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Analysis of asphalt durability based on inherent and improved performance

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HIGHLIGHTS

- The improved high temperature durability of SBS and TPS modified asphalt is better than that of improved low temperature durability. Rubber modified asphalt has a significant ability to improve low temperature durability.
- The results show that microstructure of inherent performance is more easily affected by aging than that of improved performance.
- Comparison of durability between inherent and improved performance of modified asphalt shows that even different modified asphalt can improve high and low temperature performance, the modifier does not have the same ability to improve the performance due to different durability.

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ABSTRACT

The composite performance of modified asphalt is divided into inherent performance and improved performance. The inherent performance of asphalt refers to the original performance of the virgin asphalt. The performance obtained by modifying the virgin asphalt by different methods is referred to the improved performance of the asphalt. In most studies of modified asphalt, researchers pay more attention to how to improve the performance of virgin asphalt at high and low temperatures (i.e., rutting at high temperatures and cracking at low temperatures); however, little attention has been paid to the anti-aging durability of the improved performance. In this project, the macro and micro mechanisms of modified asphalt were compared and analyzed through a series of comparative experiments on the inherent and improved performance of modified asphalt to explore the anti-aging durability of the modified asphalt based on the inherent performance and improved performance at high and low temperatures.

1. Introduction

As an important binder for asphalt pavement construction [1], the selection and quality of asphalt determine the durability of asphalt pavement to a large degree and directly affect the service life and safety of asphalt pavement. Therefore, studying the durability of road asphalt, especially the durability of asphalt materials, is of great theoretical and practical value [2–4].

Zhang et al. [5] investigated the change in molecular weight during the aging process of asphalt and found some new functional groups that were produced inside the asphalt; they also found that the change in molecular structure will lead to changes in the morphology and performance of the asphalt. P. Chen's paper concluded that temperature has a great influence on the aging of asphalt. When the temperature was above 100 °C, a dehydrogenated chemical reaction of the asphalt was produced. When the temperature was below 100 °C, an oxidation reaction of the asphalt was produced, as well as some oxygenated compounds. The chemical reaction produced by asphalt aging has an important influence on the performance of the asphalt [6]. According to Zhu et al., as the aging time is increased, the residual needle penetration and residual ductility is decreased and the softening point is increased. This means that the high temperature performance of the asphalt is increased and the low temperature performance is decreased after aging [7]. Zhang et al. [8] indicated that the variation of the performance of the asphalt during the aging progress is mainly due to the change of its interior components. When asphalt is aging, the content of its lighter components is decreased, such as oil and gelatin, and the content of the heavier components is increased, such as asphaltene. This results in a harder asphalt, which is easily broken at low temperatures. Meanwhile, the aging of the asphalt threatens the safety of the road surface. In the aging process, the low temperature performance and water stability of the asphalt mixture is

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decreased. The asphalt pavement creates the risk of road fractures and the formation of a loose mixture of asphalt in cold and wet areas [9,10]. Therefore, it is of great significance to improve the service life and performance of asphalt pavement via improving the aging durability of asphalt.

Because virgin asphalt cannot meet the requirements of the durability required in asphalt pavement, when paving with high-grade asphalt pavement, modified asphalt is often used as a binder for the asphalt mixture [11]. The modified asphalt mixture greatly improves the properties of the virgin asphalt mixture. Rasool et al. [12] pointed out that adding highly reclaimed rubber and SBS modifiers into virgin asphalt can greatly improve its ductility and its ability to resist aging. R. Liang's paper reported that rubber powder can greatly improve the viscosity and rheology of the asphalt mixture; this finding was made by observing the viscosity of the rubber powder modified asphalt mixture after short-term aging and rheological tests. At the same time, the aging behavior and rheological performance of the asphalt mixture were found to have a certain linear relationship [13]. TPS and Sasobit modifiers have a significant effect on improving the mechanical performance and anti-aging ability of the asphalt mixture ability [14–16]. Therefore, adding modifiers to improve the performance of asphalt has a significant effect on improving its anti-aging durability.

The composite performance of modified asphalt is classified into improved performance and inherent performance. The existing research has done a great deal of analysis on the composite performance of modified asphalt during the aging process, but the formation mechanism and durability of asphalt modified by different admixtures have not been discussed [17]. The purpose of this study is to compare the inherent performance and improved performance of different mixtures of modified asphalt theoretically and experimentally. This paper will discuss the formation mechanism and durability of two properties of modified asphalt, and further analyze the technical characteristics of different modifiers. On the basis of this research, a new modified asphalt material based on composite modifiers is proposed to optimize the road performance of modified asphalt. Therefore, the research results have certain scientific significance for the evaluation of modified asphalt and for the development of future research directions.

2. Test materials and contents

2.1. Test materials

2.1.1. Asphalt

Asphalt 90# (25 °C penetration is about 80–100/0.1 mm) was selected in this test, and the indexes of the asphalt are shown in Table 1.

2.1.2. Modifiers

The modifiers of SBS, TPS, Rubber and Sasobit were selected in this test (Fig. 1), and the indexes of the modifiers are shown in Tables 2–5.

2.2. Preparation of asphalt specimens

Four kinds of asphalt specimens were prepared for the comparative test. They are 4% SBS asphalt (90#), 4% TPS asphalt (90#), 16% Rubber asphalt (90#) and 2% Sasobit asphalt (90#). The technical indicators of comparing the asphalt specimens are shown in Table 6.

2.3. Test content

The above asphalt samples were selected as the research objects to carry out aging tests (aging times were 0, 5, 20 h). Then, the macroscopic comparison and microcosmic demonstration of the durability of the asphalt, based on inherent durability and inherent performance, were carried out.

2.3.1. Macro-comparison

First, 4% SBS asphalt (90#), 4% TPS asphalt (90#), 16% Rubber asphalt (90#) and 2% Sasobit asphalt (90#) specimens were obtained by modifying skill. On the basis of this, RTFOT was used to heat these specimens for 0 h, 5 h and 20 h to determine the changes in the macro evaluation indexes, such as penetration, ductility, softening point and viscosity that occurred during the aging process. The regression curves of the modified asphalt index with aging times were all linear regressions. We then compared the speed of the performance index with the changing of the aging time (the absolute value of the linear slope), and we used this to evaluate durability based on the improved and inherent performance of the modified asphalt [18,19]. The larger the slope, the faster the asphalt performance index changed with the aging time, and the changes in the asphalt performance were more affected by aging. It means the larger the slope, the worse anti-aging durability is. Conversely, the smaller the slope, the better anti-aging durability is.

2.3.2. Micro-demonstration

According to the current standard tests, four components of the asphalt were measured by the four-component analysis method. The experimental principle of the analytical method is as follows: undissolved asphaltenes (As) in the bituminous samples were precipitated by the *n*-heptane after filtration (to remove the aromatics) using silica gel. The soluble fraction was adsorbed on the activated alumina adsorption column. Then, it was washed three times, and the solution of the remaining three components was obtained. For the first washing, *n*-heptane reagent was used to produce the saturated solution (S). For the second washing, toluene reagent was used to produce the aromatic fraction (Ar) solution. For the third washing, toluene, ethanol, toluene and ethanol were used to obtain the colloidal (R) solution. Finally, the solvent was recovered in a constant temperature tank; after solvent recovery, the content of each component can be obtained by vacuum drying (vacuum degree; 93 kPa ± 1 kPa, temperature: 105 °C ± 5 °C) [20–22]. The test process is shown in Fig. 2.

In microscopic verification, first, asphalt specimens were heated by RTFOT for 0 h, 5 h and 20 h. The changes in the four components of the asphalt samples in the aging process were recorded by the above component test method. Since the four components constituted a colloidal structure of bitumen in different proportions, we took the change in the colloidal instability index Ic (Ic = (S + As)/(R + Ar) of the asphalt as an index to explore the durability based on the inherent performance and improved performance of the different modified asphalt specimens from the microscopic components. Then, the macroscopic test results were verified.

Table 1
Technical indexes of virgin asphalt.

Asphalt	Penetration/25 °C/0.1 mm	PI	Ductility/cm		Softening point/°C	Viscosity/135 °C/Pa.s
			5 °C	15 °C		
90#	93	−0.77	9	165	44.5	0.328


a) SBS b) TPS c) Rubber (80 mesh) d) Sasobit

Fig. 1. Types of modifies.

Table 2
Technical indexes of modifier SBS (LG501).

Tensile Strength/MPa	Elongation at break/%	Hardness (A)	Styrene/butadiene	Density/(kg/cm^3)
33	800	76	31/69	0.94

Table 3
Technical indexes of modifier TPS.

	Particle size/mm	Density/(g/cm^3)	Water absorption rate/%
Technical indicators	≤5	0.7–1.0	<1

3. Comparative macro-analysis on inherent and improved performance of road asphalt

The macro test data of the inherent, improved and composite performance of the virgin asphalt (90#) and the four kinds of modified asphalt specimens are shown in Table 7.

3.1. Comparative analysis of inherent performance and SBS improved performance

3.1.1. Test data processing

On the basis of the test data (Table 7), the macro test data of the 4% SBS asphalt (90#) were processed. The data processing results are shown in Table 8.

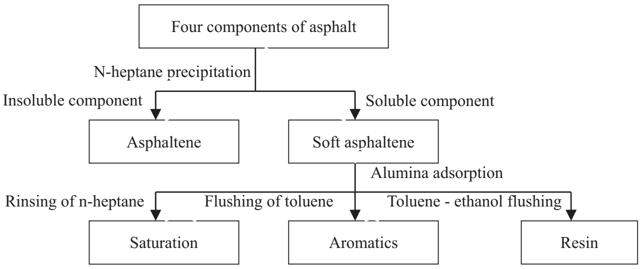


Fig. 2. Flowchart of four-component asphalt test.

3.1.2. Comparative analysis on penetration

The penetration and PI of the 4% SBS asphalt (90#) based on different performance and aging times are shown in Fig. 3. The data regression relationship is shown in Table 9.

The following conclusions can be drawn by comparing the data in Table 9.

Table 4
Technical indexes of modifier Rubber powder.

	Physical index				Chemical index			
	Relative density/(kg/cm^3)	Water content/%	Metal content/%	Fiber content/%	Ash content/%	Acetone extract/%	Carbon black content/%	Content of rubber hydrocarbon/%
Results of determination	289	0.27	0.02	0	10	10.02	32.86	51

Table 5
Technical indexes of modifier Sasobit.

	Freezing point/°C	Penetration/0.1 mm		Viscosity/135 °C/cp	Density/25 °C/(g/cm^3)	Melting point/°C
		25 °C	65 °C			
Prescribed value	≤99	≤1	≤10	10 ~ 14	–	98–110
Measured value	98	<0.7	7	12	0.94	100

Table 6
Comparison of technical indexes for asphalt specimens.

Asphalt	Penetration/0.1 mm			PI	Ductility/cm		Softening point/°C	Viscosity/135 °C/Pa.s
	25 °C	15 °C	5 °C		5 °C	15 °C		
Virgin Asphalt (90#)	93	35	12	-0.770	9.0	165.0	44.5	0.328
4%SBS Asphalt (90#)	68	27	12	0.399	35.2	86.7	72.8	1.895
4%TPS Asphalt (90#)	69	32	13	0.676	30.0	94.2	48.8	0.448
16%Rubber Asphalt (90#)	60	23	10	0.187	8.6	18.3	59.6	1.583
2%Sasobit Asphalt (90#)	66	25	11	0.187	3.5	136.5	58.9	0.288

Table 7
Comparison of aging test results for asphalt specimens.

	Aging time/h	Penetration/0.1 mm			PI	Ductility/cm		Softening point/°C	Viscosity/135 °C/Pa.s
		25 °C	15 °C	5 °C		5 °C	15 °C		
Virgin Asphalt (90#)	0	93	35	12	−0.770	9.0	165.0	44.5	0.328
	5	61	23	10	0.118	6.0	111.0	51.8	0.385
	20	32	13	6	0.657	0.5	8.2	58.2	0.870
4%SBS Asphalt (90#)	0	68	27	12	0.399	35.2	86.7	72.8	1.895
	5	44	23	11	1.976	24.4	82.3	74.0	2.112
	20	37	20	10	2.397	1.3	31.9	76.9	3.500
4%TPS Asphalt (90#)	0	69	32	13	0.676	30.0	94.2	48.8	0.448
	5	51	22	10	0.830	23.3	73.7	51.9	0.460
	20	42	20	9	1.215	0.4	8.4	56.3	0.620
16%Rubber Asphalt (90#)	0	60	23	10	0.187	8.6	18.3	59.6	1.583
	5	67	30	15	1.429	13.8	21.9	61.4	4.050
	20	44	23	13	2.903	8.6	18.6	64.3	5.550
2%Sasobit Asphalt (90#)	0	66	25	11	0.187	3.5	136.5	58.9	0.288
	5	44	21	10	1.494	3.1	44.1	59.7	0.318
	20	34	18	9	2.270	0.5	7.0	66.5	0.612

Table 8
Test data of inherent performance and improved performance (4% SBS asphalt 90#).

	Aging time/h	Penetration/0.1 mm			PI	Ductility/cm		Softening point/°C	Viscosity/135 °C/Pa.s
		25 °C	15 °C	5 °C		5 °C	15 °C		
Inherent performance	0	93	35	12	−0.770	9.0	165.0	44.5	0.328
	5	61	23	10	0.118	6.0	111.0	51.8	0.385
	20	32	13	6	0.657	0.5	8.2	58.2	0.870
Improved performance	0	-25	-8	0	1.169	26.2	−78.3	28.3	1.567
	5	-17	0	1	1.858	18.4	−28.7	22.2	1.727
	20	5	7	4	1.740	0.8	22.7	18.7	2.630
Composite performance	0	68	27	12	0.399	35.2	86.7	72.8	1.895
	5	44	23	11	1.976	24.4	82.3	74.0	2.112
	20	37	20	10	2.397	1.3	31.9	76.9	3.500

Note: Composite performance = inherent performance + improved performance.

(1) The penetration data (25 °C, 15 °C and 5 °C) shows that the anti-aging durability of penetration based on inherent performance (performance at high temperatures) is worse than that of improved performance. But the smaller the penetration is, the better the performance at high temperatures, and that is because the viscosity of the asphalt with weak penetration can be reduced, and the mechanical performance of the asphalt mixture cannot be guaranteed. It is desirable that penetration will be stable within certain suitable ranges. If penetration drops too rapidly during the aging process, this indicates a poor anti-aging durability of penetration.

(2) According to the slope of the regression equation, the anti-aged durability based on improved performance at different temperatures is better than that of the inherent performance. The contrasting results of the PI shows that the PI change rate of improved performance is slower than that of the inherent performance, and its slope is smaller. This shows that the temperature sensitivity of improved performance is weak and the anti-aging durability of performance at high temperature is better.

(3) At the beginning of the aging, the inherent penetration of the asphalt was greater than that of the modified penetration. However, the inherent penetration of the asphalt was gradually less than the modified penetration with the increase in the aging time, and the inherent penetration of the asphalt at low temperatures (15 °C, 5 °C) was less than the modified penetration. The results further indicate that the anti-aging durability of the penetration based on improved performance is better than that of the inherent performance.

To sum up, the anti-aging durability based on the inherent performance of the asphalt (performance at high temperatures) is worse than that of the improved performance. The above conclusions are based on the macro test data, and the next step is further demonstrated by the microscopic mechanism.

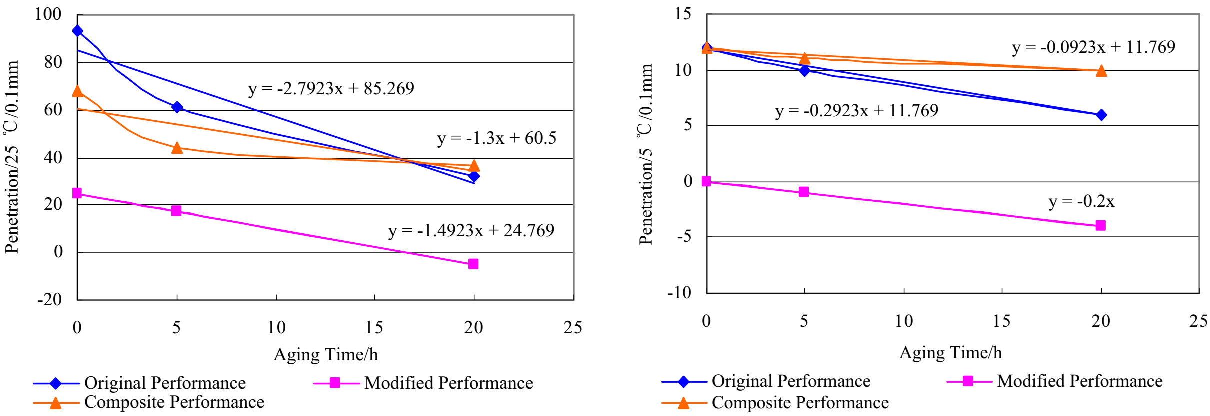
3.1.3. Comparative analysis on ductility

The ductility of SBS asphalt (90#) based on different performance and aging times is shown in Fig. 4. The data regression relationship is shown in Table 9.

The following conclusions can be obtained by comparing the data in Table 9

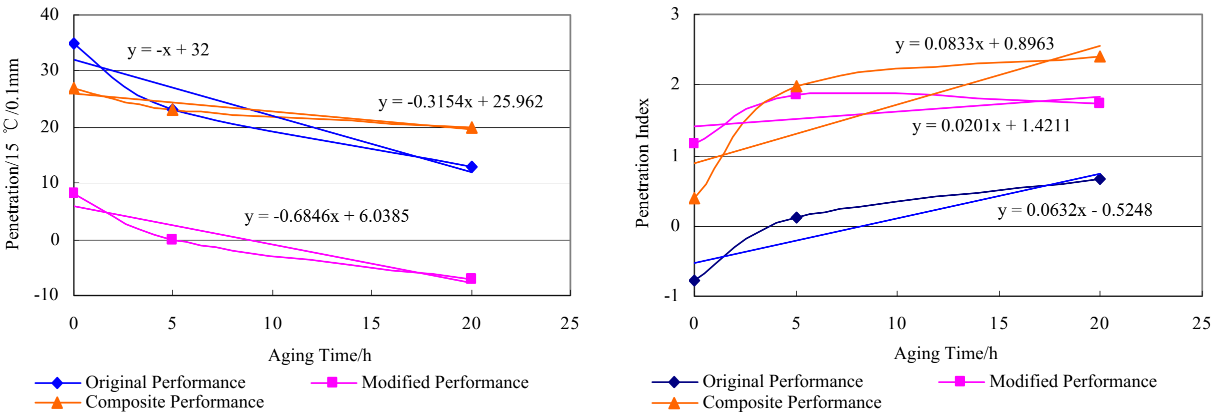
(1) The data shows that the anti-aging durability of ductility at 5 °C based on inherent performance (performance at low temperatures) is better than that of the improved performance. The larger the ductility at 5 °C, the better the performance at low temperatures. The change rate (slope) of the 5 °C inherent ductility of the asphalt is less than that of the modified ductility for the entire aging process, and, with the increase of aging time, both were close to zero.

(2) The data shows that the inherent performance of the ductility at 15 °C varies greatly with the change in the aging time, and its anti-aging durability is worse than the improved performance. The 15 °C inherent ductility of the asphalt is greater than that of the modified ductility at the beginning of the aging. As the aging time increases, it is gradually worse than the modified ductility. However, it is unclear



a) Penetration/25℃

b) Penetration/15℃



c) Penetration/5℃

d) Penetration index

Fig. 3. Relationship between penetration, PI and aging times of 4% SBS asphalt (90#) with different performance.

Table 9
Regression relation of aging test data of SBS asphalt (90#).

Indexes		Inherent performance		Improved performance		Composite performance	
		Regressive equation	Slope	Regressive equation	Slope	Regressive equation	Slope
Penetration	25 °C	y = −2.7923x + 85.269	−2.8	y = −1.4923x + 24.769	−1.5	y = −1.3x + 60.5	−1.3
	15 °C	y = −x + 32	−1.0	y = −0.6846x + 6.0385	−0.7	y = −0.3154x + 25.962	−0.3
	5 °C	y = −0.2923x + 11.769	−0.3	y = −0.2x	−0.2	y = −0.0923x + 11.769	−0.1
PI		y = 0.0632x – 0.5248	0.06	y = 0.0201x + 1.4211	0.02	y = 0.0833x + 0.8963	0.08
Ductility	5 °C	y = −0.4115x + 8.5962	−0.4	y = −1.2477x + 25.531	−1.2	y = −1.6592x + 34.127	−1.7
	15 °C	y = −7.6123x + 158.17	−7.6	y = −4.6754x + 67.062	−4.7	y = −2.8831x + 90.992	−2.9
Softening Point/°C		y = 0.6254x + 46.288	0.6	y = −0.4231x + 26.592	−0.4	y = 0.2023x + 72.881	0.2
Viscosity/135 °C		y = 0.0283x + 0.2918	0.03	y = 0.0548x + 1.5182	0.05	y = 0.0831x + 1.81	0.08

whether 15 °C ductility can represent the performance of the asphalt at low temperatures. It is reasonable to represent the performance at low temperatures by using 5 °C ductility.

(3) To sum up, the anti-aging durability of the ductility based on inherent performance (performance at low temperatures) is better than that of the improved performance. The above conclusions are based on the macro test data, and the next step is further demonstrated by the microscopic mechanism.

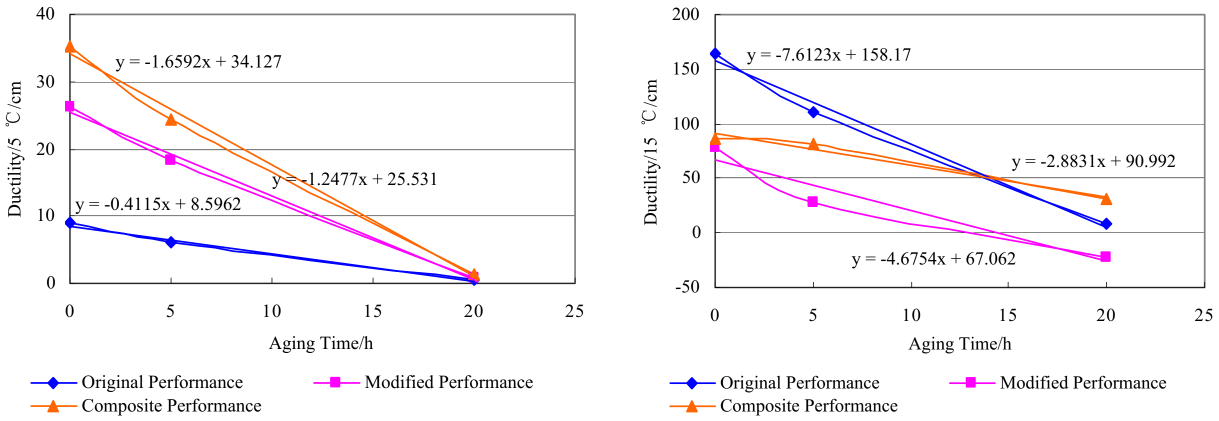
3.1.4. Comparative analysis of the other index (softening point and viscosity)

The softening point and viscosity of SBS asphalt (90#) based on different performance and aging times is shown in Fig. 5. The data regression relationship is shown in Table 9. According to the comparison of the data, the anti-aging durability of the softening point based on the inherent performance of SBS asphalt is worse than that of the improved performance, but the viscosity based on the inherent performance of SBS asphalt at 135 °C is better than that of SBS asphalt.

3.2. Comparative analysis of inherent performance and TPS improved performance

3.2.1. Test data processing

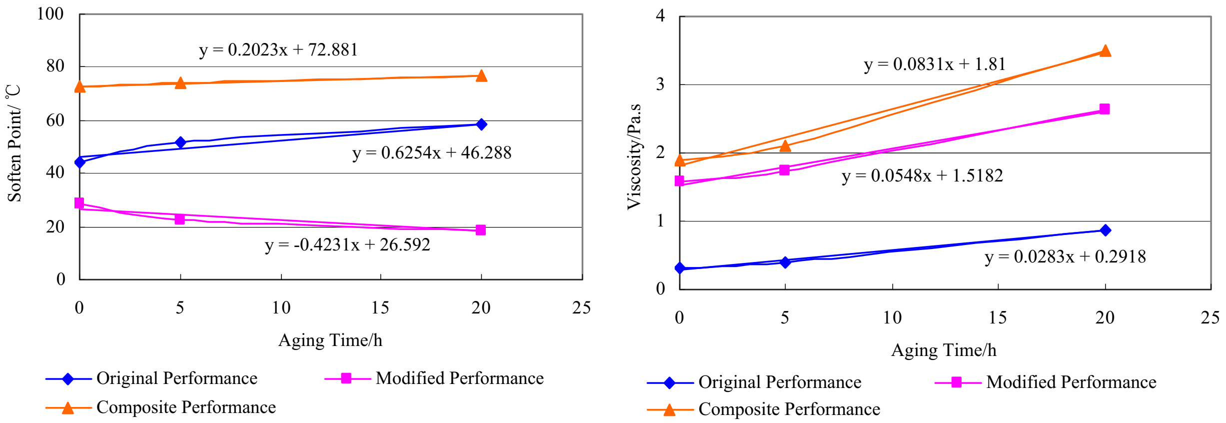
On the basis of the test data (Table 7), the macro test data of the TPS asphalt (90#) was processed. The results of this data processing are shown in Table 10.



a) Ductility 5℃

b) Ductility 15℃

Fig. 4. Relationship between ductility and aging times of 4% SBS asphalt (90#) with different performance.



a) Softening point

b) Viscosity

Fig. 5. Softening point and viscosity of SBS asphalt (90#) based on different performance and aging times.

3.2.2. Comparative analysis on penetration

The penetration and PI of TPS asphalt (90#) based on different performance and aging times are shown in Fig. 6. The data regression relationship is shown in Table 11.

The following conclusions can be drawn by comparing the data in Table 11.

(1) The data of the penetration at the three temperatures shows that the anti-aging durability of penetration based on the inherent performance of the TPS asphalt (performance at high temperatures) is worse than the improved performance, and it shows a similar change of penetration as that of the SBS asphalt. Although at the beginning of aging, the penetration at 15 °C and 25 °C based on inherent performance is bigger than the composite performance, it then drops rapidly and becomes less than that of the composite performance. Therefore, it can be concluded that the anti-aging durability of penetration based on the inherent performance of TPS asphalt is poor.

(2) According to the change of the PI and its liner slope, it can be found that the improved performance of TPS asphalt has weak temperature sensitivity. The penetration based on the inherent performance is worse than that of the improved performance. The same conclusion as (1) can be obtained by directly comparing the liner slope of the penetration based on inherent and improved performance with different aging times.

3.2.3. Comparative analysis on ductility

The ductility of TPS asphalt (90#) based on different performance and aging times is shown in Fig. 7. The data regression relationship is shown in Table 11.

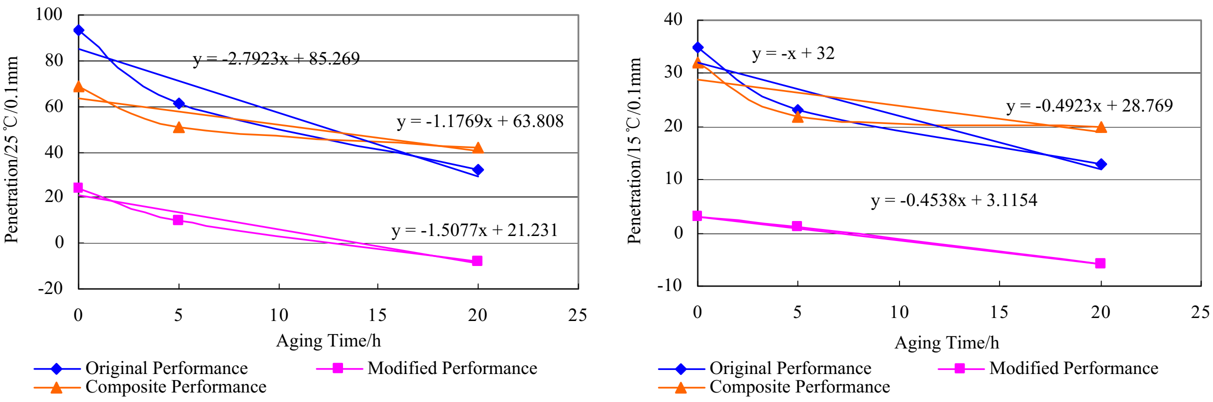
The following conclusions can be drawn by comparing the data in Table 11.

(1) The anti-aging durability of 5 °C ductility (performance at low temperature) of TPS asphalt based on inherent performance is better than that of the improved performance, and it is similar to the change of the ductility of the SBS asphalt at low temperatures. The improved performance of the ductility of TPS asphalt that aged for 20 h is reduced to the inherent performance levels. Although the overall performance of the ductility is obviously modified, according to the decreasing range of aging times, the anti-aging durability of the ductility of the TPS asphalt is poor.

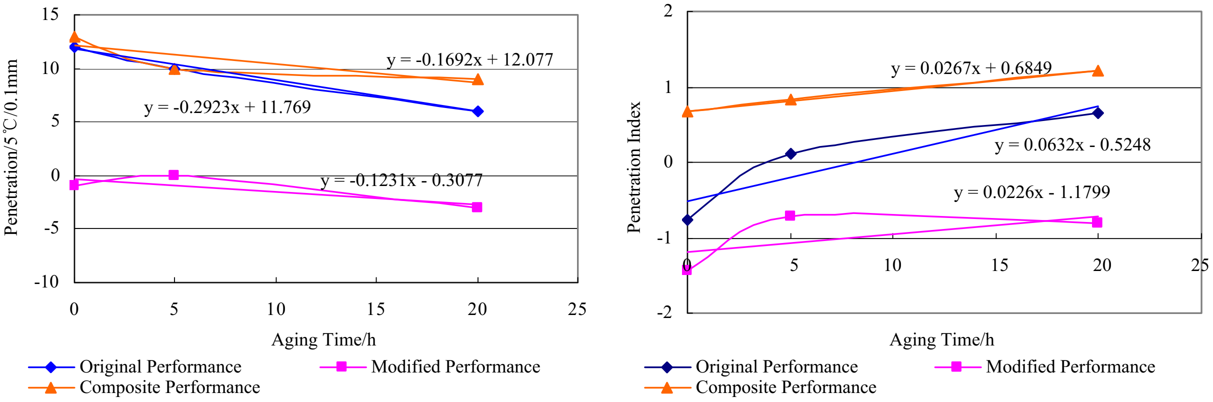
(2) The 15 °C ductility of TPS asphalt also shows the anti-aging durability based on the inherent performance is worse than the improved performance, and it is similar to the change of

Table 10
Test data of inherent performance and improved performance (4% TPS asphalt 90#).

Performance classification	Aging time/h	Penetration			PI	Ductility		Softening point/°C	Viscosity/135 °C
		25 °C	15 °C	5 °C		5 °C	15 °C		
Inherent performance	0	93	35	12	−0.770	9.0	165.0	44.5	0.328
	5	61	23	10	0.118	6.0	111.0	51.8	0.385
	20	32	13	6	0.657	0.5	8.2	58.2	0.870
Improved performance	0	1	−3	−24	1.446	21.0	−70.8	4.3	0.120
	5	0	−1	−10	0.712	17.3	−37.3	0.1	0.075
	20	3	6	8	0.816	−0.1	−2.4	−1.1	−0.029
Composite performance	0	69	32	13	0.676	30.0	94.2	48.8	0.448
	5	51	22	10	0.830	23.3	73.7	51.9	0.460
	20	42	20	9	1.215	0.4	8.4	56.3	0.620



a) Penetration/25℃ b) Penetration/15℃

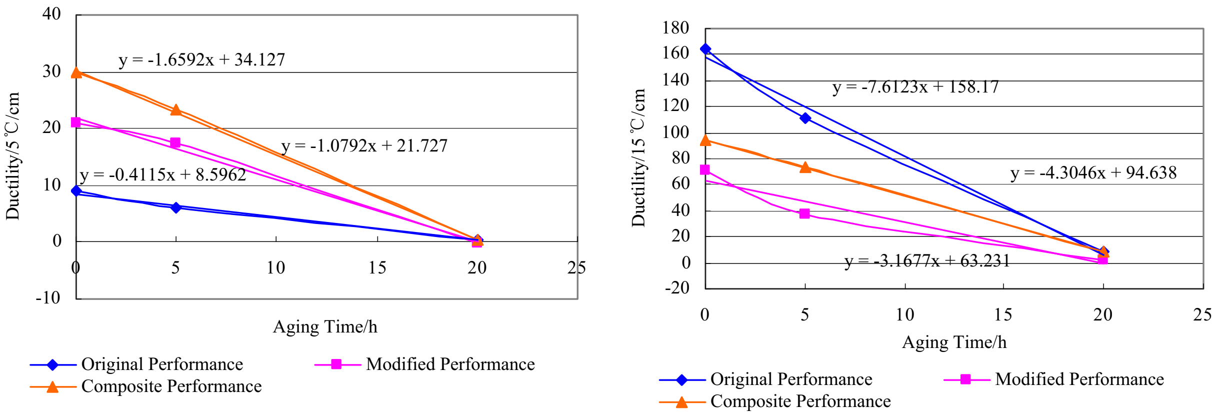


c) Penetration/5℃ d) Penetration index

Fig. 6. Penetration and PI of TPS asphalt (90#) based on different performance and aging times.

Table 11
Regression relation of aging test data of TPS asphalt (90#).

Indexes		Inherent performance		Improved performance		Composite performance	
		Regressive equation	Slope	Regressive equation	Slope	Regressive equation	Slope
Penetration	25 °C	y = −2.7923x + 85.269	−2.7	y = −1.5077 + 21.231	−1.5	y = −1.1769x + 63.808	−1.2
	15 °C	y = −x + 32	−1.0	y = −0.4538x + 3.1154	−0.5	y = −0.4923x + 28.769	−0.5
	5 °C	y = −0.2923x + 11.769	−0.3	y = −0.1231x − 0.3077	−0.1	y = −0.1692x + 12.077	−0.2
PI		y = 0.0632x − 0.5248	0.05	y = 0.0226x − 1.1799	0.02	y = 0.0267x + 0.6849	0.03
Ductility	5 °C	y = −0.4115x + 8.5962	−0.4	y = −1.0792x + 21.727	−1.1	y = −1.6592x + 34.127	−1.6
	15 °C	y = −7.6123x + 157.87	−7.6	y = −3.1677x + 63.231	−3.2	y = −4.3046x + 94.638	−4.3
Softening Point/°C		y = 0.5823x + 46.38	0.6	y = 0.2262x − 2.984	0.2	y = −0.3562x + 49.36	0.4
Viscosity/135 °C		y = 0.0164x + 0.3173	0.03	y = 0.0073x − 0.1164	0.007	y = 0.0091x + 0.4337	0.009



a) Ductility 5℃

b) Ductility 15℃

Fig. 7. Ductility of TPS asphalt (90#) based on different performance and aging times.

the SBS asphalt ductility at low temperatures. It is further verified that 5 °C ductility is reasonable to represent the performance of the asphalt at low temperatures.

3.2.4. Comparative analysis of other indexes (softening point, viscosity)

The softening point and viscosity of TPS asphalt (90#) based on different performance and aging times is shown in Fig. 8. The data regression relationship is shown in Table 11. According to the changing amplitude (slope) of the curve, both the softening point and the 135 °C viscosity of TPS asphalt based on the inherent performance are worse than that of the improved performance. It is considered that the softening point and 135 °C viscosity can be the evaluation indexes for judging the anti-aging durability at high temperatures of the asphalt. Therefore, from the comparison of SBS asphalt and TPS asphalt, it can be preliminarily concluded that the inherent performance of the modified asphalt is better than that of the improved performance. However, the anti-aging durability based on the inherent performance at high temperatures is worse than that of the improved performance.

3.3. Comparative analysis of inherent performance and rubber improved performance

3.3.1. Test data processing

On the basis of the test data (Table 7), the macro test data of the rubber asphalt (90#) is processed. The data processing results are shown in Table 12.

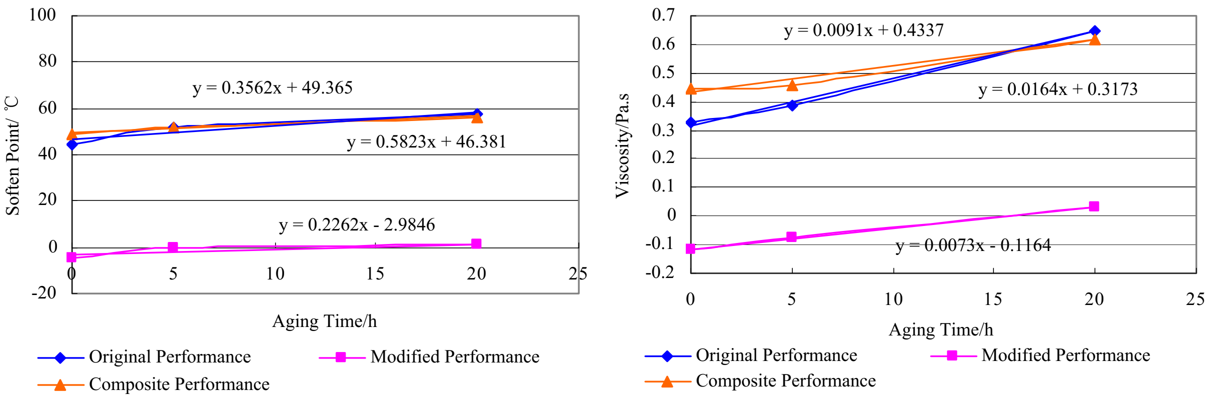
3.3.2. Comparative analysis on penetration

The penetration and PI of rubber asphalt (90#) based on different performance and aging times is shown in Fig. 9. The data regression relationship is shown in Table 13.

The following conclusions can be obtained by comparing the data in Table 13.

(1) The data of the asphalt penetration shows that the penetration based on the improved performance of rubber asphalt is better than that of the inherent performance. This basically conforms to the previous experimental conclusions. However, it can be found that the linear relation slope of the penetration at 25 °C and 15 °C of rubber asphalt based on the inherent performance and improved performance are very close. According to the actual change curve (the dotted line), it can be seen that the improved performance of rubber asphalt in the short-term aging stage is obviously larger, and then gradually slows down; its decline rate is less than the inherent performance. The 5 °C penetration of rubber asphalt shows a better anti-aging durability based on the inherent performance than that of the improved performance. In addition, the composite performance of the penetration of rubber asphalt first increases and then decreases with the increasing of the aging time.

(2) The analysis of PI shows that the penetration of rubber asphalt based on improved performance has little temperature sensitivity, but the change rate of PI is faster. Therefore, according to the analysis of PI, it can be concluded that the



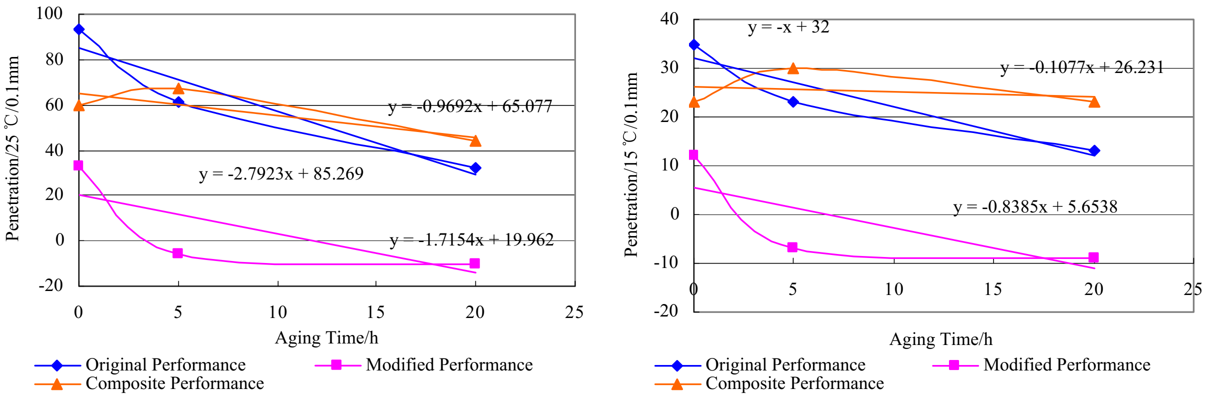
a) Softening point

b) Viscosity

Fig. 8. Softening point and viscosity of TPS asphalt (90#) based on different performance and aging times.

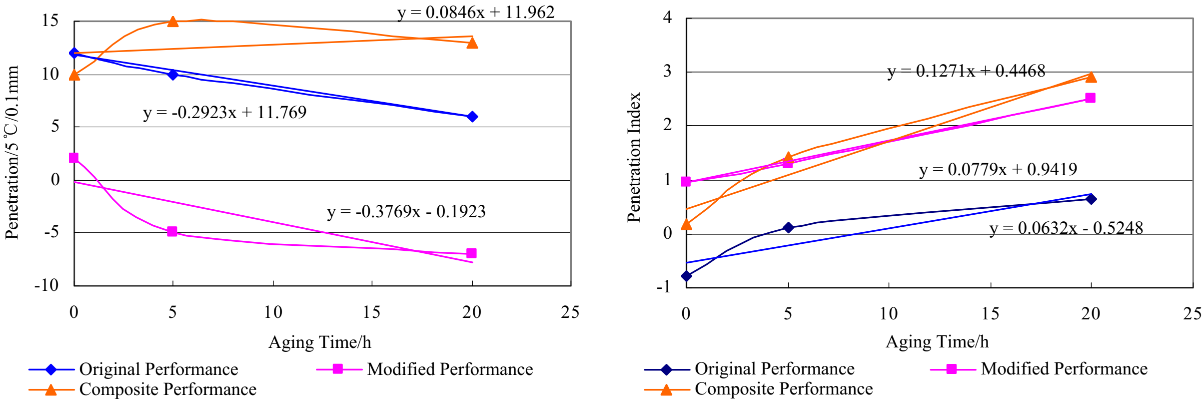
Table 12
Test data of inherent performance and improved performance (16% rubber asphalt 90#).

Performance classification	Aging time/h	Penetration			PI	Ductility		Softening point/°C	Viscosity/135 °C
		25 °C	15 °C	5 °C		5 °C	15 °C		
Inherent performance	0	93	35	12	−0.770	9.0	165.0	44.5	0.328
	5	61	23	10	0.118	6.0	111.0	51.8	0.385
	20	32	13	6	0.657	0.5	8.2	58.2	0.870
Improved performance	0	−2	−12	−33	0.957	−0.4	−146.7	15.1	1.255
	5	5	7	6	1.311	7.8	−89.1	9.6	3.665
	20	7	9	10	2.504	8.7	7.8	6.9	4.901
Composite performance	0	60	23	10	0.187	8.6	18.3	59.6	1.583
	5	67	30	15	1.429	13.8	21.9	61.4	4.050
	20	44	23	13	2.903	8.6	18.6	64.3	5.550



a) Penetration/25℃

b) Penetration/15℃



c) Penetration/5℃

d) Penetration index

Fig. 9. Penetration and PI of rubber asphalt (90#) based on different performance and aging times.

Table 13
Aging test data regression relationship of rubber asphalt (90#).

Indexes		Inherent performance		Improved performance		Composite performance	
		Regressive equation	Slope	Regressive equation	Slope	Regressive equation	Slope
Penetration	25 °C	y = −2.7923x + 85.269	−2.7	y = −1.7154x + 19.962	−1.5	y = −0.9692x + 65.077	−1.2
	15 °C	y = −x + 32	−1.0	y = −0.8385x + 5.6538	−0.5	y = −0.1077x + 26.231	−0.5
	5 °C	y = −0.2923x + 11.769	−0.3	y = −0.3769x − 0.1923	−0.1	y = 0.0846x + 11.962	−0.2
PI		y = 0.0632x − 0.5248	0.05	y = 0.0779x + 0.9419	0.02	y = 0.1271x + 0.4468	0.03
Ductility	5 °C	y = −0.4115x + 8.5962	−0.4	y = −0.3638x − 2.3346	−1.1	y = −0.08x + 11	−1.6
	15 °C	y = −7.6123x + 157.87	−7.6	y = −7.4331x + 137.94	−3.2	y = −0.0392x + 19.927	−4.3
Softening Point/°C		y = 0.5823x + 46.38	0.6	y = 0.3569x − 13.508	0.4	y = −0.2254x + 59.888	0.2
Viscosity/135 °C		y = 0.0164x + 0.3173	0.03	y = 0.1592x + 1.946	0.16	y = 0.1757x + 2.263	0.18

anti-aging durability of rubber asphalt based on the inherent performance is better than that of the improved performance. This also illustrates the particularity of rubber asphalt.

3.3.3. Comparative analysis on ductility

The ductility of rubber asphalt (90#) based on different performance and aging times is shown in Fig. 10. The data regression relationship is shown in Table 13.

The following conclusions can be drawn by comparing the data in Table 13.

(1) The data of the 5 °C ductility of rubber asphalt shows that its anti-aging durability based on the improved performance changes greatly, mainly in the short-term aging stage. If considering the effect of the best storage time (7 h) for this material, it can be seen that the change rate of the 5 °C ductility of the improved performance of rubber asphalt is smaller than that of the inherent performance. This is contrary to the previous research conclusions.

(2) The data of the 15 °C ductility of rubber asphalt shows that its anti-aging durability based on the inherent performance is basically the same as that of the improved performance. The particularity of rubber asphalt is further explained.

3.3.4. Comparative analysis of other indexes (softening point, viscosity)

The softening point and viscosity of rubber asphalt (90#) based on different performance and aging times are shown in Fig. 11. The data regression relationship is shown in Table 13. According to the changing amplitude (slope) of the curve, the anti-aging durability of the softening point of rubber asphalt based on the inherent performance is worse than that of the improved performance. However, the anti-aging durability of the 135 °C viscosity of rubber asphalt based on the inherent performance is better than that of the improved performance.

In summary, the resulting consistency of rubber asphalt and SBS/TPS asphalt is not the same. A further study of rubber asphalt is suggested.

3.4. Comparative analysis of inherent performance and Sasobit improved performance

3.4.1. Test data processing

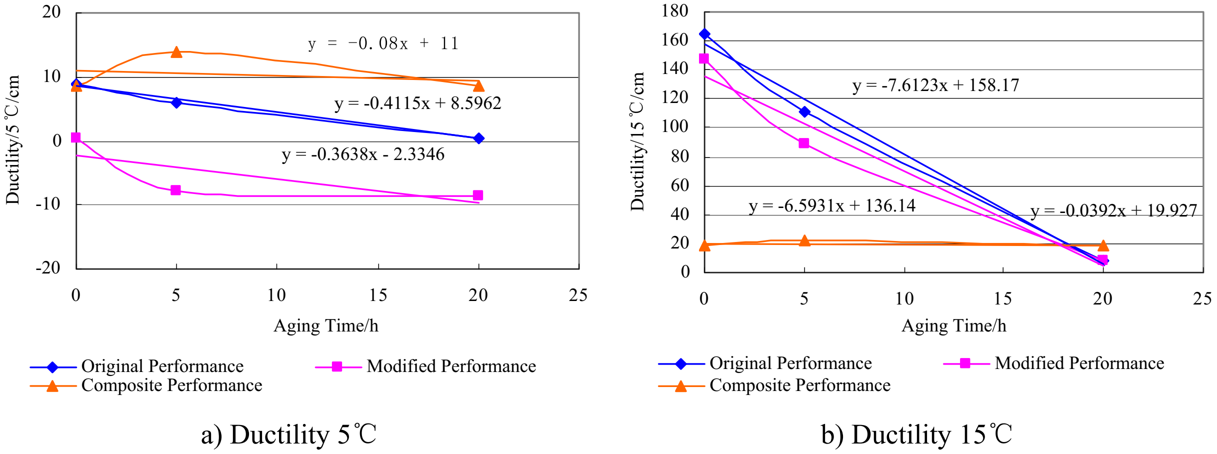
On the basis of the test data (Table 7), the macro test data of Sasobit asphalt (90#) was processed. The data processing results are shown in Table 14.

3.4.2. Comparative analysis of penetration

The penetration and PI of Sasobit asphalt (90#) based on different performance and aging times is shown in Fig. 12. The data regression relationship is shown in Table 15.

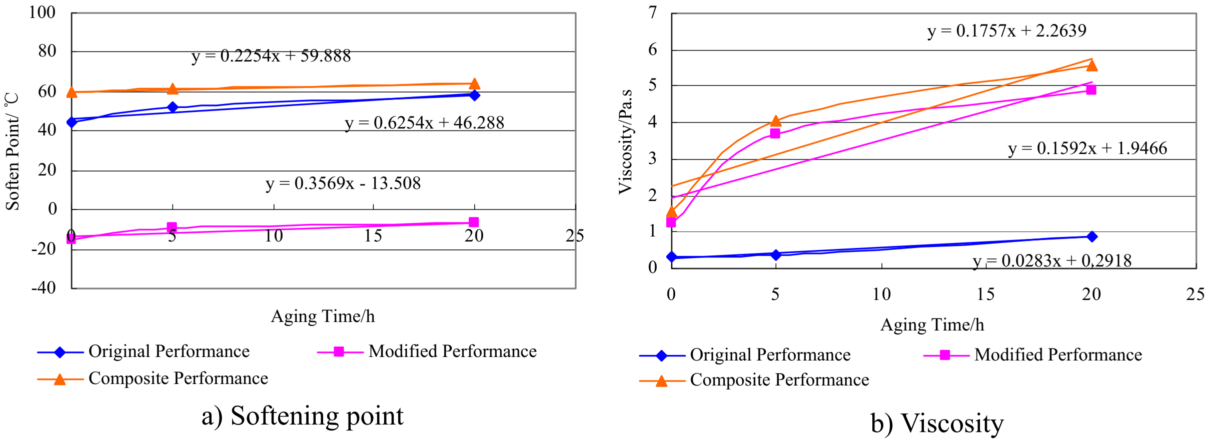
The following conclusions can be drawn by comparing the data in Table 15.

(1) The data of penetration of Sasobit asphalt at three different temperatures shows that the changing rate of its penetration



a) Ductility 5℃ b) Ductility 15℃

Fig. 10. Ductility of rubber asphalt (90#) based on different performance and aging times.

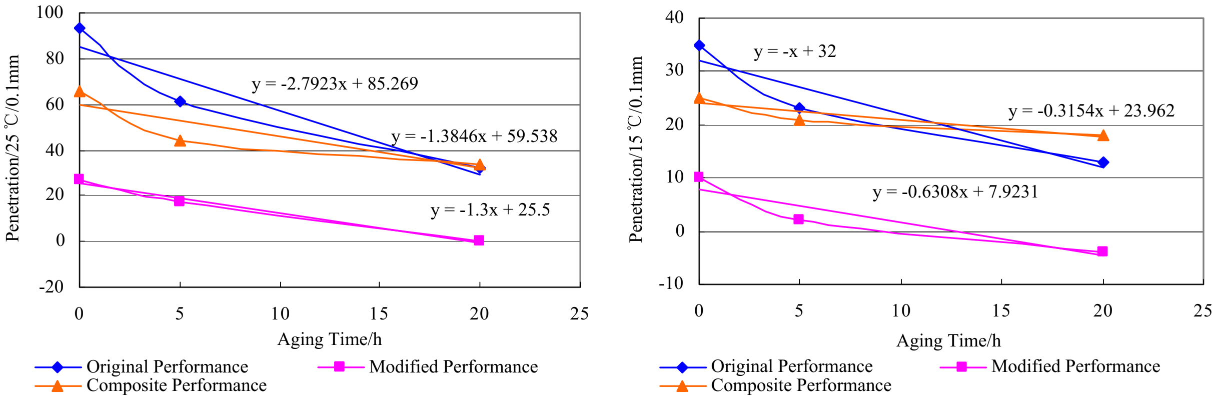


a) Softening point b) Viscosity

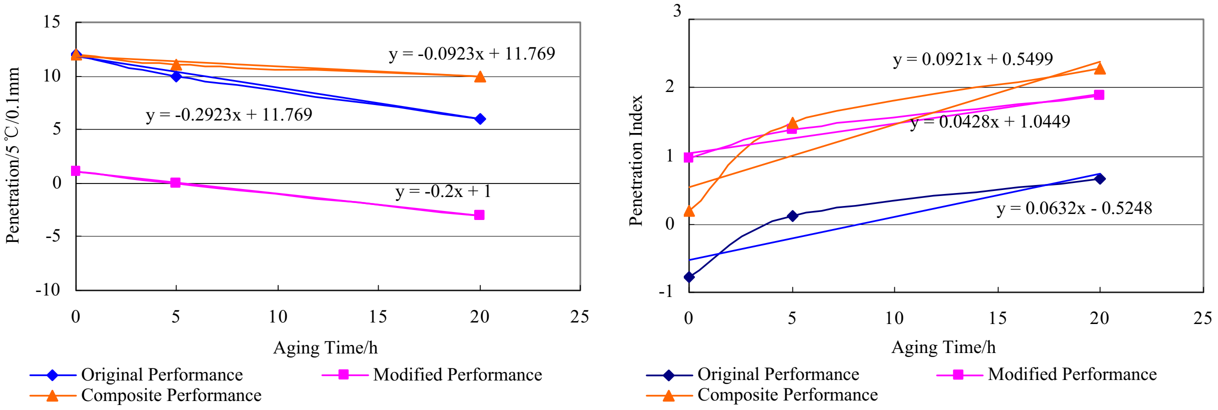
Fig. 11. Softening point and viscosity of rubber asphalt (90#) based on different performance and aging times.

Table14
Test data of inherent performance and improved performance (2% Sasobit asphalt 90#).

Performance classification	Aging time/h	Penetration			PI	Ductility		Softening point/°C	Viscosity/135 °C
		25 °C	15 °C	5 °C		5 °C	15 °C		
Inherent performance	0	93	35	12	−0.770	9.0	165.0	44.5	0.328
	5	61	23	10	0.118	6.0	111.0	51.8	0.385
	20	32	13	6	0.657	0.5	8.2	58.2	0.870
Improved performance	0	−1	−10	−27	0.957	−5.5	−28.5	14.4	−0.04
	5	0	−2	−17	1.376	−2.9	−66.9	7.9	−0.067
	20	3	4	0	1.871	0	−3.8	9.1	−0.037
Composite performance	0	66	25	11	0.187	3.5	136.5	58.9	0.288
	5	44	21	10	1.494	3.1	44.1	59.7	0.318
	20	34	18	9	2.270	0.5	7.0	66.5	0.612



a) Penetration/25℃ b) Penetration/15℃



c) Penetration/5℃ d) Penetration index

Fig. 12. Penetration and PI of Sasobit asphalt (90#) based on different performance and aging times.

based on the inherent performance is rapid, and its anti-aging durability is worse than that of the improved performance. According to the actual relation curve, it can be seen that the short-term aging of Sasobit asphalt has significant influence on its inherent performance.

(2) The data of PI of Sasobit asphalt shows that its anti-aging durability based on the inherent performance is worse than that of the improved performance. According to the actual relation curve, the improved performance of the penetration of Sasobit asphalt has low temperature sensitivity, and the overall change is relatively stable. The inherent performance changes greatly, especially in the short-term aging stage.

3.4.3. Comparative analysis on ductility

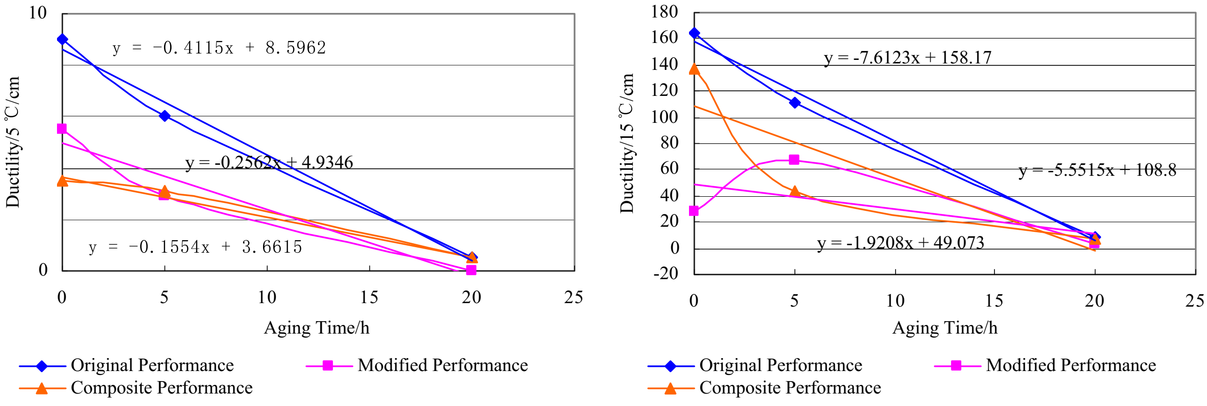
The ductility of Sasobit asphalt (90#) based on different performance and aging times is shown in Fig. 13. The data regression relationship is shown in Table 15.

The following conclusions can be obtained by comparing the data in Table 15.

(1) The data of the 5 °C ductility shows that the anti-aging durability of Sasobit asphalt based on the inherent performance is worse than that of the improved performance. This is contrary to the previous conclusions of studies of other modified asphalt. The possible reason is that the organic wax type of

Table 15
Aging test data regression relationship of Sasobit asphalt (90#).

Indexes		Inherent performance		Improved performance		Composite performance	
		Regressive equation	Slope	Regressive equation	Slope	Regressive equation	Slope
Penetration	25 °C	y = −2.7923x + 85.269	−2.7	y = −1.3x + 25.5	−1.3	y = −1.3846x + 59.538	−1.4
	15 °C	y = −x + 32	−1.0	y = −0.6308x + 7.9231	−0.5	y = −0.3154x + 23.962	−0.5
	5 °C	y = −0.2923x + 11.769	−0.3	y = −0.2x + 1	−0.1	y = −0.0923x + 10.769	−0.2
PI		y = 0.0632x − 0.5248	0.05	y = 0.0428x + 1.0449	0.02	y = 0.0921x + 0.5499	0.03
Ductility	5 °C	y = −0.4115x + 8.5962	−0.4	y = −0.2562x + 4.9346	−1.1	y = −0.1554x + 3.6615	−1.6
	15 °C	y = −7.6123x + 157.87	−7.6	y = −1.9208x + 49.073	−3.2	y = −5.5515x + 108.8	−4.3
Softening Point/°C		y = 0.5823x + 46.38	0.6	y = 0.1854x − 120.12	0.19	y = 0.3969x + 58.392	0.4
Viscosity/135 °C		y = 0.0164x + 0.3173	0.03	y = 0.0006x − 0.0528	0.001	y = 0.017x + 0.2645	0.017



a) Ductility 5℃

b) Ductility 15℃

Fig. 13. Ductility of Sasobit asphalt (90#) based on different performance and aging times.

the Sasobit modifier is easily crystallized at low temperatures, and this makes the asphalt brittle and hard. After adding the Sasobit modifier to virgin asphalt, its performance at low temperatures (5 °C ductility) decreased. Therefore, the inherent value of the 5 °C ductility is further reduced, and brittleness easily occurs after the material is aged for a period of time, and at that point, the ductility test will inevitably have large errors.

(2) The data of the 15 °C ductility shows that the anti-aging durability of Sasobit asphalt based on the inherent performance is worse than that of the improved performance. But this is only a conclusion based on the slope of the linear relationship. In fact, the linear relationship is poorly correlated. From the actual change curve, it can be seen that 15 °C ductility based on improved performance changes significantly in the stage of short-term aging, and it is basically the same as the changing rate of the inherent performance with the increase in aging time. The result shows that the anti-aging durability of the ductility of Sasobit asphalt based on the inherent performance is better than that of the improved performance. This also proves that it is uncertain whether 15 °C ductility can represent the performance at low temperatures.

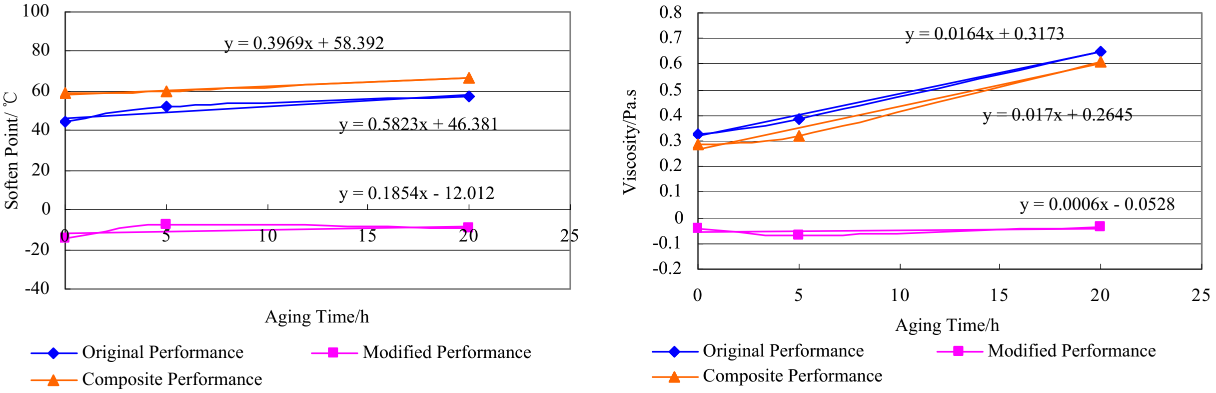
3.4.4. Comparative analysis of other indexes (softening point, viscosity)

The softening point and viscosity of Sasobit asphalt (90#) based on different performance and aging times is shown in Fig. 14. The data regression relationship is shown in Table 15. According to the changing amplitude (slope) of the curve, which is different from other modified asphalt, the Sasobit modifier can effectively reduce the 135 °C viscosity of asphalt, and the overall trend of its inherent performance and composite performance are very similar; however, the changing rate of the improved performance is less than that of the inherent performance. Therefore, the anti-aging durability of the softening point and the 135 °C viscosity of Sasobit asphalt based on the improved performance is better than that of the inherent performance

4. Microscopic mechanism demonstration of asphalt’s inherent and improved performance

Four components of the asphalt were tested for the above modified asphalt (Fig. 15), and the four component test data of 5 different asphalt specimens with different aging times was obtained (Table 16). The saturated and aromatic components are the soft components of the asphalt, which have a great influence on the penetration of the asphalt. Colloid and asphaltene are the hard components of the asphalt. Colloid plays a major role in gum dissolution, and it has a significant influence on the ductility of asphalt. Asphaltene mainly increases the consistency of the soft components. The four components form the colloid structure of the asphalt according to the proportion of the different components.

To analysis the change regulation of components of different modified asphalt in the process of aging, at the same time, the anti-aging durability based on inherent performance and improved performance of different modified asphalt specimens were analyzed by using the change of the asphaltic colloidal instability index Ic (Ic = (S + As)/(R + Ar)) as indexes (Table 17).



a) Softening point b) Viscosity

Fig. 14. Softening point and viscosity of Sasobit asphalt (90#) based on different performance and aging times.

a) Solvent recovery unit b) Four components of asphalt

Fig. 15. Separation of four components of asphalt.

Table16
Determination of four components of different asphalt specimens.

Asphalt	Aging time/h	S/%	Ar/%	R/%	As/%
Virgin asphalt (90#)	0	30.89	36.47	16.97	7.58
	5	29.79	35.87	14.33	11.38
	20	28.21	33.42	11.93	17.87
4%SBS asphalt	0	12.34	37.93	33.13	10.05
	5	11.72	35.33	31.25	14.1
	20	11.06	29.21	27.28	22.5
4%TPS asphalt	0	16.05	33.23	32.84	11.22
	5	15.82	29.67	31.54	16.14
	20	14.76	25.71	28.23	22.36
16% Rubber asphalt	0	25.63	35.97	25.79	9.82
	5	23.14	28.59	25.61	13.94
	20	20.15	24.98	24.76	19.72
2%Sasobit asphalt	0	27.11	32.78	23.27	8.89
	5	26.59	31.89	22.45	13.65
	20	24.48	27.97	20.86	19.23

Note: S, Ar, R, As – stand for saturation, aromatic, colloid and asphaltene.

4.1. Results and analysis of the SBS asphalt test

The experimental data of SBS asphalt (90#) was processed, and the colloidal instability index Ic of SBS asphalt (90#) with different aging times was obtained (Table 18 and Fig. 16). The change of the colloidal instability index reflects the anti-aging durability of asphalt in a microcosmic aspect. The greater the change of the colloid instability index is, the worse the anti-aging durability of the asphalt. It can be seen that with the increase in the aging time, the change rate of the Lc of the improved performance of the SBS asphalt is less than that of the inherent performance. This shows that the improved performance of the anti-aging durability of SBS asphalt is better than that of the inherent performance.

4.2. Results and analysis of the TPS asphalt test

The Ic of the TPS asphalt with different aging times is shown in Table 19 and Fig. 17. It can be seen that the Ic changing rate of the

Table 17
Relationship between Ic and aging time of different asphalt specimens.

Asphalt	Aging time/h		
	0	5	20
	Ic		
Virgin asphalt (90#)	0.72	0.82	1.04
4%SBS asphalt	0.32	0.39	0.59
4%TPS asphalt	0.41	0.52	0.68
16% Rubber asphalt	0.57	0.68	0.80
2%Sasobit asphalt	0.64	0.72	0.90

Table 18
Test data on colloidal instability index of SBS asphalt (90#).

Performance classification	Aging time/h		
	0	5	20
Inherent performance	0.72	0.82	1.04
Improved performance	−0.4	−0.43	−0.45
Composite performance	0.32	0.39	0.59

improved performance of the TPS asphalt is less than that of the improved performance. This shows that the improved performance of the anti-aging durability of the TPS asphalt is better than that of the inherent performance.

4.3. Results and analysis of the rubber asphalt test

The Ic variation of rubber asphalt with different aging times is shown in Table 20 and Fig. 18. It can be seen that in the changing of the colloid instability coefficient, the improved performance of rubber asphalt is less than that of the inherent performance. This shows that the anti-aging durability of rubber asphalt based on improved performance is better than that of the inherent performance.

4.4. Results and analysis of the Sasobit asphalt test

The Ic variation of Sasobit asphalt with different aging times is shown in Table 21 and Fig. 19. It can be seen that the changing rate Ic of the improved performance of Sasobit asphalt is less than that of the inherent performance, which shows that the anti-aging durability of Sasobit asphalt is based on improved performance and is better than that of inherent performance.

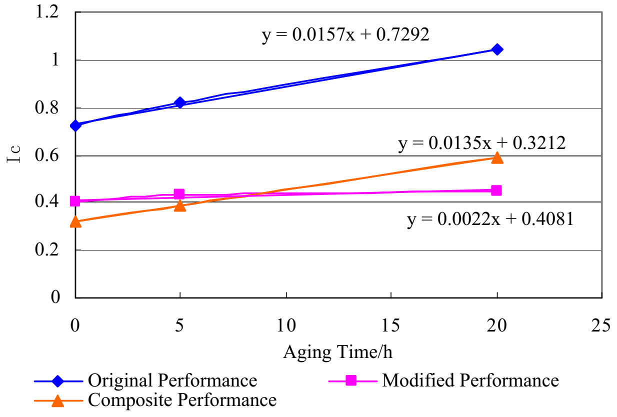


Fig. 16. Ic of SBS asphalt (90#) based on different performance and aging times.

Table 19
Test data on colloidal instability index of TPS asphalt (90#).

Performance classification	Aging time/h		
	0	5	20
Inherent performance	0.72	0.82	1.04
Improved performance	−0.31	−0.3	−0.36
Composite performance	0.41	0.52	0.68

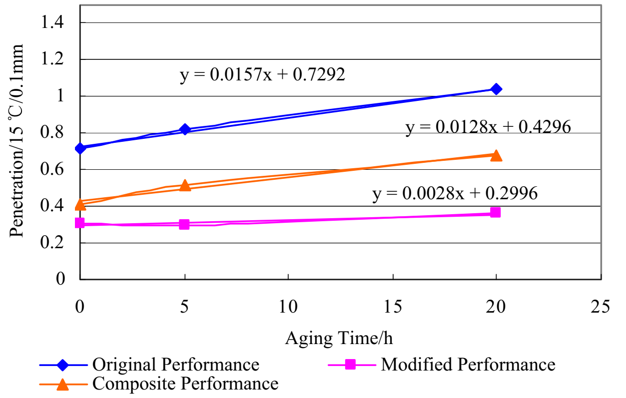


Fig. 17. Ic of different TPS asphalt (90#) based on different performance and aging times.

Table 20
Test data on colloidal instability index of rubber asphalt (90#).

Performance classification	Aging time/h		
	0	5	20
Inherent performance	0.72	0.82	1.04
Improved performance	−0.15	−0.14	−0.24
Composite performance	0.57	0.68	0.80

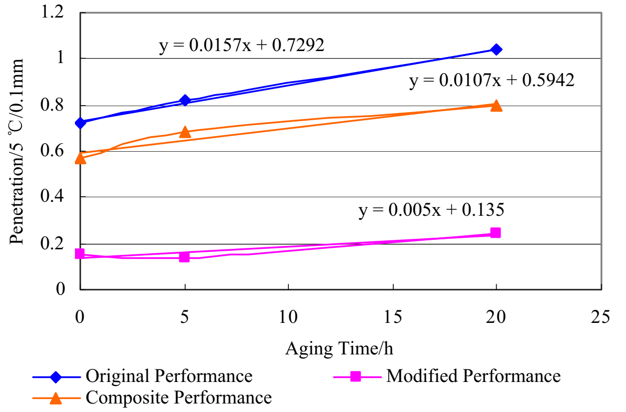


Fig. 18. Ic of different rubber asphalt (90#) specimens based on different performance and aging times.

5. Conclusions

(1) Through comparative analysis of the anti-aging durability of different modified asphalt specimens based on inherent performance and improved performance, the following conclusions can be obtained: for SBS and TPS modified asphalt, taking penetration (performance at high temperatures) and 5 °C ductility (performance at low temperatures) as indexes, the anti-aging durability of the penetration based on the inherent performance is less than that of the improved performance. The anti-aging durability of 5 °C ductility based on inherent performance is better than that of improved performance. This indicates that the improved high temperature durability of SBS and TPS modified asphalt is better than that

Table 21
Experimental data on colloidal instability index of Sasobit asphalt (90#).

Performance classification	Aging time/h		
	0	5	20
Inherent performance	0.72	0.82	1.04
Improved performance	−0.08	−0.1	−0.14
Composite performance	0.64	0.72	0.90

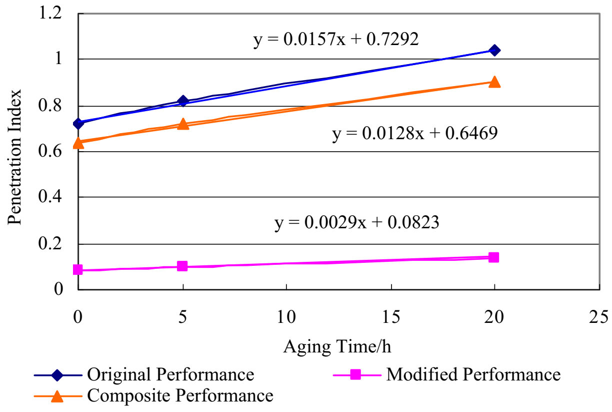


Fig. 19. Ic of Sasobit asphalt (90#) with different aging times.

of the improved low temperature durability. These two kinds of modified asphalt are suitable for paving pavement in high temperature climate areas.

(2) The improved performance and inherent performance of rubber modified asphalt were analyzed. The inherent performance of the needle penetration (high temperature performance) is better than that of the improved performance, but the inherent performance durability of 5 °C ductility (low temperature performance) is worse than that of the improved performance. The results were contrary to the results of the SBS and TPS modified asphalt. This suggests that the particularity of rubber modified asphalt is a factor. It also indicates that rubber modified asphalt has a significant ability to improve low temperature durability and is suitable for pavement construction in cold areas. For Sasobit asphalt, the improved performance of the needle penetration (high temperature performance) and 5 °C ductility (low temperature performance) is better than that of the inherent performance. This indicates that Sasobit asphalt is balanced in improving high and low temperature capacity.

(3) The macroscopic analysis results of four modified asphalt specimens were demonstrated by four components of the modified asphalt. The results show that the microstructure of inherent performance is more easily affected by aging than that of improved performance. The overall performance of different modified asphalt specimens based on improved performance is better than that of inherent performance.

(4) The comparison between durability based on the inherent performance of modified asphalt versus durability based on improved performance shows that even different modified asphalt specimens can improve the high and low temperature performance of asphalt, and that the modifier does not have the same ability to improve high and low temperature performance due to the different durabilities based on inherent performance and improved performance. The findings have a certain technical reference value for further scientific research of modified asphalt that may help identify a selection of modified asphalt suitable for use in construction, and that may help to develop new modifiers.

6. Conflict of interest

The authors claim no conflicts of interest.

Acknowledgments

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