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Study on the performance and aging low temperature performance of GO / SBS modified asphalt

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ABSTRACT

Graphene oxide (GO) has attracted more and more attention in asphalt pavement due to its excellent performance. However, most current research is limited to GO modified base asphalt, and the modification effect is insignificant. In this paper, GO / SBS-modified asphalt was prepared by high-speed shearing. The effects of GO on the physical properties, storage stability, low-temperature performance, and aging resistance of SBS-modified asphalt were studied. A low-temperature beam bending test analyzed the low-temperature performance of GO / SBS composite modified asphalt mixture before and after aging. The results show that adding GO improves SBS-modified asphalt's high-temperature performance, aging resistance, and storage stability. When the content of GO is 0.75%, the physical properties of modified asphalt are the best. The low-temperature rheological properties of modified asphalt with GO before aging are slightly lower than those of SBS-modified asphalt. However, adding GO improves the low-temperature rheological properties of GO/SBS modified asphalt after aging. GO-modified asphalt slightly improves the low-temperature toughness of the mixture under non-aging and short-term aging. However, it still makes the mixture maintain good low-temperature performance under long-term aging. GO / SBS modified asphalt mixture has excellent low-temperature crack resistance before and after aging, and GO / SBS composite modified asphalt can effectively alleviate the damaging effect of aging on the low-temperature crack resistance of asphalt mixture and prolong the service life of the pavement.

Keywords: Pavement engineering; GO; Modified asphalt; Low temperature performance; Aging performance.

1. INTRODUCTION

Asphalt pavement is prone to fatigue cracking, rutting, and other pavement diseases due to its material and structural composition, reducing its service life. Adding a modifier is the most effective way to improve the performance of the asphalt mixture. Various performance indexes of polymer-modified asphalt, rubber asphalt, and emulsified-modified asphalt have been studied in the laboratory [1]. Among them, SBS-modified asphalt has shown great potential in meeting the needs of the pavement industry. However, some problems with the pavement use of SBS-modified asphalt exist [2, 3]. For example, under the repeated action of heavy traffic load and harsh climatic conditions, the performance of SBS-modified asphalt pavement has yet to be further improved, and the modification method is relatively simple. The pavement is prone to early damage and performance degradation and cannot even meet the highway's technical requirements.

In recent years, with the development of nanotechnology, some researchers introduced nanomaterials to solve the problems of polymer modified asphalt, such as using nanomaterials with small sizes and unique physical and chemical properties [4], which effectively improving the compatibility of polymers [5]. Because of these unique effects, more and more nanoparticles are used to improve the performance of asphalt materials [6]. Among them, the most widely used experimental and analytical research is graphene series materials, which have also been used to improve the performance of polymers [7, 8]. However, graphene is limited by existing production technologies and relatively high prices and is unsuitable for large-scale production and large-volume applications. GO is the precursor of graphene, which is convenient for mass production, has a low price, and inherits many beneficial characteristics of graphene.

Due to its high potential energy barrier, a variety of gases (such as He, O2, CO2, etc.) will be shielded by GO, which can inhibit the aging and crack resistance of polymers, and is very suitable for the modification of typical viscoelastic polymer compounds such as asphalt [9, 10]. In addition, the surface of GO contains many polar oxygen-containing groups, such as a carboxyl group, hydroxyl group, epoxy group, and an ester

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group, which makes it have highly active sites and easy to be compounded by the polymer matrix. It has been widely used as a polymer reinforcing material [11] to improve the high-temperature mechanical properties and aging resistance of the material [12]. However, there are few studies on the low-temperature performance of GO-modified polymer, especially the low-temperature performance after aging. The commonly used SBS-modified asphalt has excellent low-temperature performance [13, 14].

Based on this, it can be considered to use GO and SBS together for asphalt modification. The two-dimensional nano-sheet structure GO runs through the micron-scale chain SBS, which can form a dense and stable spatial structure and be embedded in the asphalt system to improve the low-temperature performance of asphalt to improve the comprehensive technical performance of asphalt binder [15, 16]. In this study, GO content's effect on composite-modified asphalt's performance was investigated by testing the physical properties of GO / SBS-modified asphalt. The low-temperature performance and low-temperature performance of GO / SBS composite modified asphalt were investigated by force ductility test and bending rheometer test. The beam bending test studied the low-temperature performance of GO / SBS composite-modified asphalt mixture before and after aging.

2. MATERIALS AND METHODS

2.1. Materials

This paper uses AH-70 # matrix asphalt as the matrix asphalt, and the technical indicators are shown in Table 1. SBS-modified asphalt is prepared in the laboratory based on matrix asphalt, that is, by adding 5.0% SBS modifier to AH-70 # matrix asphalt, and the technical indexes are shown in Table 2. Among them, benzene SBS-T6302 linear styrene-butadiene copolymer was used as the preparation modifier. The graphene oxide powder prepared by the Guoheng Technology Co., Ltd. chemical method was selected as the GO. It has high purity, a small lamellar diameter, and high content of oxygen-containing functional groups in its structure. The technical indicators are shown in Table 3.

2.2. Preparation of GO / SBS modified asphalt

In order to make GO uniformly dispersed in asphalt, the test materials used in this study were prepared by the laboratory preparation molding method, and GO / SBS-modified asphalt was prepared by the high-speed shear method. The preparation steps are as follows.

Firstly, the matrix / modified asphalt was heated to 145 °C for 2 h in a metal container to remove the moisture in the asphalt. Then GO with mass fractions of 0.25%, 0.5%, 0.75%, and 1.0% (mass ratio of GO to matrix asphalt) was added to the metal container, and the high-speed shearing machine was opened and sheared

Table 1: AH-70 # base asphalt basic performance technical indicators.

TESTING ITEMS	BASE ASPHALT	TECHNICAL REQUIREMENTS
(25 °C, 100g, 5s) Penetration (0.1 mm)	66.9	60~80
Softening point (°C)	49.1	≥44
(5cm · min^{-1}, 10 °C) Ductility (cm)	25.0	≥10
60 °C dynamic viscosity (Pa · s)	198	≥180

Table 2: SBS modified asphalt basic performance technical indicators.

TESTING ITEMS	SBS MODIFIED ASPHALT	TECHNICAL REQUIREMENTS
(25 °C, 100g, 5s) Penetration (0.1 mm)	58.3	40~60
Softening point (°C)	82.5	≥60
(5cm · min^{-1}, 5 °C) Ductility (cm)	34.5	≥20
135 °C dynamic viscosity (Pa · s)	1.14	≤3

Table 3: GO basic performance technical indicators.

APPEARANCE	PURITY	OXYGEN CONTENT	NUMBER OF LAYERS	THICKNESS	LAYER DIAMETER
Black powder	98%	>7wt.%	1~2	0.8~1nm	0.5~10 μm

at 170 °C for 30 min at a speed of 4500 rpm. After the high-speed shear stage, the asphalt mixture is sheared at 600 r / min at 170 °C for 30 min and then placed in an oven at 170 °C for 2 h. The final product is GO / SBS modified asphalt.

2.3. Physical performance test

According to the relevant test steps of JTG E20-2011, the penetration (25 °C), softening point and ductility (5 °C) of GO / SBS modified asphalt were tested, respectively. DMA tested the glass transition temperature of modified asphalt. The storage stability of GO / SBS composite-modified asphalt was studied using the 48 h segregation softening point difference of graphene oxide-modified asphalt as the evaluation index.

2.4. Aging test

The short-term aging and long-term aging treatment of modified asphalt were carried out by laboratory thin film oven aging test (TFOT) and pressure aging test (PAV). The effect of thermal oxygen aging on the low-temperature performance of different GO / SBS composite-modified asphalt was simulated. In the film oven aging test (TFOT), the heating temperature of the film oven aging test was 163 ± 1 °C, and the aging time was 5h. In the long-term thermal-oxidative aging experiment of PAV, the test temperature is 100 °C, the pressure in the pressure vessel is 2.1 ± 0.1 MPa, and the aging time is 20 h.

2.5. Beam bending rheometer (BBR) test

The BBR test was carried out according to T0629-2011 in JTG E20-2011 specification. Firstly, the modified asphalt before and after differential aging treatment was heated to the fluid state, poured into a beam mold of 12.5 mm × 12.5 mm × 6.25 mm, and cooled to room temperature. Then the asphalt was cooled in anhydrous ethanol at –5 °C for 15 min and demoulded. Then the samples were soaked at –6 °C, –12 °C, –18 °C, –24 °C, and –30 °C for 1 h, and then a constant load of 980 ± 250 mN was applied according to the operation procedure. The asphalt samples' creep stiffness S and creep rate m were recorded at 60 s.

2.6. Force ductility test

The test method is based on T0605-2011. The tensile strength and specimen displacement are tested during the test. The maximum yield force and toughness are used as evaluation indexes. The test temperature is 5 °C, and the tensile rate is 50 mm/min.

2.7. Three-point beam bending test

According to the T 0715-2011 mixture beam bending test, the specimens of 300 mm × 300 mm × 50 mm were formed by wheel rolling at room temperature (25 °C), and then they were placed in a 15 °C environment box for 5 days. After demolding, they were cut into prismatic trabecular specimens of 250 mm × 30 mm × 35 mm. Before and after differential aging treatment, the trabecular specimens were placed in a thermostatic tank at –10 °C for 2 hours. The low-temperature crack resistance of the asphalt mixture was evaluated by the flexural tensile strength, the maximum flexural strain at the bottom of the beam, and the flexural stiffness modulus measured when the specimen was destroyed. The test temperature is –10 °C, and the loading speed is 50 mm/min.

2.8. Mineral aggregate gradation design

The coarse aggregate used in this study is basalt, the fine aggregate is ground limestone, and the mineral powder is ground limestone. The aggregate and mineral powder indicators meet the requirements of the 'Highway Asphalt Pavement Construction Technical Specification' (JTG F40-2004). In this paper, the gradation is based on the gradation range of AC-13C coarse and dense graded mineral aggregate in the specification JTG F42-2005, and the pass rate of the 2.36 mm sieve hole is controlled to be less than 40%. The gradation curve is shown in Figure 1, and the oil-stone ratio is 4.8%.

3. PERFORMANCE OF GO / SBS COMPOSITE MODIFIED ASPHALT

3.1. Physical properties of modified asphalt

3.1.1. Conventional performance indicators of asphalt

Penetration is the consistency of asphalt, which can be used to evaluate its ability to resist shear failure. Under certain conditions, it can reflect the hardness of asphalt. The softening point refers to the temperature at which the asphalt is softened and drooped by heat. To a certain extent, it characterizes the temperature stability of

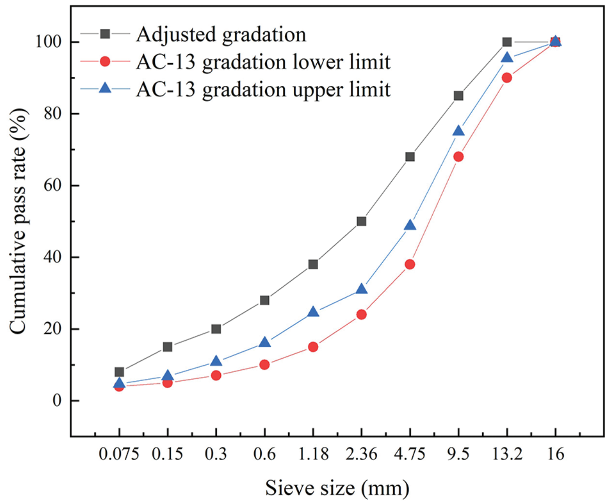

Figure 1: AC-13C coarse dense grading.

Table 4: Basic technical indicators of GO / SBS composite modified asphalt.

GO CONTENT (%)	0	0.25	0.5	0.75	1
Penetration (0.1 mm)	58.3	55.8	54.9	54.3	55.1
Softening point (°C)	82.1	84.3	85.8	86.5	85.2
5 °C ductility (cm)	34.6	34.4	34.3	34.4	34.5
135 °C dynamic viscosity (Pa · s)	1.11	1.19	1.23	1.25	1.24

asphalt, reflecting its viscosity, high-temperature stability, and temperature sensitivity. Ductility is an important empirical index to evaluate the plasticity of asphalt, which can characterize the ductility of asphalt at low temperatures to a certain extent. Asphalt viscosity can be used to characterize the ability of asphalt to resist shear deformation, which is an important index to evaluate the high-temperature rheological properties of asphalt. The conventional performance test results of GO / SBS modified asphalt binder are shown in Table 4.

It can be seen from Table 4 that the penetration of GO / SBS composite-modified asphalt decreases first and then increases with the increase of GO content, indicating that the addition of an appropriate amount of GO can reduce the penetration of SBS-modified asphalt, increase the viscosity and enhance the deformation resistance of asphalt. The softening point of composite modified asphalt increases first and then decreases with the increase of GO content, indicating that adding an appropriate amount of GO can increase the softening point, viscosity, and high-temperature stability of modified asphalt, which is consistent with the results of penetration. With the increase of GO, the ductility decreases first and then increases, which is slightly lower than that of SBS-modified asphalt without GO. With the increase of GO content, the viscosity of composite-modified asphalt also shows a trend of increasing first and then decreasing, which is higher than that of SBS-modified asphalt without GO, indicating that GO could improve the high-temperature stability of SBS-modified asphalt. The effect is the best when the GO content is 0.75%.

From the analysis results of conventional performance indicators of asphalt, the addition of GO can reduce the penetration of SBS-modified asphalt, increase the softening point and increase the viscosity of asphalt, indicating that GO can effectively improve the high-temperature stability of SBS-modified asphalt. Because ductility is also an empirical index, the low-temperature performance of GO / SBS-modified asphalt cannot be characterized by ductility change alone, so more tests are needed to characterize the composite-modified asphalt.

3.1.2. Storage stability

For modified asphalt, storage stability affects the quality stability and use of the effect of modified asphalt. In this paper, the softening point difference is used as the evaluation index of storage stability, and the test results are shown in Figure 2.

It can be seen from Figure 2 that with the increase of GO content, the segregation softening point difference of modified asphalt shows a trend of decreasing first and then increasing. When the GO content is 0.5%, the minimum value is 1.2 °C, and the maximum value is 1.7 °C when the content is 1%. The 48h segregation

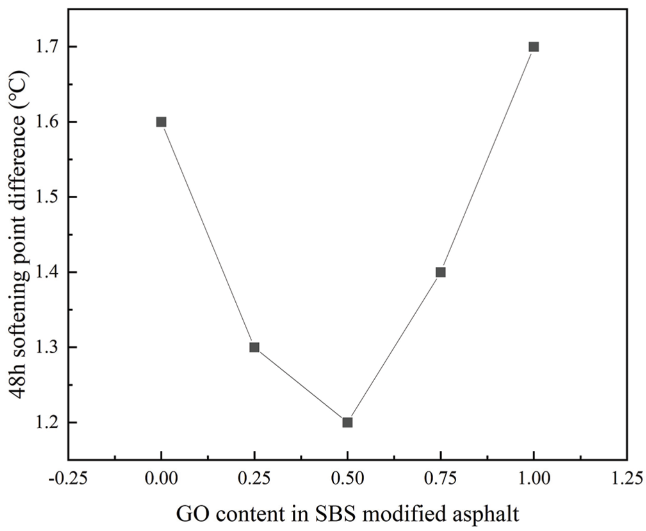

Figure 2: Storage stability change of GO / SBS composite modified asphalt.

softening point difference index meets the requirements of less than 2.5 °C in the JTG F40-2004 specification, indicating that the GO / SBS composite modified asphalt has good thermal storage stability and can meet the long-distance transportation demand after factory processing. The segregation softening point test results show that a proper amount of GO can improve the thermal storage stability of asphalt binder, and excessive addition of GO will increase the unevenness of SBS-modified asphalt, but the overall segregation is still controllable. This is related to the particle size of GO material. Compared with SBS, the particle size of GO is smaller, and a small amount of GO can be uniformly dispersed in SBS modified asphalt matrix. However, excessive GO will lead to agglomeration and accumulation, so the storage stability is better under appropriate GO and uniform mixing.

3.2. Low temperature performance of modified asphalt

3.2.1. Glass transition temperature

The glass transition temperature (Tg) is a temperature limit that reflects the transition of the asphalt binder from a viscoelastic state to a glassy state. It is a low-temperature performance index based on the rheological properties of asphalt. Asphalt's glass transition temperature Tg refers to the temperature at which the asphalt changes from a low-temperature glassy state to a medium-temperature viscoelastic state. The asphalt exhibits hard and brittle characteristics below the Tg temperature and is prone to fracture under external force. Therefore, the temperature range of asphalt should be above the Tg temperature. The Tg temperature can be used as an indicator to reflect the low-temperature performance of the material. The lower the Tg temperature, the more comprehensive the viscoelastic temperature range and the better the low-temperature performance. The glass transition temperature of GO / SBS modified asphalt is shown in Figure 3.

It can be seen from Figure 3 that with the increase of GO content, the Tg temperature decreases first and then increases, indicating that the incorporation of SBS and GO improves the low-temperature performance of asphalt. Among them, the low-temperature performance of 0.75% GO is the best because the appropriate amount of GO can improve the toughness of asphalt, and the temperature stress in SBS-modified asphalt can be quickly released by GO and improve the low-temperature performance of asphalt. Excessive GO will exist in the interior of asphalt molecules. Based on the lubricity of GO itself, it may promote the internal movement of asphalt and increase the risk of cracking, resulting in a slight decline in the low-temperature performance of asphalt.

3.2.2. Low temperature fracture resistance

The low-temperature fracture resistance of GO / SBS composite-modified asphalt was evaluated by 5 °C force ductility test.

It can be seen from Figure 4 that with the increase of GO content, the maximum yield force and toughness of composite-modified asphalt increased first and then decreased, reaching the maximum at 0.75%. At 0.75% content, composite-modified asphalt yield force and toughness were 68.9% and 48.9% higher than those

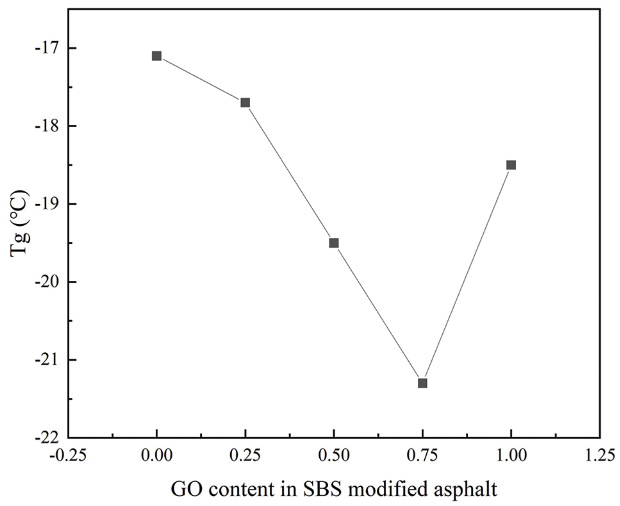

Figure 3: Tg change of GO / SBS composite modified asphalt.

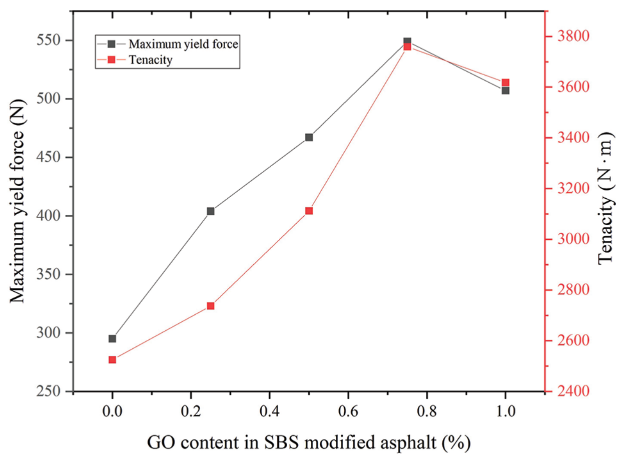

Figure 4: GO / SBS composite modified asphalt force ductility test results.

of SBS-modified asphalt, respectively, indicating that the addition of GO could effectively improve the low-temperature fracture resistance of SBS-modified asphalt.

3.2.3. Low temperature rheological properties

In order to characterize the effect of GO content on the low-temperature creep performance of asphalt, the creep stiffness modulus and creep rate of GO / SBS composite modified asphalt under different aging conditions were obtained by BBR test at 60 s. The creep rate reflects the stress relaxation ability and sensitivity of asphalt binder stiffness with time. The larger the value, the stronger the low-temperature cracking resistance of asphalt. The stiffness modulus refers to the anti-cracking ability of asphalt. The smaller the value, the better the low-temperature performance of asphalt. Because the creep displacement of the unaged GO / SBS composite modified asphalt tested at –6 °C in the test is greater than the equipment limit value, the test data is not obtained. It also shows that the modified asphalt still has good flexibility at –6 °C. The creep stiffness modulus and the creep rate of GO / SBS-modified asphalt at low temperatures are shown in Figure 5 and Figure 6, respectively.

Figure 5 and Figure 6 show that for unaged and short-term aged GO / SBS composite modified asphalt, the creep stiffness modulus is less than 300 MPa at –18 °C, and the creep rate is more significant than 0.3. According to the relevant requirements in the SHRP plan, the low-temperature crack resistance of GO / SBS composite-modified asphalt is good. From Figure 5, it can be seen that with the decrease in test temperature, the creep stiffness modulus of modified asphalt also increases, especially from –24 °C to 30 °C, the modulus doubles, indicating that the decrease in temperature will aggravate the stiffness of asphalt, which is more likely to cause low-temperature cracking. The stiffness modulus of unaged, short-term, and long-term aging increases, indicating that asphalt often becomes hard and brittle after aging after adding GO, the creep stiffness modulus

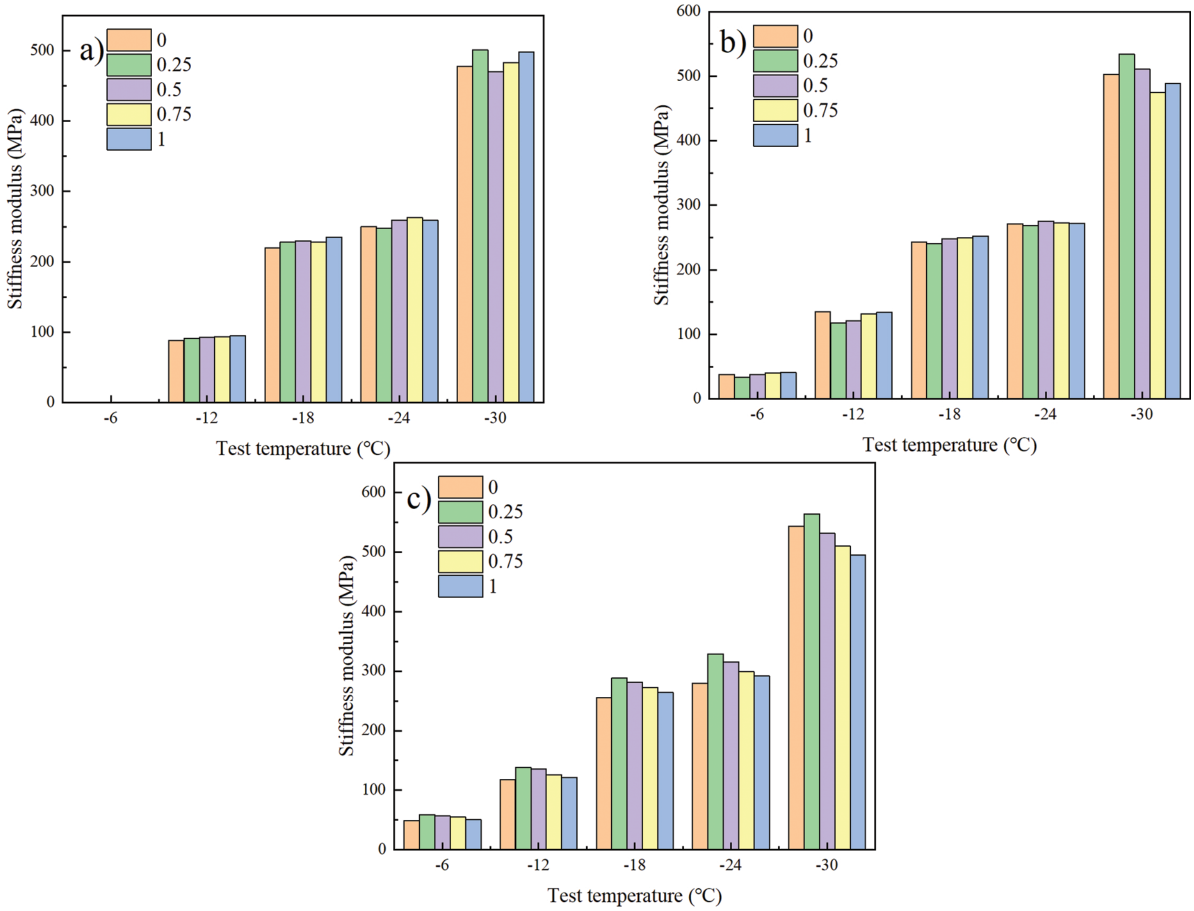

Figure 5: Creep stiffness modulus of GO / SBS composite modified asphalt at low temperature: (a) Unaged asphalt; (b) TFOT aging asphalt; (c) PAV aging asphalt.

of the unmodified modified asphalt increases, which has a particularly negative impact on the low-temperature crack resistance of the asphalt. However, the decreasing trend of the low-temperature performance of GO / SBS composite-modified asphalt caused by the increase of GO content does not increase with the decrease in temperature. The stiffness modulus of modified asphalt after short-term and long-term aging is reduced due to the addition of GO, especially for long-term aging modified asphalt. The higher the GO content, the lower the stiffness modulus. This is because adding GO protects the polymer network structure and hinders the volatilization of lightweight asphalt components to a certain extent. The addition of GO increases the stiffness modulus of SBS modified asphalt to a certain extent. However, it also increases the creep rate. Whether it is the stiffness modulus or the creep rate, it has little change compared with SBS modified asphalt, and generally still has relatively excellent low temperature performance.

It can be seen from Figure 6 that the creep rate of modified asphalt decreases with the decrease in test temperature, indicating that the decrease in temperature will reduce the stress relaxation ability of asphalt. Overall, whether aged modified asphalt or unaged modified asphalt, the creep rate of modified asphalt is improved after adding GO. In long-term and short-term aging modified asphalt, the higher the GO content, the higher the creep rate. This shows that adding GO improves the low-temperature performance of SBS-modified aged asphalt. This is because the exfoliated structure of GO extends the path of oxygen into the asphalt matrix, effectively blocking oxygen and thereby improving the anti-aging performance of asphalt.

Comparing the stiffness modulus S value and creep rate m value before and after aging, the low-temperature performance of modified asphalt with GO before aging is slightly lower than that of SBS-modified asphalt. However, after aging, the low-temperature performance of GO-modified asphalt is improved, indicating that the addition of GO has a particularly adverse effect on the low-temperature performance of the original SBS-modified asphalt. However, due to the excellent anti-aging performance of GO after aging, the low-temperature performance of the aged modified asphalt is improved, indicating that the addition of GO is beneficial to the durability of SBS-modified asphalt pavement.

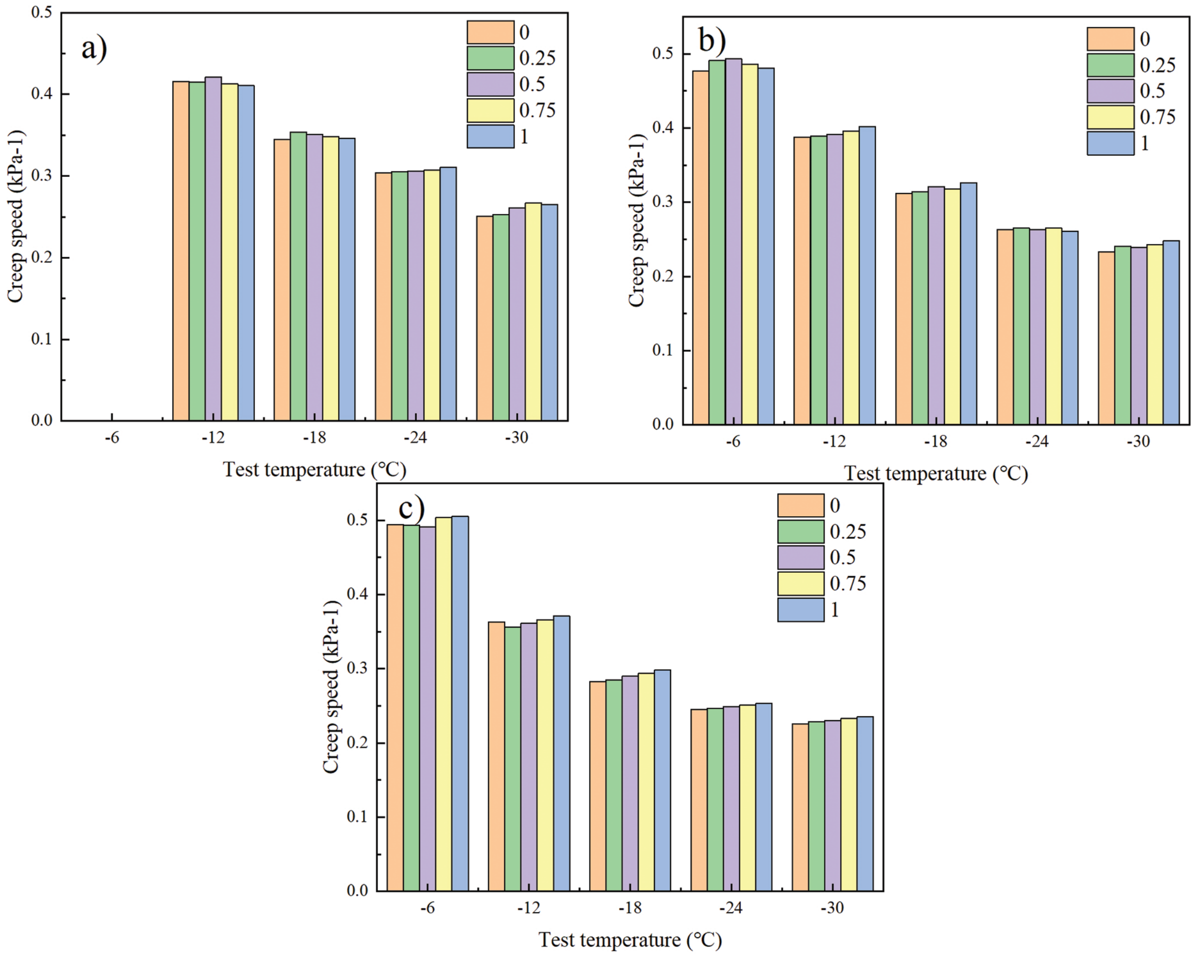

Figure 6: Creep rate of GO / SBS composite modified asphalt at low temperature: (a) Unaged asphalt; (b) TFOT aging asphalt; (c) PAV aging asphalt.

Table 5: Low temperature bending test results of AC-13C mixture.

TECHNICAL INDICATORS		BASE ASPHALT	GO MODIFIED ASPHALT	SBS MODIFIED ASPHALT	GO / SBS COMPOSITE MODIFIED ASPHALT
Low temperature flexural strength (MPa)	Before aging	8.64	11.26	11.35	12.76
	After TFOT aging	6.15	9.06	9.27	10.98
	After PAV aging	3.89	5.91	5.85	8.36
Low temperature bending strain (με)	Before aging	2465	2501	2783	2864
	After TFOT aging	1785	2307	2476	2673
	After PAV aging	981	1725	1684	2169
Low temperature stiffness modulus (MPa)	Before aging	4183	4001	3775	3697
	After TFOT aging	4995	4664	4607	4558
	After PAV aging	6595	5572	5695	4995

4. LOW TEMPERATURE BENDING PERFORMANCE OF MIXTURE

The research results of the physical properties of GO / SBS composite modified asphalt show that the overall performance is the best when the GO content is 0.75%. In order to further study the effect of GO / SBS composite modified asphalt, GO-modified asphalt and GO / SBS composite modified asphalt mixture with GO content of 0.75% and SBS content of 4.5% were prepared. A low-temperature beam bending test studied the low-temperature performance of different asphalt mixtures before and after aging. The experimental results are shown in Table 5.

The low-temperature bending strength is the ultimate tensile strength reflecting the resistance of the asphalt mixture to temperature stress relaxation. The larger the value, the stronger the resistance of the asphalt mixture to temperature stress relaxation and the better the low-temperature crack resistance. From Table 5, it can be seen that the three modified asphalts all effectively improve the low-temperature flexural tensile strength of the mixture, and the GO / SBS composite modified asphalt mixture has the most significant increase. The low-temperature flexural tensile strength of matrix asphalt, GO-modified asphalt, SBS-modified asphalt, and GO / SBS composite-modified asphalt mixture after short-term aging decreased by 28.8%, 19.5%, 18.3%, and 13.9%, respectively, compared with that before aging, and the long-term aging decreased by 55.0%, 47.5%, 48.4%, and 34.5% respectively compared with that before aging. The low-temperature flexural strength of GO / SBS composite modified asphalt mixture decreases the least, and the low-temperature performance can still maintain a high level after aging, indicating that the anti-aging performance of GO / SBS composite modified asphalt mixture is excellent.

It can also be seen from Table 5 that the three modified asphalts effectively improve the low-temperature bending strain and reduce the low-temperature stiffness modulus of the matrix asphalt mixture. The GO / SBS composite-modified asphalt mixture has the most pronounced effect. After short-term aging, the low-temperature bending strain of the three modified asphalt mixtures is above 2400με. In contrast, after long-term aging, only the GO / SBS-modified asphalt mixture remains above 2000με. After short-term aging, the low-temperature stiffness modulus of the three modified asphalt mixtures is below 5000 MPa.

In contrast, after long-term aging, only the GO / SBS-modified asphalt mixture remains below 5000 MPa. The surface GO / SBS composite-modified asphalt mixture has the best low-temperature toughness and crack resistance. It can also be found that GO-modified asphalt has a slight improvement in the low-temperature toughness of the mixture under non-aging and short-term aging. However, it still makes the mixture maintain good low-temperature performance under long-term aging. The possible reason is that the content of light components in GO-modified asphalt is small, and the flake GO particles are dispersed in the asphalt, which makes the walking path of light components and free oxygen complicated, and GO enhances the cohesion between the components of asphalt. Therefore, it can effectively slow down the volatilization of lightweight components during aging and reduce the effect of aging on the stiffness and elastic-plastic properties of the asphalt mixture. In addition, the layered structure film formed by GO can effectively prevent the invasion of thermal oxygen and prevent the internal mixture from being further aged, thus slowing down the effect of aging on the low-temperature crack resistance of the asphalt mixture. In general, GO / SBS composite-modified asphalt can effectively alleviate the damaging effect of aging on the low-temperature crack resistance of the asphalt mixture and prolong the pavement's service life.

5. CONCLUSIONS

In this paper, GO / SBS modified asphalt with different GO content was prepared. The effect of GO content on the performance of composite-modified asphalt was explored by testing the physical properties and low-temperature performance of GO / SBS-modified asphalt. The low-temperature performance of GO / SBS composite modified asphalt and mixture before and after aging was studied by bending rheometer test and low-temperature beam bending test.

(1) The results show that GO can effectively improve the high-temperature stability of SBS-modified asphalt. GO / SBS composite modified asphalt has good heat storage stability, which can meet the long-distance transportation demand after factory processing. Adding GO can reduce the penetration of SBS-modified asphalt, increase the softening point and increase the viscosity of asphalt. When the GO content is 0.75%, the performance of composite-modified asphalt is the best.

(2) With the increase of GO content, the Tg temperature of GO / SBS modified asphalt decreased first and then increased, while the maximum yield force and toughness increased first and then decreased. When the GO content is 0.75%, the Tg is the minimum –21.3 °C, and the maximum yield strength and toughness are the maximum values of 549N and 3759N · m, respectively.

(3) Comparing the stiffness modulus S value and creep rate m value before and after aging, the low-temperature performance of GO / SBS composite-modified asphalt is slightly lower than that of SBS-modified asphalt before aging. However, after aging, the low-temperature performance of GO / SBS composite-modified asphalt is improved.

(4) GO-modified asphalt, SBS-modified asphalt, and GO / SBS composite-modified asphalt effectively improve the mixture's low-temperature flexural strength and flexural strain and reduce the stiffness modulus. The low-temperature performance of GO / SBS composite modified asphalt mixture is the best, and the low-temperature performance can still maintain a high level after aging. GO-modified asphalt slightly

improves the low-temperature toughness of the mixture under non-aging and short-term aging. However, it still makes the mixture maintain good low-temperature performance under long-term aging. GO / SBS composite-modified asphalt can effectively alleviate the damaging effect of aging on the low-temperature crack resistance of asphalt mixture and prolong the pavement's service life.

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