial strong UV radiation aging device is shown in Figure 7. It consists of two installed 1000 W strong UV lamps on top, two air circulation fans that are set to simulate the ventilation environment, and a ø140 mm × 9.5 mm flat disc that holds the sample.

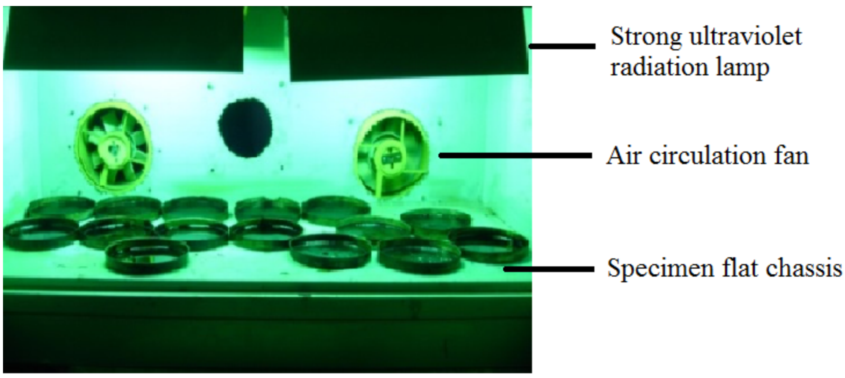


Figure 7. Artificial strong UV radiation aging test.

According to the relevant literature, take Lhasa, Tibet in China for example, its total annual radiation value is 195 kcal/cm^2 and the annual radiation time is 3006 h. The radiation intensity of the UV lamp is 1000 W × 2, the intensity on the unit surface is 390.3 kcal/cm^2. Thus continuous exposure over 48 h is equivalent to two years of natural radiation in Lhasa. We loaded LS and Rhinophalt agent into six plates, each 15 g, about 1 mm thick, and put them into the device and regularly rotated the position to ensure uniform radiation. We observed the appearance change after UV aging to analyze the changes in morphology and rheological properties, and calculated the average UV aging mass loss rate after 8, 12, 24, and 48 h to analyze the remaining amount of active ingredients, then contrasted them with the results of the Rhinophalt.

5. Road Performance Test Results Analysis

5.1. Penetration

The UV radiation spread with aging asphalt molecules into a 1 mm depth. Because of the existing voids, the depth of radiation ultimately reaches the maximum individual particle mix size, which is about 10 mm. Therefore, we use 10 mm as the standard penetration depth. The average penetration depth results at 0.5–24 h are shown in Figure 8.

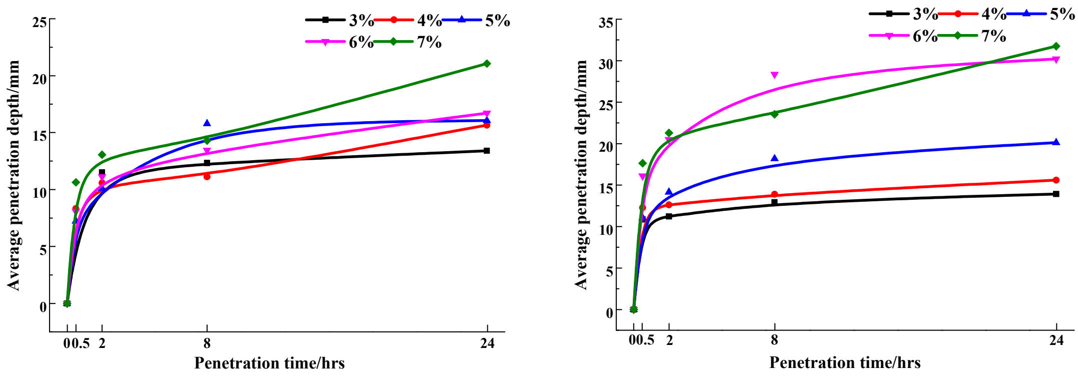


Figure 8. The comparison of average penetration depth. (**a**) 0.5 kg/m^2; (**b**) 1 kg/m^2.

In 0.5 kg/m^2, the surface groove of the specimen was fully filled, a bubble came out from a larger gap that the agent was quickly penetrating and the average penetration depth in 5–7% porosity was over 10 mm after 2 h. It kept growing and reached 15–20 mm after 24 h. In 1 kg/m^2, the average penetration depth reached 10 mm after 2 h, and 15–30 mm after 24 h. We can see that both dosages can completely penetrate the aged asphalt layer. The permeation depth in 2 h and 8 h accounted for about 50% and 75% of the whole 24 h results. The first 2 h was the main infiltration period. By chosing 1 kg/m^2 a faster and deeper penetration effect can be obtained, but it requires higher maintenance costs. In summary, the pavement should be closed at least 2 h after spraying the LS pre-maintenance agent, a conditional section can be extended to 8 h and above. 0.5 kg/m^2 can ensures sufficient penetration depth and effect while controlling the cost.

5.2. Restore Performance

The results of the matrix asphalt with adding 25, 35, and 45% asphalt mass of LS pre-maintenance agent and Rhinophalt are shown in Table 7.

Table 7. The asphalt indexes comparison results.

Indexes	Original	Aging 3 hrs	25% LS	35% LS	45% LS	25% Rhinophalt	35% Rhinophalt	45% Rhinophalt
Softening point/°C	45.9	53.3	51.5	36.6	20.3	43.3	39.8	22.1
25 °C Penetration/0.1 mm	100.2	62.3	75.7	197	223	95.8	207	218
15 °C Ductility/cm	158.4	67.1	33	29.6	20.9	31.5	27.9	20.3

From Table 7, the softening point declined with the increase of the LS pre-maintenance agent. 25 °C penetration increased significantly compared to 3 h aging. The softening point in adding 45% LS and Rhinophalt agent decreased by 63% and 57%. 25 °C penetration increased by 261% and 247% and it can be seen that the LS pre-maintenance agent was similar to Rhinophalt on restorative performance. The softening point and penetration of the aged asphalt varied greatly with the increase of the agent. In general, when 25 °C penetration drops below 2 mm, severe cracking of the road surface occurs.

Above 3 mm acquires good crack resistance ability, which means the LS pre-maintenance agent can significantly improve the anti-cracking ability of asphalt at low temperature. For the softening point, it is an important index to show the temperature sensitivity of the asphalt. Reducing the softening point after adding the LS pre-maintenance agent is very beneficial and improves the low temperature crack resistance of the asphalt. As for ductility, it is generally accepted that the road surface is in a crackable state if 15 °C ductility is less than 5 cm. 15 °C ductility in adding two agents were both more than 20 cm, which can meet the requirements of anti-cracking and water sealing. The effect of the two agents on the asphalt indexes were slightly different, because of the solvent oil in the LS pre-maintenance agent, which was more volatile than the naphtha in Rhinophalt, this produced the difference during the process of heating. In summary, the LS pre-maintenance agent had good restorative ability to the aged asphalt, which can effectively improve asphalt low temperature performance.

5.3. Light Aging Resistance

The UV aging mass loss rate (*MLR*) calculation method is shown in Equation (2), the average *MLR* results are shown in Figure 9.

$$MLR = \frac{G_1 - G_2}{G_1} \times 100\% \tag{2}$$

MLR—Mass loss rate, %;
G_2—The residual mass of the sample after light aging, g;
G_1—The initial mass of sample before light aging, g.

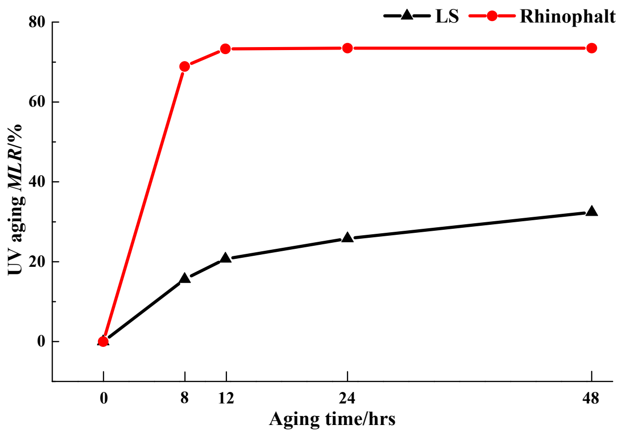
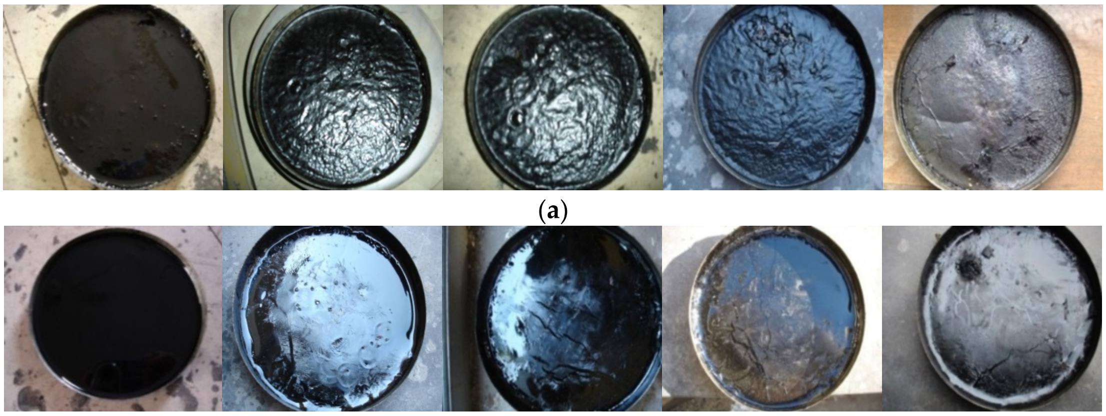


Figure 9. Mass loss rate (*MLR*) results versus UV aging time.

From Figure 9, the *MLR* of the LS pre-maintenance agent was obviously less than the Rhinophalt, moreover, its trend was more stable; after 48 h it reached 32.4%. The results of the Rhinophalt changed fast within 8 h and stabilized after 12 h, finally reaching 73.5%.

The appearance comparison results are shown in Figure 10.

As shown in Figure 10, the two materials were all black liquid before aging and their surfaces were smooth and consistent. For the LS pre-maintenance agent, the surface formed thin film with slight wrinkles after 8 h, the folds were further deepened with slight cracks after 12 h, the film shrunk, lower liquids became harder and brittle after 24 h, and the surface completely hardened after 48 h. For Rhinophalt, on the specimen appeared small holes and the material continuously reduced and began to harden after 8 h. The crack appeared after 12 h. The specimen was completely hardened and had lost its consistency and viscosity after 24 h.



(**a**)

(**b**)

Figure 10. Appearance comparison after UV aging (0, 8, 12, 24, 48 h); (**a**) LS pre-maintenance agent; (**b**) Rhinophalt.

In summary, the LS pre-maintenance agent was completed aged after 48 h UV radiation, which was 2 years of natural UV radiation in Lhasa, and much longer in other lower radiation areas. The anti-light aging time of Rhinophalt was only 25% of the LS pre-maintenance agent. From the light aging resistance effect, the UV aging *MLR* of the LS pre-maintenance agent in 48 h was 32.4%. The film formed during the early aging stage can hinder the UV effect on a lower structure, thus the result of Rhinophalt was 73.5%, more than two times the LS agent. Most of the components had lost, only leaving a little rock asphalt. We can see that the LS pre-maintenance agent had better anti-light aging effects than the Rhinophalt, and can meet the requirements of pre-maintenance in strong UV areas. We can choose to spray a year and a half after the first pre-maintenance work, supply the function loss, and repair micro-cracks due to UV radiation and low temperature shrinkage, and thus prevent the disease development of the asphalt layer.

6. Conclusions

The study aims at the early damage of asphalt pavement in strong UV radiation areas, develops a LS pre-maintenance agent, determines its optimum composition ratio through indoor tests, and studies its effect on road performance. The main conclusions are as follows:

(1) The asphalt pavement maintenance function is determined and the main components of the LS pre-maintenance agent are rock asphalt, reducing agent, penetrant, solvent oil, dispersant, and LS agent. The raw material types are determined by contrast tests.

(2) The optimum ratio of the components is determined based on the best proportion of penetrant and solvent oil for solubility ability. The best proportion for quick-drying, long-term storage ability, and the amount of dispersant and LS agent, rock asphalt, reducing agent, penetrant and solvent oil is 30:20:20:30. The LS agent is 5% of the four components total mass. The dispersant is 0.4%.

(3) Digital image technology is used in the permeability test to provide accurate measurements of the LS pre-maintenance agent penetration depth. The results showed that the pavement should be closed at least 2 h after spraying and can extended to 8 h time permitting. The dosage of 0.5 kg/m^2 can ensure sufficient penetration effect.

(4) Use the RTFOT test to compare the LS pre-maintenance agent regeneration effect to the indexes of aged asphalt. The results will show that it has excellent restore and activation ability to the aged asphalt and greatly improves the low temperature anti-cracking ability of asphalt pavement.

(5) Compare the appearance and *MLR* results of the LS pre-maintenance agent after the artificial UV radiation aging test. The anti-light aging time of the LS pre-maintenance agent can last 2 years in

Lhasa. Its light resistance performance is much better than the Rhinophalt agent, which can meet the requirements of pre-maintenance work in strong UV radiation areas.

Author Contributions: Y.T. and B.M. conceived and designed the experiments; Y.T. and K.T. performed the experiments; N.L. and X.Z. analyzed the data; K.T. contributed reagents/materials/analysis tools; Y.T. wrote the paper.

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