

Research on properties of Al₂O₃/SBR composite modified asphalt

cong xu

Xinyang University

pei yu

xxytmy@yeah.net

Xinyang University

shanchun fu

Xinyang University

Research Article

Keywords: modified asphalt, styrene-butadiene rubber (SBR), nano-Al₂O₃, rheological properties

Posted Date: October 14th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-11215413/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: No competing interests reported.

Research on properties of Al₂O₃/SBR composite modified asphalt

Abstract

In this study, SBR (4 wt% by weight of base asphalt) and nano-Al₂O₃ (2 wt%, 4 wt%, 6 wt%, and 8 wt% by weight of base asphalt) were used to prepare composite modified asphalts for improving the service performance of asphalt pavement. Conventional and rheological tests were carried out to reveal the service performance of the modified asphalts. The results show that SBR can improve the low-temperature crack resistance and fatigue resistance of asphalt. Compared with the base asphalt, the ductility and fatigue life of the SBR-modified asphalt were increased by 57.8% and 63.7%, respectively. Meanwhile, with the increase of Al₂O₃ content, the penetration of the composite modified asphalt gradually decreased, while the softening point and rutting factor (G/sinδ) increased significantly, indicating that the high-temperature deformation resistance was remarkably enhanced. When the Al₂O₃ content was 8%, the rutting factor of the modified asphalt at 64 °C was increased by 132.8% compared with that of the 4% SBR-modified asphalt. However, an excessively high Al₂O₃ content would have an adverse effect on the low-temperature crack resistance. SBR improves the flexibility and fatigue resistance of asphalt by constructing an elastic network structure, while Al₂O₃ mainly enhances the high-temperature stability of the system through its filling effect; therefore, the two modifiers exhibit a good synergistic modification effect. Based on the comprehensive performance analysis, when the Al₂O₃ content ranges from 2% to 4%, the composite modified asphalt can balance the high-temperature stability and low-temperature crack resistance, exhibiting excellent service performance.

Keywords modified asphalt, styrene-butadiene rubber (SBR), nano-Al₂O₃, rheological properties

1 . Introduction

With the rapid development of transportation infrastructure and the continuous increase in the proportion of heavy-load traffic, higher requirements have been placed on the service performance of asphalt pavement. Traditional asphalt pavement is prone to rutting deformation under high temperature and vehicle loading [1], and is prone to cracking at low temperatures. The frequent occurrence of these distresses will seriously shorten the service life of asphalt pavement [2]. Therefore, composite modification of asphalt has become an important approach to improve the service performance of asphalt pavement.

Currently, polymers are widely used in asphalt modification. Among them, styrene-butadiene rubber (SBR) has attracted extensive attention because of its excellent elastic properties and low cost [3]. Yao and Wang [4] investigated the modification mechanism of SBR in emulsified asphalt by means of DSR, FTIR, and SEM, and found that SBR and asphalt molecules interpenetrate each other to form a network structure, which contributes to the improvement of fatigue resistance and low-temperature crack resistance. By conducting rheological tests, Liu et al [5], found that SBR can increase the complex modulus and decrease the phase angle of asphalt, enhancing its elastic response. Meanwhile, SBR can form a continuous polymer network structure in asphalt, which allows the stress to be effectively dispersed, thereby improving the fatigue resistance. Moreover, after SBR modified the high-modulus recycled asphalt, its creep stiffness decreased while the creep rate increased, indicating that SBR can effectively alleviate the low-temperature brittleness of high-modulus asphalt caused by excessive stiffness [6]. By means of molecular dynamics, Nie et al [7], found that the butadiene segments in SBR can entangle and adsorb with asphalt molecules, forming a flexible network structure that absorbs more energy during crack propagation, thus improving the fracture toughness of the material. In addition, Ji Z et al [8], further revealed the compatibility mechanism between SBR and base asphalt based on molecular dynamics simulations, finding that the binding energy between SBR and asphalt molecules decreases with increasing temperature, and the solubility parameter is the key factor determining their compatibility, which provides a molecular-level theoretical basis for the uniform dispersion of SBR in asphalt and the formation of an elastic network. Sun et al [9], found that SBR melts with the increase of temperature, which enhances its adhesion and further improves the rutting resistance at high temperatures. Meanwhile, SBR molecules are tightly bound in the asphalt system by van der Waals forces, greatly improving the interstructural bonding and low-temperature crack resistance. Yang et al [10], conducted the composite modification of asphalt with waterborne epoxy resin and SBR emulsified asphalt, and the results showed that SBR can improve the toughness and workability of asphalt mixtures, while the epoxy resin enhances the high-temperature performance of asphalt; the synergistic effect of the two significantly improved the comprehensive performance of the material. Zhang et al [11], adopted SBR and montmorillonite for the composite modification of asphalt, and the results showed that the storage modulus and deformation resistance of asphalt were improved, and SBR can enhance the structural stability of modified asphalt. Numerous studies have indicated that SBR mainly forms a spatial network structure through physical swelling and molecular chain entanglement, thereby improving the penetration, ductility, and elastic recovery of asphalt, as well as the fatigue cracking resistance and moisture damage resistance of

mixtures [12,13]. However, the improvement effect of single SBR on the high-temperature performance of asphalt is relatively limited, and permanent deformation is prone to occur under heavy loading. Therefore, it is difficult to meet the service requirements by modifying asphalt with SBR alone.

In recent years, nanomaterials have exhibited excellent modification effects on asphalt because of their size effect and interface effect. Among them, nano- Al_2O_3 , which possesses the advantages of large specific surface area, good stability, and low cost, is regarded as a nano-modifier with broad application potential [14]. Nano- Al_2O_3 can effectively improve the microstructure of asphalt through filling and interface-reinforcement effects, thereby enhancing the high-temperature deformation resistance of asphalt [15]. Sun and Li [16] systematically investigated the effect of nano- Al_2O_3 on the rheological properties of SBS-modified asphalt, finding that nano- Al_2O_3 can simultaneously enhance the high-temperature rutting resistance and aggregate bonding performance of asphalt without significant adverse effects on low-temperature performance. However, another study [17] pointed out that when the nano- Al_2O_3 content exceeds 3%, the fatigue damage tolerance of asphalt decreases, indicating that there exists a reasonable content range for nano- Al_2O_3 . Studies have shown that nano- Al_2O_3 increases the softening point and viscosity of asphalt but decreases its ductility, and nano- Al_2O_3 can significantly reduce the temperature sensitivity of asphalt and enhance its hardness. Meanwhile, nanomaterials can inhibit the molecular motion of asphalt and improve its high-temperature stability and anti-aging performance [18]. Yibas et al [19], reported that nano- Al_2O_3 can improve the storage stability of polymer-modified asphalt and enhance the cohesion between asphalt and aggregate, thereby improving the cracking resistance and moisture damage resistance of asphalt mixtures. Mubarak et al [20], reported that 5% Al_2O_3 caused the most obvious increase in the rutting factor and complex shear modulus of asphalt and significantly improved the creep recovery performance, endowing the modified asphalt with excellent rutting resistance. However, the improvement effect weakened with the increase of dosage [21]. Tahmouresi et al [22], reported that nano- Al_2O_3 and expanded nano-clay can effectively improve the skid resistance and noise reduction of asphalt mixtures. Moreover, nano- Al_2O_3 can enhance the bonding between asphalt and aggregate and optimize the internal stress distribution. Chelovian et al [23], adopted nano- Al_2O_3 to modify SMA mixtures, and the results showed that nano- Al_2O_3 can significantly improve the dynamic creep performance, rutting resistance, and fatigue life of asphalt mixtures. In addition, relevant studies have pointed out that nano- Al_2O_3 can fill the micro-pores in the asphalt colloidal system, increase the contact points between particles, and construct a more stable network structure, thereby alleviating the phase separation problem of polymer-modified asphalt and improving its storage stability and anti-aging

performance [24]. Although previous studies have explored the composite modification of nano- Al_2O_3 with SBS [25] and graphene with SBR [26], research on the nano- Al_2O_3 /SBR composite system remains relatively limited. In particular, there is a lack of systematic multi-scale rheological evaluation covering high temperature (MSCR), intermediate temperature (LAS), and low temperature (BBR), and the optimal content range of nano- Al_2O_3 has not been clearly determined.

In summary, SBR can improve the low-temperature performance and fatigue resistance of asphalt, while nano- Al_2O_3 can enhance the high-temperature stability of asphalt. Therefore, the combined use of the two in asphalt modification is expected to give full play to their respective advantages and achieve a balance between the high- and low-temperature properties of asphalt. Based on this, in this study, SBR with a content of 4% and nano- Al_2O_3 with different contents (2%, 4%, 6%, and 8%) were used to compound modify the base asphalt. Conventional and rheological tests were carried out to investigate the effect of nano- Al_2O_3 on the performance of SBR-modified asphalt, to reveal the synergistic mechanism of the two modifiers, and to determine the reasonable Al_2O_3 content. This study will provide a theoretical basis for the engineering application of nanomaterial-modified asphalt.

2. Materials and test methods

2.1 Base material

In this study, 70# base asphalt was used for modification, and its performance indicators are presented in Table 1. All the performance indicators of the base asphalt meet the specification requirements. SBR can effectively improve the low-temperature crack resistance of asphalt, while nano- Al_2O_3 , which possesses a large specific surface area and good surface activity, is beneficial to enhancing the interfacial interaction between the modifier and asphalt. The performance indicators of the modifiers are shown in Table 2.

Table 1 .Performance of base asphalt

Indicator	Penetration	Ductility (10 °C)	Softening point	Density
Result	68.4 dmm	26.8 cm	46.7 °C	1.01 g/cm ³

Table 2 Performance indicators of modifiers

Modifier	Indicator	Result
----------	-----------	--------

SBR	Appearance	Milky white particles
	Styrene content	24.6 %
	Density	0.946 g/cm ³
	Tensile strength	≥20MPa
Nano-Al ₂ O ₃	Appearance	White powder
	Purity	≥99%
	Specific surface area	120 m ² /g

2.2 Preparation Process

In this study, a high-shear mixer was used to prepare the modified asphalt. Firstly, the base asphalt was heated to a flowing state at 160 °C, and then 4% SBR (by weight of base asphalt) was added and sheared at 3000 r/min for 30 min at 160 °C to fully disperse the SBR into the asphalt. Subsequently, 2%, 4%, 6%, and 8% Al₂O₃ (by weight of base asphalt) were respectively added to the SBR-modified asphalt, and the blend was sheared at 6000 r/min for 50 min at 180 °C to improve the dispersion uniformity of the nanoparticles. Finally, the modified asphalt was kept in an oven at 180 °C for 60 min to allow the SBR to fully swell and promote the stability of nano-Al₂O₃ in the system, thereby obtaining the Al₂O₃/SBR composite modified asphalt. For the convenience of subsequent analysis, the abbreviations of different types of modified asphalts are presented in Table 3.

Table 3. Abbreviations of modified asphalts.

Type	Abbreviation
Base asphalt	NA
4%SBR modified asphalt	4%SBR
4%SBR+2%Al ₂ O ₃ modified asphalt	SA-2
4%SBR+4%Al ₂ O ₃ modified asphalt	SA-4
4%SBR+6%Al ₂ O ₃ modified asphalt	SA-6
4%SBR+8%Al ₂ O ₃ modified asphalt	SA-8

2.3 Conventional tests

To evaluate the physical properties of the modified asphalts, conventional tests, including penetration, softening point, ductility, and segregation tests, were performed on the asphalt samples according to the Standard Test Methods of Bitumen and Bituminous Mixtures for Highway Engineering (JTG E20). The

penetration test was conducted at 25 °C with a standard needle of 100 g for 5 s, and the apparatus is shown in Fig. 1. The softening point was determined by the ring-and-ball method, and the test setup is shown in Fig. 2. The segregation test was carried out by measuring the softening points of the asphalt samples taken from the top and bottom sections of the segregation tube. The ductility test was conducted at 15 °C, and the ductility tester is shown in Fig. 3.



Fig. 1 Asphalt penetration tester

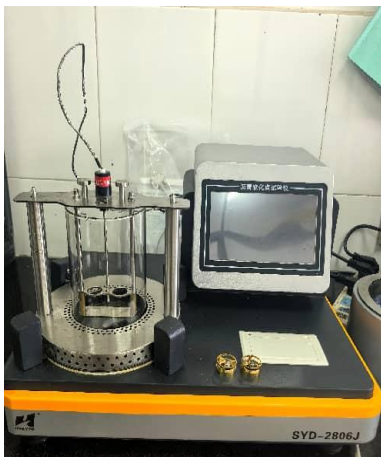


Fig. 2 Asphalt softening point tester



Fig. 3 Asphalt ductility tester

2.4 Rheological tests

As shown in Fig. 4, a dynamic shear rheometer (DSR) was used to conduct the temperature sweep (TS), multiple stress creep recovery (MSCR), and linear amplitude sweep (LAS) tests. As shown in Fig. 5, a bending beam rheometer (BBR) was used to conduct the low-temperature BBR test. These tests were designed to evaluate the rheological properties of the modified asphalts at high, intermediate, and low temperatures. The TS test was conducted at temperatures ranging from 46 °C to 82 °C with a loading frequency of 10 rad/s, and the rutting factor ($G/\sin\delta$) was adopted as the evaluation index. The MSCR test was conducted at 64 °C under stress levels of 0.1 kPa and 3.2 kPa, and the non-recoverable creep compliance (J_{nr}) and recovery rate (R) were adopted as the evaluation indices. The LAS test was conducted at 25 °C with loading strains of 2.5% and 5% and a frequency range of 0.2–30 Hz, and the fatigue life was adopted as the evaluation index. The BBR test was conducted at -18 °C, and the creep stiffness (S) and creep rate (m -value) were adopted as the evaluation indices.



Fig. 4 Dynamic shear rheometer (DSR)

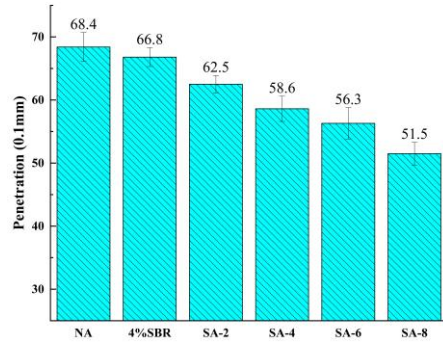


Fig. 5 Bending beam rheometer (BBR)

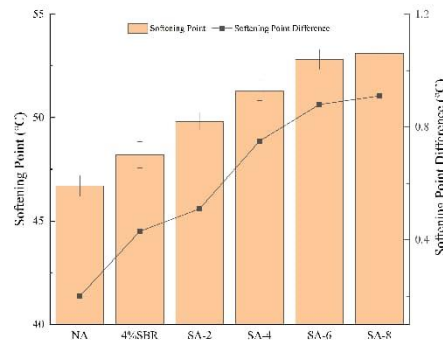
3. Results and discussion

3.1 Conventional properties

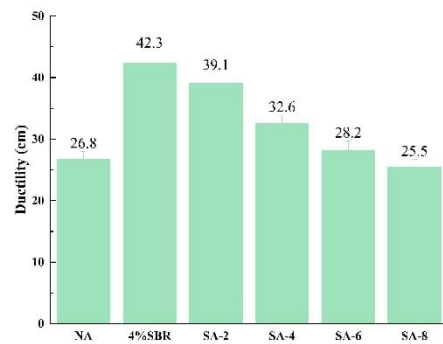
Conventional tests were conducted on the modified asphalts, and the results are shown in Fig. 6.



(a) Penetration



(b) Softening point



(c) Ductility

Fig. 6 Conventional test results

As shown in Fig. 6(a), after the addition of 4% SBR to the base asphalt, the penetration decreased to 66.8 with a slight reduction, indicating that SBR has little effect on the hardness of asphalt. However, with the increase of Al_2O_3 content, the penetration of the composite modified asphalt gradually decreased. Compared with the SBR-modified asphalt, the penetration of SA-2, SA-4, SA-6, and SA-8 decreased by 6.4%, 12.3%,

15.7%, and 22.9%, respectively. The results indicate that nano- Al_2O_3 can significantly improve the hardness and stiffness of asphalt; its filling effect and interfacial interaction effectively restrict the movement of asphalt molecular chains, making the asphalt harder overall. Moreover, in terms of the softening point difference obtained from the segregation test, although the softening point difference increased with the increase of nano- Al_2O_3 content, it was still significantly lower than the 2.5 °C requirement for the softening point difference of polymer-modified asphalt specified in the segregation test. This indicates that the Al_2O_3 /SBR composite modified asphalt still possesses good storage stability. This is consistent with the findings of Gong et al [27] and Wang et al [28], namely that the introduction of nanomaterials can effectively inhibit the phase separation of polymer-modified asphalt and improve high-temperature storage stability by increasing the viscosity of the system, hindering the migration and floating of polymer molecules, and forming a physical barrier layer at the asphalt-polymer interface.

As shown in Fig. 6(b), with the increase of Al_2O_3 content, the softening point of the composite modified asphalt increased significantly. Compared with the SBR-modified asphalt, the softening points of SA-2, SA-4, SA-6, and SA-8 increased by 3.3%, 6.4%, 9.5%, and 10.2%, respectively, with a maximum increase of 13.7% relative to the base asphalt. Nano- Al_2O_3 can increase the hardness of asphalt and, at the same time, significantly enhance the high-temperature stability and deformation resistance of asphalt.

As shown in Fig. 6(c), after the addition of 4% SBR, the ductility of asphalt increased to 42.3 cm with an increase of 57.8%, indicating that SBR has a good improvement effect on the low-temperature ductility of asphalt. With the increase of Al_2O_3 content, the ductility of the composite modified asphalt gradually decreased. Compared with the SBR-modified asphalt, the ductility of SA-2, SA-4, SA-6, and SA-8 decreased by 7.6%, 22.9%, 33.3%, and 39.7%, respectively. The ductility of SA-8 was slightly lower than that of the base asphalt, which indicates that excessive nanoparticles would weaken the low-temperature crack resistance of asphalt. In summary, SBR can significantly improve the low-temperature performance of asphalt, while nano- Al_2O_3 enhances the high-temperature performance of asphalt by increasing its hardness. However, with the increase of Al_2O_3 content, it has an adverse effect on the low-temperature toughness of asphalt.

3.2 High-temperature rheological properties

The high-temperature rheological properties of the modified asphalts were evaluated by the TS and MSCR tests, and the results of the rutting factor, creep recovery rate, and Jnr are presented in Fig. 2 and Fig. 3, respectively.

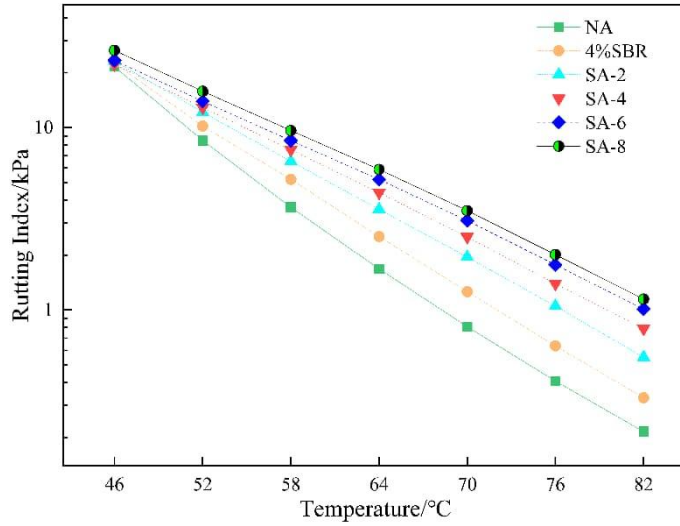
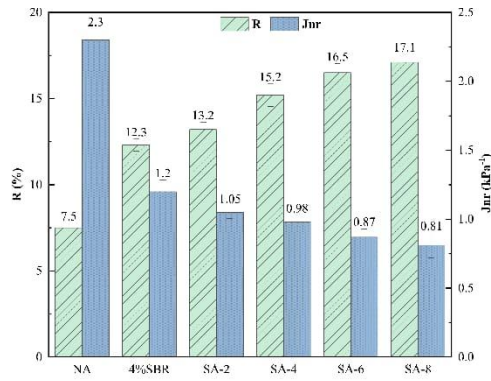


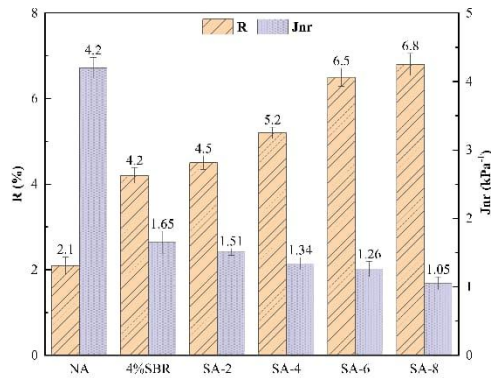
Fig. 7 Rutting factor test results.

As shown in Fig. 7, the rutting factor of asphalt shows a significant decreasing trend with the increase of temperature, indicating that high temperature weakens the deformation resistance of asphalt. Overall, SBR increases the rutting factor of asphalt to a certain extent, and with the increase of Al_2O_3 content, the high-temperature deformation resistance of asphalt gradually enhances. However, with the increase of Al_2O_3 content, the increase amplitude of the rutting factor of the composite modified asphalt gradually decreases. To quantitatively evaluate the high-temperature performance of the modified asphalts, a comparative analysis of the rutting factor at 64 °C was conducted. At 64 °C, compared with the base asphalt, the rutting factor of the 4% SBR-modified asphalt increased by 50.6%. Moreover, with the increase of nano- Al_2O_3 content, the rutting factor further increased. Compared with the base asphalt, the increase amplitudes of the rutting factor of SA-2, SA-4, SA-6, and SA-8 were 111.9%, 162%, 208.9%, and 250.6%, respectively. The results indicate that nano- Al_2O_3 has a significant improvement effect on the high-temperature rutting resistance of asphalt. However, from the perspective of the increase rate of the rutting factor, when the Al_2O_3 content increased from 2% to 6%, the rutting factor increased from 3.56 kPa to 5.19 kPa, with an increase of approximately 45.8%; when the content increased from 6% to 8%, the rutting factor only increased by 13.5%. This indicates that the high-temperature performance of the composite modified asphalt does not increase indefinitely with the increase of Al_2O_3 content, but gradually tends to level off at a high Al_2O_3 content.

Fig. 8 shows the MSCR test results of the modified asphalts at 0.1 kPa and 3.2 kPa. The R value reflects the elastic recovery performance of asphalt under loading; the larger the value, the stronger the high-temperature deformation resistance. The Jnr value characterizes the non-recoverable creep compliance; the smaller the value, the stronger the rutting resistance.



(a) 0.1 kPa



(b) 3.2 kPa

Fig. 8 MSCR test results

As can be seen from Fig. 8(a), at 0.1 kPa, the R value of the base asphalt is only 7.5% and the Jnr is as high as 2.3 kPa⁻¹, indicating that its elastic recovery ability is poor and it is prone to permanent deformation. After the addition of 4% SBR, the recovery rate increased to 12.3% and the Jnr decreased to 1.2 kPa⁻¹; compared with the base asphalt, the recovery rate increased by 64% and the Jnr decreased by 47.8%. This is mainly because SBR absorbs the light components in asphalt and swells, forming a continuous elastic network structure, which enhances the elastic recovery performance of the modified asphalt. Moreover, with the increase of Al₂O₃ content, the R value of the composite modified asphalt continuously increases and the Jnr

decreases. The recovery rates of SA-2, SA-4, SA-6, and SA-8 are 13.2%, 15.2%, 16.5%, and 17.1%, respectively, which are 7.3%, 23.6%, 34.1%, and 39% higher than those of the SBR-modified asphalt. The Jnr values decrease to 1.05, 0.98, 0.87, and 0.81 kPa^{-1} , respectively, which are 12.5%, 18.3%, 27.5%, and 32.5% lower than those of the SBR-modified asphalt. Nanoparticles possess a large specific surface area and can form a strong interfacial interaction with asphalt components, while exerting a filling effect, increasing the stiffness of the system and restricting the flow of asphalt molecules; thus, nano- Al_2O_3 can further enhance the rutting deformation resistance of asphalt [29].

As can be seen from Fig. 8(b), at 3.2 kPa, the recovery rate of asphalt decreases and the Jnr increases. Taking SA-8 as an example, the R value decreases from 17.1% to 6.8%, with a decrease of 60.2%; the Jnr increases from 0.81 kPa^{-1} to 1.05 kPa^{-1} , with an increase of 29.6%. This indicates that under high-stress loading conditions, the internal structure of asphalt suffers more severe damage, leading to a weakened elastic recovery ability and an increased risk of permanent deformation. However, compared with the base asphalt and the SBR-modified asphalt, the composite modified asphalt still exhibits good deformation resistance. With the Al_2O_3 content increased to 8%, compared with the SBR-modified asphalt, the recovery rate of SA-8 increases by 61.9% and the Jnr decreases by 36.4%, which indicates that the composite modified asphalt still has excellent permanent deformation resistance under heavy loading. At 3.2 kPa, when the nano- Al_2O_3 content increases from 6% to 8%, the increase amplitude of the R value is only 4.6% and the decrease amplitude of the Jnr is 16.7%. Although increasing the Al_2O_3 content can enhance the permanent deformation resistance of asphalt, the performance improvement amplitude decreases.

The high-temperature rheological results indicate that SBR improves the elastic recovery performance of asphalt by constructing an elastic network, while nano- Al_2O_3 increases the stiffness of asphalt and inhibits molecular flow through filling enhancement and interfacial strengthening effects. The synergistic effect of the two enables the composite modified asphalt to exhibit a higher recovery rate and a lower non-recoverable creep compliance, thereby significantly improving the high-temperature rutting resistance of asphalt. From the perspective of the high-temperature rheological results, when the Al_2O_3 content exceeds 6%, although the high-temperature performance still improves, the increase amplitude is relatively small.

3.3 Intermediate-temperature fatigue

Fig. 9 presents the fatigue life results of the modified asphalts at strains of 2.5% and 5%. The higher the fatigue life, the stronger the cracking resistance of asphalt under loading and the better the fatigue resistance.

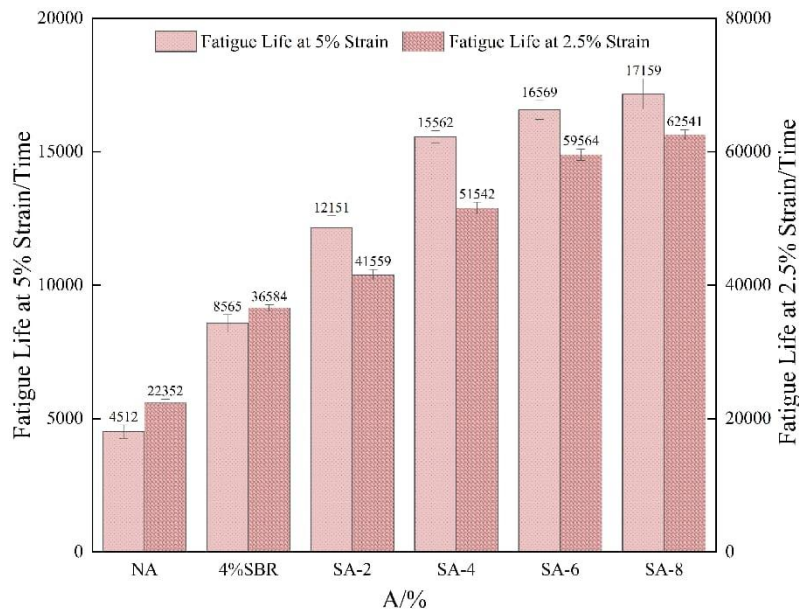


Fig. 9 LAS test results.

As can be seen from Fig. 9, at a strain of 2.5%, the fatigue life of the base asphalt is only 22,352 cycles, while after the addition of 4% SBR, the fatigue life increases to 36,584 cycles with an increase of 63.7%, indicating that SBR can improve the fatigue resistance of asphalt. This is mainly because the flexible butadiene segments in SBR improve the deformation coordination ability of asphalt, enabling it to dissipate more energy under cyclic loading, thereby delaying the development of fatigue cracks [30]. Moreover, with the increase of Al_2O_3 content, the fatigue life increases significantly. The fatigue lives of SA-2, SA-4, SA-6, and SA-8 are 41,559, 51,542, 59,564, and 62,541 cycles, respectively, which are 13.6%, 40.9%, 62.8%, and 70.9% higher than those of the 4% SBR-modified asphalt. The results indicate that there is an obvious synergistic enhancement effect between nano- Al_2O_3 and SBR, which can further improve the ability of asphalt to resist fatigue damage.

When the loading strain increases from 2.5% to 5%, the fatigue life of the base asphalt is only 4,512 cycles, while after modification with 4% SBR, it increases to 8,565 cycles with an increase of 89.8%. With the increase of Al_2O_3 content, compared with the SBR-modified asphalt, the fatigue lives of SA-2, SA-4, SA-6, and SA-8 increase by 41.9%, 81.7%, 93.4%, and 100.3%, respectively. Compared with the base asphalt, the increase amplitude of the fatigue life of SA-8 is 280.3%, which indicates that under higher strain conditions, the enhancement effect of Al_2O_3 on the fatigue performance is more significant. Meanwhile, with the increase of strain level, the decrease amplitude of the composite modified asphalt is significantly reduced, indicating that it is less sensitive to the change of strain level and can maintain good fatigue failure resistance under large loading.

3.4 Low-temperature crack resistance

The BBR test results are presented in Fig. 10. The creep stiffness (S) is used to characterize the low-temperature deformation resistance of asphalt; the smaller the value, the lower the possibility of stress concentration in asphalt at low temperatures. The m -value reflects the stress relaxation performance of asphalt; the larger the m -value, the better the thermal shrinkage resistance of asphalt and the lower the risk of low-temperature cracking.

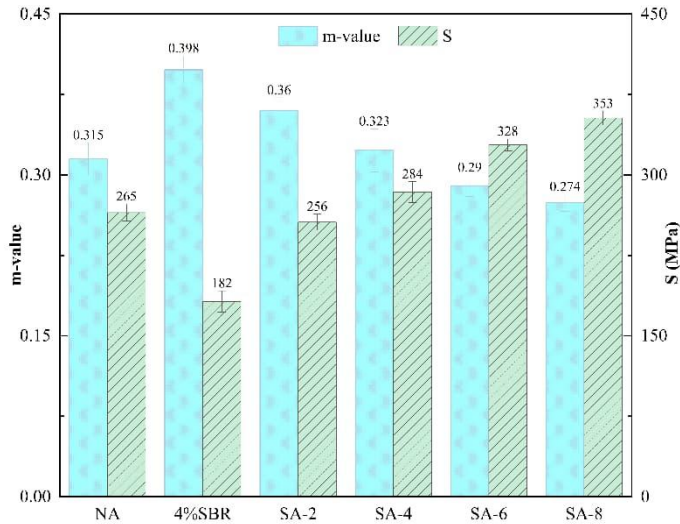


Fig. 10 BBR test results.

As can be seen from Fig. 10, after the addition of 4% SBR to the base asphalt, the S value decreases from 265 MPa to 182 MPa, and the m -value increases from 0.315 to 0.398. The results indicate that SBR can improve the stress relaxation performance of asphalt and reduce the risk of low-temperature cracking. This is mainly because after the flexible butadiene segments in SBR are compatible with asphalt, the asphalt system possesses better deformation coordination ability, thereby enhancing its low-temperature crack resistance [31]. However, with the increase of Al_2O_3 content, the S value of the modified asphalt gradually increases, while the m -value continuously decreases. The S values of SA-2, SA-4, SA-6, and SA-8 are 256, 284, 328, and 353 MPa, respectively, which are 40.7%, 56%, 80.2%, and 94% higher than those of the 4% SBR-modified asphalt. The m -values decrease by 9.5%, 18.8%, 27.1%, and 31.2%, respectively. This indicates that with the increase of Al_2O_3 content, the stiffness of asphalt gradually increases, while the stress relaxation performance significantly decreases.

When the Al_2O_3 content is 2%, the S value of SA-2 is 256 MPa and the m -value is 0.36, and its low-temperature performance is still better than that of the base asphalt, which indicates that a low content of Al_2O_3 still endows the composite modified asphalt with good low-temperature crack resistance. However,

when the Al_2O_3 content increases to 6% and 8%, the S values are 328 MPa and 353 MPa, respectively, and the m -values decrease to 0.29 and 0.274, which indicates that excessive Al_2O_3 leads to the stiffening of the system, thereby being detrimental to the low-temperature crack resistance. This is mainly because nano- Al_2O_3 possesses high modulus and rigidity, and the filling and interfacial enhancement effects generated with asphalt restrict the movement ability of asphalt molecular chains, reducing the stress relaxation performance of the material at low temperatures.

3.5 Analysis of optimal content

Based on the conventional and rheological test results, the composite effect of SBR and Al_2O_3 significantly improves the performance of asphalt. SBR absorbs the light components in asphalt and swells, forming a continuous elastic network structure, which improves the stress relaxation performance and energy dissipation ability of asphalt and significantly enhances its low-temperature crack resistance and fatigue resistance. Nano- Al_2O_3 , on the other hand, restricts the movement of asphalt molecular chains through filling and interfacial enhancement effects, improving the permanent deformation resistance of asphalt and enhancing its high-temperature stability. However, an excessively high Al_2O_3 content leads to the hardening of asphalt, which has an adverse effect on the low-temperature performance. When the Al_2O_3 content is 2%, SA-2 can maintain good high- and low-temperature performance, while SA-6 and SA-8, although possessing good high-temperature performance, cause a significant decrease in the low-temperature performance. Considering both the high- and low-temperature performance comprehensively, the optimal Al_2O_3 content is 2%–4%.

4 Conclusions

Composite modified asphalts were prepared using 4% SBR and different contents of Al_2O_3 , and their performance was evaluated through conventional and rheological tests. The main conclusions are as follows: (1) SBR can significantly improve the low-temperature performance and fatigue resistance of asphalt. Compared with the base asphalt, the ductility of the 4% SBR-modified asphalt increases by 57.8%, and the fatigue life increases by 63.7%–89.8%. Al_2O_3 can significantly improve the high-temperature stability of SBR-modified asphalt. With the increase of Al_2O_3 content, the modified asphalt becomes harder, resulting in a gradual decrease in penetration and an increase in softening point; nano- Al_2O_3 can effectively enhance the permanent deformation resistance of asphalt.

(2) Al_2O_3 and SBR have an obvious synergistic modification effect. SBR can improve the elastic recovery performance, low-temperature crack resistance, and fatigue resistance of asphalt, while Al_2O_3 mainly improves the stiffness and high-temperature deformation resistance of the system through its filling effect. The composite effect of the two endows the modified asphalt with excellent performance.

(3) With the increase of Al_2O_3 content, the high-temperature performance of the composite modified asphalt continuously improves, while the low-temperature performance gradually decreases. When the Al_2O_3 content exceeds 4%, the ductility decreases and the BBR indicators deteriorate, indicating a reduction in the crack resistance of asphalt. Meanwhile, the improvement amplitude of the high-temperature performance gradually decreases, showing an obvious phenomenon of diminishing marginal effect.

(4) Based on the comprehensive analysis of conventional performance, high-temperature rheological performance, low-temperature crack resistance, and fatigue performance, when the Al_2O_3 content is 2%–4%, the composite modified asphalt can maintain good high-temperature stability and low-temperature crack resistance, exhibiting the best modification effect.

References

1. C. Qian, W. Fan, Evaluation and characterization of properties of crumb rubber/SBS modified asphalt, *Materials Chemistry and Physics* 253 (2020) 123319, <https://doi.org/10.1016/j.matchemphys.2020.123319>.
2. A.M. Yarahmadi, G. Shafabakhsh, A. Asakereh, Laboratory investigation of the effect of nano CaCO_3 on rutting and fatigue of stone mastic asphalt mixtures, *Construction and Building Materials* 317 (2022) 126127, <https://doi.org/10.1016/j.conbuildmat.2021.126127>.
3. Y. Xue, C. Liu, S. Lv, D. Ge, Z. Ju, G. Fan, Research on rheological properties of CNT-SBR modified asphalt, *Construction and Building Materials* 361 (2022) 129587, <https://doi.org/10.1016/j.conbuildmat.2022.129587>.
4. X. Yao, Y. Wang, Performance and enhancement mechanisms of compound modified emulsified asphalt and its cold recycled mixture, *Construction and Building Materials* 503 (2025) 144565. <https://doi.org/10.1016/j.conbuildmat.2025.144565>.
5. Z. Liu, Y. Chen, J. Pang, Y. Yang, J. Gao, L. Jing, An SBR-based toughness enhancement for high modulus recycled asphalt binder, *Construction and Building Materials* 514 (2026) 145509, <https://doi.org/10.1016/j.conbuildmat.2026.145509>.

6. Y. Li, D. Ge, Z. Ju, S. Lv, Y. Xue, Y. Xue, L. Peng, Study on Performance and Mechanism of SBR and Bio-Oil Recycled SBS Modified Asphalt, *Polymers* 14(23) (2022) 5096. <https://doi.org/10.3390/polym14235096>
7. F. Nie, C.L. Chow, D. Lau, Molecular dynamics study on the cohesive fracture properties of functionalized styrene-butadiene rubber modified asphalt, *Resources, Conservation and Recycling* 208 (2024) 107715, <https://doi.org/10.1016/j.resconrec.2024.107715>.
8. Ji Z, Wu X, Zhang Y, Milani G. Aging Behavior and Mechanism Evolution of Nano-Al₂O₃/Styrene-Butadiene-Styrene-Modified Asphalt under Thermal-Oxidative Aging. *Materials*. 2023; 16(17):5866. <https://doi.org/10.3390/ma16175866>.
9. Sun J S, Guo X R, Feng D Y, et al. Comparative study on properties of SBS/SBR/crumb rubber composite modified asphalt and high-viscosity modified asphalt[J]. *Plastics Science and Technology*. 2024,52(12):44-50.DOI:10.15925/j.cnki.issn1005-3360.2024.12.008.
10. J. Yang, Z. Zhang, Y. Fang, Compatibility evaluation between waterborne epoxy resin and SBR latex modified asphalt emulsion, *Journal of Traffic and Transportation Engineering (English Edition)* 11(1) (2024) 160-171, <https://doi.org/10.1016/j.jtte.2021.07.008>.
11. B. Zhang, M. Xi, D. Zhang, H. Zhang, B. Zhang, The effect of styrene-butadiene-rubber/montmorillonite modification on the characteristics and properties of asphalt, *Construction and Building Materials* 23(10) (2009) 3112-3117, <https://doi.org/10.1016/j.conbuildmat.2009.06.011>.
12. M. Vamegh, M. Ameri, S.F. Chavoshian Naeni, Performance evaluation of fatigue resistance of asphalt mixtures modified by SBR/PP polymer blends and SBS, *Construction and Building Materials* 209 (2019) 202-214, <https://doi.org/10.1016/j.conbuildmat.2019.03.111>.
13. M. Liao, Z. Liu, Y. Gao, L. Liu, S. Xiang, Study on UV aging resistance of nano-TiO₂/montmorillonite/styrene-butadiene rubber composite modified asphalt based on rheological and microscopic properties, *Construction and Building Materials* 301 (2021) 124108, <https://doi.org/10.1016/j.conbuildmat.2021.124108>.
14. Z. Zhao, S. Wu, Q. Liu, C. Yang, Y. Zou, P. Wan, Feasibility assessment of CeO₂ nanoparticles as aging-resistant agent of asphalt, *Construction and Building Materials* 330 (2022) 127245, <https://doi.org/10.1016/j.conbuildmat.2022.127245>.

15. V.F.d.S. Neto, L.C.d.F.L. Lucena, A.G. de Barros, A.E.d.F.L. Lucena, P.G.T.M. Filho, Rheological evaluation of asphalt binder modified with zinc oxide nanoparticles, *Case Studies in Construction Materials* 17 (2022) e01224, <https://doi.org/10.1016/j.cscm.2022.e01224>.
16. J. Sun, Z. Ji, Q. Xu, Y. Lu, S. Li, Influence of nano- Al_2O_3 on the evolution of molecular weight, morphology, and rheology of SBS-modified asphalt, *Journal of Materials in Civil Engineering* 35 (10) (2023) 04023361, <https://doi.org/10.1061/JMCEE7.MTENG-16088>.
17. W.B. Broering, J.V.S. de Melo, A.L. Manfro, Modification of the asphalt binder with nano-aluminum oxide: An alternative to improve the thermal conductivity and the rheological properties of the asphalt matrix, *Journal of Testing and Evaluation* 52 (2) (2024) 1109–1128, <https://doi.org/10.1520/JTE20230402>.
18. A.M. Adnan, J. Wang, Enhancement of rheological performance and compatibility of tire rubber-modified asphalt binder with the addition of graphene, *Construction and Building Materials* 402 (2023) 133038, <https://doi.org/10.1016/j.conbuildmat.2023.133038>.
19. Y. Mamuye, M.-C. Liao, N.-D. Do, Nano- Al_2O_3 composite on intermediate and high temperature properties of neat and modified asphalt binders and their effect on hot mix asphalt mixtures, *Construction and Building Materials* 331 (2022) 127304, <https://doi.org/10.1016/j.conbuildmat.2022.127304>.
20. B. Yang, S. Liu, Z. Liu, Y. Hou, C. Yu, J. Ding, C. Deng, Corrosion resistance of Al_2O_3 – SiC –C castables reinforced by sol-gel method prepared titanium carbide modified graphite, *Materials Chemistry and Physics* 348 (2026) 131585, <https://doi.org/10.1016/j.matchemphys.2025.131585>.
21. M. Mubarak, S.I.A. Ali, A. Ismail, N.I.M. Yusoff, Rheological Evaluation of Asphalt Cements Modified with ASA Polymer and Al_2O_3 Nanoparticles, *Procedia Engineering* 143 (2016) 1276–1284, <https://doi.org/10.1016/j.proeng.2016.06.135>.
22. G. Tahmouresi, M. Amouzadeh Omrani, H. Divandari, A. Seyedkazemi, Laboratory study of the surface-physical behavior of asphalt mixtures containing LECA and modified with nano- Al_2O_3 , *Results in Engineering* 30 (2026) 109823, <https://doi.org/10.1016/j.rineng.2026.109823>.
23. A. Chelovian, G. Shafabakhsh, Laboratory evaluation of Nano Al_2O_3 effect on dynamic performance of stone mastic asphalt, *International Journal of Pavement Research and Technology* 10(2) (2017) 131–138, <https://doi.org/10.1016/j.ijprt.2016.11.004>.

24. A.M. Adnan, J. Wang, Investigation of the effects of nano-Al₂O₃ addition on compatibility, rutting and fatigue properties of styrene-butadiene-rubber modified asphalt, *Construction and Building Materials* 416 (2024) 135267, <https://doi.org/10.1016/j.conbuildmat.2024.135267>.
25. H.J. Kadhim, A. Modarres, S. Al-Busaltan, Rheological and microstructural properties of nano-composite bitumen modified by nano-alumina and low-SBS content, *Case Studies in Construction Materials* 20 (2024) e03244. <https://doi.org/10.1016/j.cscm.2024.e03244>.
26. L. Wang, F. Liang, Z. Li, Q. Zhao, Investigation on the rheological properties and microscopic characteristics of graphene and SBR composite modified asphalt, *Coatings* 13 (7) (2023) 1279, <https://doi.org/10.3390/coatings13071279>.
27. Z. Ren, Y. Zhu, Q. Wu, M. Zhu, F. Guo, H. Yu, J. Yu, Enhanced storage stability of different polymer modified asphalt binders through nano-montmorillonite modification, *Nanomaterials* 10 (4) (2020) 641, <https://doi.org/10.3390/nano10040641>.
28. Y. Wang, Y. Xiong, M. Yue, et al., Identifying the thermal storage stability of polymer-modified asphalt with carbon nanotubes based on its macroperformance and micromorphology, *Advances in Materials Science and Engineering* 2021 (2021) 6637999, <https://doi.org/10.1155/2021/6637999>.
29. W. Li, X. Ji, K. Gai, Y. Yang, Q. Wang, T. Zhao, Regulating crystalline behavior to create fully crystallized α -Al₂O₃-mullite continuous ceramic fibers derived from the melt-spinning of polymer precursor, *Ceramics International* 51(6) (2025) 7897-7905, <https://doi.org/10.1016/j.ceramint.2024.12.226>.
30. A. Eltwati, M.R. Hainin, F. Tarhuni, E. Jusli, M. Alamri, Effect of waste engine oil and warm mix additive on the physical, rheological, and short-term aging attributes of Styrene–Butadiene Rubber-modified asphalt binders, *Case Studies in Construction Materials* (2024) e03433, <https://doi.org/10.1016/j.cscm.2024.e03433>.
31. P. Xu, Y. Wang, Y. Bi, Z. Chen, J. Gao, W. Wang, Enhancing crack resistance of asphalt pavements in high-altitude areas through high solubility Rubber/SBS composite modified asphalt, *Fuel* 404 (2026) 136351, <https://doi.org/10.1016/j.fuel.2025.136351>.