International Journal of Advances in Applied Sciences (IJAAS)
Vol. 14, No. 3, September 2025, pp. 793~803
ISSN: 2252-8814, DOI: 10.11591/ijaas.v14.i3.pp793-803

Eco-friendly durable asphalt using maleic-modified rosin ester

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Article Info

Article history:

Received Sep 16, 2024
Revised May 23, 2025
Accepted Jun 8, 2025

Keywords:

Asphalt pen 60/70
Maleic rosin ester
Modified asphalt
Penetration
Softening point

ABSTRACT

Asphalt, a crucial component of transportation infrastructure, particularly in regions with high traffic loads and extreme climates, often lacks the necessary elasticity, strength, and durability. Various asphalt modifiers have been explored, but many struggle with cost, thermal stability, and environmental impact. This study, however, investigates maleic-modified rosin ester, a gum rosin derivative, as a sustainable and cost-effective asphalt modifier. The base asphalt was heated to 150-190 °C, sheared at 100 rpm, and combined with 4-20% maleic rosin ester and sulfur. The modified asphalt was subjected to tests, including penetration, softening point, ductility, density, kinematic viscosity, Fourier transform infrared (FTIR), and dynamic shear rheometer (DSR) tests. The results are promising, showing that maleic rosin ester enhances penetration resistance and softening points while maintaining ductility and viscosity within acceptable limits. Chemical analysis confirmed improved adhesion, crosslinking, and thermal stability, making the modified asphalt more deformation-resistant. This suggests that maleic-modified rosin ester is a viable alternative to synthetic polymers, offering improved durability and sustainability. The enhanced durability of the modified asphalt provides confidence in its long-term performance, making it a reliable choice for transportation infrastructure.

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1. INTRODUCTION

The rapid population growth and economic expansion in Indonesia and several other Asian countries have led to increasing traffic crowding, which, combined with the high volume of land transportation, has resulted in significant pavement issues. The extreme equatorial climate, indicated by high temperatures and intense rainfall, has significantly contributed to the degradation of road surfaces, making asphalt pavement failures a critical issue. Common types of road failures include rutting due to excessive traffic loads, fatigue cracking from cyclic stress, and thermal cracking due to temperature fluctuations [1]. These issues lead to high maintenance costs and frequent repairs, creating economic burdens for developing nations. Consequently, there is an urgent need for cost-effective and high-performance asphalt modifications that can enhance road durability under severe environmental and loading conditions [2]–[5].

The research has focused on modifying asphalt with a renewable substance to improve the longevity of asphalt mixtures and, consequently, asphalt pavements to prevent road pavement failure. Various modifications have been explored to enhance their mechanical properties, including altering the asphalt binder with synthetic polymers or chemicals [6]–[10], incorporating crumb rubber [11], fibers [12], and biomass-derived materials [13] into the mixture [14], among others [15]. Mahmood and Kattan [16] found that adding a low concentration of styrene-butadiene-styrene (SBS) at 5-10% to asphalt mixtures enhanced the composite's viscosity, penetration resistance, and tensile strength. However, SBS is expensive, limiting its feasibility for large-scale applications in developing countries. Furthermore, the water stability performance of the asphalt mixture improved with the inclusion of glass, nylon, and polyester fibers. Various synthetic and natural fibers, such as coconut, corn, palm, and sisal, improved the tensile strength and cracking resistance [17], [18]. Polyester fibers in the asphalt mixture notably improved low-temperature durability and cracking resistance [19]. However, natural fibers tend to absorb water, which can weaken the asphalt matrix over time. This could lead to premature degradation and increased susceptibility to loss of adhesion between binder and aggregate. Additionally, concerns have been raised regarding the long-term environmental impact and sustainability of synthetic fiber. Biomass-derived asphalt modifiers, such as waste vegetable oils and biobased polymers, have been investigated to enhance asphalt flexibility and performance. However, these modifiers often face challenges related to thermal stability and aging resistance, highlighting the ongoing need for research and development in the field of asphalt technology [18]–[20].

Despite advancements in asphalt modification using various materials, including synthetic polymers, fibers, and biomass-derived substances, a notable research gap remains concerning the application of maleic-modified rosin ester as an asphalt modifier. While previous studies have explored the use of pine resin derivatives, such as crude pine resin and gum rosin, to enhance the properties of asphalt mixtures [20], they did not explicitly address maleic-modified rosin ester influence on asphalt's mechanical and rheological properties. Rosin ester is a promising material for enhancing the quality of asphalt. It is a natural, sustainable, low-cost, thermally stable asphalt modifier derived from pine resin and readily modifiable through chemical processes. Pine resin, mainly from tropical regions, is a valuable and abundant resource with a wide range of potential applications [20]–[22]. Rosin ester exhibits viscoelastic properties, combining the characteristics of both solids and liquids. Its versatility makes it a valuable component in various industries [23]. The addition of maleic anhydride to modified rosin has been found to significantly improve the mechanical and crystallization properties of aliphatic polyesters. This improvement is primarily due to the presence of polar functional groups such as carboxylic acid groups (-COOH) or anhydride (-COCO-), which enhance adhesion and form strong chemical bonds with polar compounds. The maleic-modified rosin also demonstrates excellent thermal stability, making it ideal for heat-resistant applications and resistant to oxidation due to the formation of stable chemical bonds. Furthermore, the maleic modification promotes crosslinking within the resin's structure, creating a robust three-dimensional network that further enhances thermal stability and inhibits oxidation at elevated temperatures [22], [24]. Maleic anhydride groups can improve the resin's glass transition temperature (Tg). This modification can result in a higher melting or softening point by reducing its susceptibility to deformation or flow at high temperatures [25]. It enhances mechanical properties while maintaining economic feasibility and making it a promising alternative for developing nations. It also addresses critical performance limitations observed in conventional bio-based asphalt modifiers.

The commonly used base asphalt in highway infrastructure construction is the 60/70 penetration asphalt type (Asphalt pen 60/70) with a softening point value of 48 °C. In response to extreme weather conditions and high traffic loads, the addition of maleic-modified asphalt has emerged as a practical and cost-effective alternative for producing a suitable performance asphalt binder. By combining maleic-modified rosin and sulfur in the proper mass ratio with asphalt and carrying out the mixture operation at a suitable temperature, we can produce an improved asphalt binder at a lower cost. Therefore, this study investigates the practical implications of using maleic-modified rosin ester on the viscosity, softening point, and thermal stability of asphalt, providing valuable insights for future construction projects.

2. RESEARCH METHOD

2.1. Raw materials

PT. Dhisa Manunggal Karya of Surabaya, Indonesia, provided the 60-70 pen base asphalt, and its performance index test results are listed in Table 1. The maleic-modified rosin was provided by PT. Indopicri, also located in Surabaya, Indonesia, and its technical properties are listed in Table 2. Both the 60/70 pen base asphalt and maleic-modified rosin are used without prior treatment. Sulfur was supplied by Bratachem Surabaya.

2.2. Preparation method

The preparation of modified asphalt follows a systematic process to ensure optimal dispersion, chemical interaction, and performance enhancement [26]. First, the base asphalt is heated to 150-190 °C and sheared at 100 rpm. It is equipped with temperature control to facilitate uniform blending and prevent premature degradation of components. Then, 4-20 wt.% of maleic-modified rosin ester was gradually added to the molten asphalt while maintaining continuous stirring to achieve progressive incorporation and even distribution within the asphalt matrix. The appropriate amount of sulfur was added to the mixture to promote crosslinking, and the mixture was sheared at the same rotating speed for one hour to ensure a homogeneous mixture. The experimental variations of modified rosin composition on pen 60/70 base asphalt are detailed in Table 3.

Table 1. The properties of base asphalt

Parameter	Unit	Measured value	Technical requirement
Penetration (25 °C)	0.1 mm	66	60-70
Softening point	°C	49.5	48-56
Ductility (25 °C)	cm	140	≥100
Density	g/mL	1.03	1.01-1.06
Kinematic viscosity	cst	495	-

Table 2. The properties of the modified maleic rosin ester

Parameters	Unit	Properties
Appearance	-	Particles
Viscosity (Gardner, 70% in toluene)	-	Z2-Z4
Acid value	mg KOH/g	≤35
Color (Gardner)	-	≤3
Softening point	°C	130±5

Table 3. The maleic rosin ester mass ratio experiments

Sample	Pen 60/70 base asphalt (%)	Rosin ester (%)	Sulphur (%)
A	100	0	0
B	96	4	0.0013
C	95	5	0.0013
D	90	10	0.0013
E	85	15	0.0013
F	80	20	0.0013

2.3. Characterization of modified asphalt

After the production of the asphalt-modified mixture, physical tests were conducted to assess various key properties. These tests included measuring asphalt penetration at 25 °C, determining the specific gravity, assessing kinematic viscosity at 135 °C, evaluating the softening point, and testing ductility at 25 °C. Each of these properties was tested under specific Indonesian National Standards: SNI 2456: 2011 for asphalt penetration, SNI 2441: 2011 for specific gravity, SNI 03-6641-2000 for kinematic viscosity, SNI 2434: 2011 for softening point, and SNI 2442: 2011 for ductility. The results of these tests were carefully analyzed to ensure the asphalt mixture met the quality and performance criteria set by these national standards.

Fourier transform infrared (FTIR) spectroscopy is a valuable tool for analyzing the changes in functional groups and molecular structures in asphalt after adding modifiers. This technique helps to reveal the modification mechanisms of the additives on the asphalt. The FTIR spectra of the base asphalts, binders, and modified asphalts were obtained using a Cary 630 FTIR spectrometer manufactured by Agilent Technologies (California, USA). The scanning range for the FTIR analysis was from 4,000-650 cm^{-1}, ensuring a comprehensive view of the relevant infrared absorption bands. The spectrometer was set to a resolution of 4 cm^{-1}, allowing for precise and detailed spectral data collection.

The dynamic shear rheometer (DSR) test method was employed to analyze the viscoelastic characteristics of both asphalt and modified asphalt. This test measures key parameters such as the rutting factor ($G^*/\sin \delta$) and phase angle (δ), which are crucial for evaluating the high-temperature performance of the asphalt. For the base asphalt, the test was conducted at 52, 58, 64, and 70 °C temperatures. In contrast, the modified asphalt was tested at a broader range of temperatures, including 52, 58, 64, 70, and 76 °C. The DSR test was conducted at a mean frequency of 1.59 Hz to obtain accurate and consistent results.

3. RESULTS AND DISCUSSION

This study explores the impact of the mass ratio of modified maleic rosin ester and temperature on modified asphalt's physical and chemical properties. The research focuses on understanding how variations in these factors influence the performance and characteristics of the asphalt mixture. In addition to the mass ratio and temperature, other key variables, such as sulfur composition, mixing duration, and shear speed, are also being considered. By examining these factors, the study identifies the optimal conditions for modifying asphalt to improve its quality and durability.

3.1. The effect of maleic rosin ester mass ratio on physical properties of modified asphalt

The study aimed to examine how maleic rosin ester's composition affects modified asphalt's properties. The process involved mixing 60/70 base asphalt with maleic rosin ester and sulfur at a shear speed of 100 rpm and a mixing temperature of 190 °C for 1 hour. During the experiments, the asphalt used was a 60/70 pen base, and the composition ranged from 80 to 100%. The modified rosin ester used ranged from 0-20%, while the sulfur, which acts as a crosslinking agent, was either present at 0.0013% or not used. Sulfur can enhance the elasticity and flexibility of asphalt, making it more resistant to cracking, deformation, and rutting.

Table 4 presents the physical properties of maleic-modified rosin ester-modified asphalt and compares it with the technical requirements of synthetic elastomer-modified asphalt. The key parameters analyzed include penetration at 25 °C, kinematic viscosity at 135 °C, softening point, ductility at 25 °C, and specific density. Base asphalt has a high penetration value (66 mm), indicating its relative softness. As the rosin ester content increases, penetration gradually decreases, reaching 4 mm at 20% rosin ester. The 95:5 and 96:4 compositions meet the minimum penetration requirement (≥40 mm), making them optimal for applications requiring balanced hardness and flexibility. Compositions with >10% rosin ester become excessively hard, which may cause brittleness and cracking under thermal stress. We found that the maleic rosin ester increases the viscosity of asphalt, making the asphalt harder. It correlates with incorporating maleic rosin ester, which contributes to greater hardness in the modified asphalt system. Maleic rosin ester is associated with increased crosslinking, encouraging the development of a three-dimensional network within the modified asphalt. Due to its acid group, maleic rosin ester can release protons (H+), initiating a reaction with asphalt molecules containing carboxylic groups (COOH). This crosslinking enhances the strength and stability of the asphalt but simultaneously makes it harder and less penetrable. The interaction between maleic rosin esters and carboxylic groups in asphalt significantly impacts the viscoelastic properties of the material, thus influencing the penetration value. The results are findings that align with existing research [14], [27], [28] where rosin ester modified asphalt exhibits improved hardness and rutting resistance, but needs optimization to prevent excessive rigidity.

Additionally, Table 4 demonstrates an increase in the modified asphalt's kinematic viscosity compared to the base asphalt pen 60/70. All compositions meet the viscosity requirement (≤3,000 cSt). The viscosity increases with the rosin ester content from 495 cSt in the 100:0 (A) composition to 956 cSt in the 90:10 (D) composition, showing a more structured network due to enhanced molecular interactions. However, at 20% rosin ester (F), viscosity drops to 152 cSt, which may indicate a change in the material's flow properties, possibly due to phase separation or reduced compatibility at high modification levels. Our findings confirm that rosin ester increases viscosity in moderate amounts, but excessive use may disrupt optimal flow properties. The incorporation of maleic rosin ester leads to an enhancement in asphalt viscosity. Not only does the molecular structure of rosin ester contribute to higher viscosity, but the chemical interactions between rosin ester and asphalt molecules also substitute a more complex and interconnected molecular network, thus elevating asphalt viscosity. This bonding leads to stronger intermolecular interactions and improved cohesion among asphalt molecules, further increasing asphalt viscosity. Arabani *et al.* [29] found that acid-treated asphalt increased viscosity, improving rutting resistance but sometimes making mixing difficult. Karahançer [26] also noted that rosin-based curing agents increased asphalt viscosity, similar to the trend observed in this study.

Adding rosin ester to the modified asphalt can enhance the softening point, as demonstrated in Table 4. The compositions from 96:4 (B) onwards meet this requirement, with the softening point increasing as the elastomer content increases, indicating improved temperature resistance. Adding 4-20% rosin ester can elevate the softening point of modified asphalt by up to 33% compared to the softening point of the base pen 60/70 asphalt. Compositions B-F (≥4% rosin ester) meet the softening point requirement, confirming that rosin ester enhances high-temperature stability. Rosin ester modifications effectively increase heat resistance, making it comparable to synthetic polymers. It aligned with Jia *et al.* [12] showed that synthetic fiber-reinforced asphalt increased the softening point but sometimes reduced ductility, and Yan *et al.* [30] found that petroleum resin modifications increased the softening point by up to 15%. This situation occurs because maleic rosin ester makes the network structure formed inside the asphalt denser, more stable, and improves the structural strength and the high-temperature performance of the modified asphalt. The study indicates that the resistance of modified asphalt to high-temperature deformation is remarkably improved by incorporating modified rosin ester. A higher rosin ester content enhances the softening point of modified asphalt. This improvement is attributed to the chemical bond between modified rosin ester and asphalt and the high melting point of rosin ester. The mixture's melting point tends to increase when rosin ester is mixed with asphalt, limiting the movement of asphalt molecules and enhancing high-temperature stability.

Table 4. Modified asphalt physical properties of different maleic rosin ester mass ratios

Parameters	Technical requirements of synthetic elastomer modified asphalt	Composition [asphalt: rosin ester]; Sulphur 0.0013%; T=190 °C; n=100 rpm; t =1 h)				
		100:0 (A)	96:4 (B)	95:5 (C)	90:10 (D)	85:15 (E)
Penetration 25 °C (0.1 mm)	≥40	66	39	35	20	10
Kinematic viscosity 135 °C (cSt)	≤3,000	495	766	779	956	915
Softening point (°C)	≥54	49.5	55	55	58.9	62
Ductility 25 °C (cm)	≥100	140	140	140	140	20
Specific density	≥1	1.03	1.04	1.04	1.04	1.05

The study also reveals that ductility remains stable by adding up to 10% rosin ester. However, exceeding 10% makes the asphalt very brittle, significantly reducing ductility to 98.6% of the base asphalt's ductility value. This is consistent with the observed trends, where compositions from 100:0 (A) to 90:10 (D) maintain a high ductility, exceeding the required standards. However, at 15-20% rosin ester, ductility drops drastically, making the asphalt brittle and susceptible to cracking. The trend is similar to Mahmood and Ahmed [17], who observed that natural fibers enhanced tensile strength but reduced ductility. Karahançer [26] also found that rosin modification increased hardness but decreased ductility. It confirms that moderate rosin ester content maintains ductility, but excessive content leads to brittleness.

The specific gravity of modified asphalt increases due to the higher specific gravity of rosin ester than asphalt. Consequently, an increased rosin ester composition leads to higher specific gravity in modified asphalt than in the base pen 60/70 asphalt. All compositions meet the minimum specific density requirement of ≥1, with values ranging from 1.03-1.05, confirming that rosin ester does not negatively impact compaction. It had similar results to Guha and Assaf [15] in that cement-modified asphalt had a similar density increase, which improved load-bearing capacity.

The study found that adding maleic-modified rosin ester significantly enhanced penetration resistance, softening point, and viscosity while maintaining acceptable ductility and density. Ductility parameters are met when the composition contains up to 10% rosin ester; beyond this threshold, the ductility of the modified asphalt falls short of technical standards, indicating increased brittleness. In summary, the 96:4 (B) and 95:5 (C) compositions offer the best overall balance, meeting all technical requirements and providing a favorable combination of penetration, viscosity, softening point, ductility, and density. In contrast, compositions with higher maleic rosin ester content, such as 85:15 (E), demonstrate diminishing returns in penetration and ductility, which could negatively impact the asphalt's performance in practical applications. The results are in line with SBS-modified asphalt for its ability to improve penetration resistance and softening point [26]. However, it is costly and environmentally challenging. Maleic-modified rosin ester is a viable alternative to synthetic polymers, while offering a more sustainable and cost-effective solution.

3.2. The effect of mixing temperature on the physical properties of modified asphalt

The temperature at which asphalt is mixed significantly impacts its properties and performance in various applications. The components may not mix properly when the temperature is too low, leading to a rough and inconsistent mixture. Conversely, excessively high temperatures can cause the asphalt to age prematurely, affecting its characteristics. This study investigated the effects of varying mixing temperatures at 190, 170, and 150 °C on a modified asphalt composition of 96% 60/70 base asphalt, 4% rosin ester, and 0.0013% sulfur. The parameters assessed include penetration, kinematic viscosity, softening point, ductility, and density, which are critical in determining the asphalt's performance and durability. The results, summarized in Table 5, demonstrate that the penetration at 25 °C remains close to the target value of ≥40, with readings of 39, 44, and 42 for the respective temperatures. This suggests a minor variation in penetration but is still within the acceptable range for good workability. Specifically, at 150 °C, the penetration value is lower than at 170 °C, suggesting that the higher viscosity at this lower temperature hinders the interaction between rosin ester and asphalt components, resulting in poorer homogeneity. Conversely, at 190 °C, while the asphalt viscosity decreases, the exceptionally high temperature may lead to asphalt coagulation, oxidation, and the loss of volatile components, resulting in a harder asphalt with a decreased penetration value. The table further illustrates that the optimal mixing temperature for this specific asphalt composition is around 170 °C, where the penetration value meets the required specification of ≥40.

Additionally, kinematic viscosity at 135 °C remains well below the maximum allowable limit of ≤3,000 cSt across all tested temperatures, though it increases slightly as the temperature decreases, ranging from 766.2 cSt at 190 °C to 827.7 cSt at 150 °C. This indicates that the material maintains suitable flow properties for application. Moreover, the softening point slightly exceeds the minimum specification of ≥54 °C, suggesting the material exhibits good thermal stability. This consistency across temperatures suggests that the softening point is relatively stable, although more reliable results may be achieved at the extremes of the tested temperature range. Ductility at 25 °C is consistently high, exceeding the minimum required value of 100 cm, indicating excellent flexibility at lower temperatures. Density remains constant at 1.041-1.044, above the minimum required value of 1, ensuring adequate structural integrity for the modified asphalt. The trends of the study are consistent with studies on modified asphalts, where modifiers like rosin ester improve specific characteristics like ductility and penetration while maintaining acceptable viscosity and softening point. Research in [31], [32] has shown similar improvements in ductility and softening point with the use of modifiers, suggesting that the modification process enhances the asphalt's performance under various environmental conditions, particularly in maintaining workability at lower temperatures and ensuring durability at higher temperatures.

The optimal mixing temperature for this modified asphalt composition is around 170 °C, where most properties either meet or closely approach the required specifications. While slightly higher or lower temperatures still produce acceptable results, some trade-offs in penetration and softening points exist. The consistent ductility and kinematic viscosity across all temperatures suggest that these properties are relatively unaffected by changes in mixing temperature, indicating stability under varying conditions.

Table 5. Modified asphalt physical properties at different mixing temperatures

Parameter	Modified asphalt according to specification 2010	Mixing temperature (°C) at composition [asphalt: rosin ester=96:4]; Sulphur=0.0013%; n=100 rpm; t=1 h		
		190	170	150
Penetration 25 °C (0.1 mm)	≥40	39	44	42
Kinematic viscosity 135 °C (cSt)	≤3,000	766.2	770.2	827.7
Softening point (°C)	≥54	55	54.2	54
Ductility at 25 °C (cm)	≥100	140	140	140
Density	≥1	1.041	1.044	1.041

Table 6 provides a detailed comparison of the asphalt parameters for pen 60/70 asphalt, polymer-modified asphalt, and rosin ester-modified asphalt, highlighting the superior qualities of the maleic rosin ester modification. Mixing 96% asphalt, 4% gum rosin ester, and 0.0013% sulfur at a temperature of 170 °C for 90 minutes yields a modified asphalt that meets the requirements of the 2010 general specifications for polymer-modified asphalt. The resulting gum rosin ester modified asphalt demonstrates a balanced performance across several critical parameters. The softening point of 54.4 °C is slightly higher than that of synthetic elastomer-modified asphalt, indicating a similar but slightly superior heat resistance. Additionally, the penetration value of 45 (0.1 mm) suggests that the modified asphalt is also hard but slightly softer than the synthetic elastomer modified asphalt, yet still within acceptable limits, making it well-suited for various applications.

The ductility value, which exceeds 140 cm, exceeds the required limit and highlights the modified asphalt's superior flexibility and resilience, showing it is even more flexible and able to withstand more strain before breaking. This high ductility is crucial for resisting permanent deflection and cracking, particularly in regions with significant thermal cycling. The gum rosin ester-modified asphalt has a density of 1.041 g/mL, which is slightly higher, suggesting it may have slightly better structural integrity. The specific gravity of 1.041 g/mL indicates that the modified asphalt has adequate compaction properties, ensuring stability and load-bearing capacity. Furthermore, the viscosity at 135 °C, measured at 809 cSt, remains well within the acceptable range, suggesting that the asphalt has a medium level of viscosity and is easy to apply while maintaining sufficient thickness to resist flow under traffic load.

Table 6. The comparison of base and modified asphalt with synthetic elastomer modified asphalt technical requirement

Parameters	Asphalt pen 60/70	Synthetic elastomer modified asphalt	Gum rosin ester modified asphalt
Softening point, °C	≥48	≥54	54.4
Penetration, 0.1x mm	60-70	Min. 40	45
Ductility, cm	≥100	≥100	140
Density, g/mL	Min. 1	Min. 1	1.041
Viscosity, cSt @135 °C	≥300	≤3,000	809

The maleic rosin ester-modified asphalt exceeds several critical specifications, including softening point, ductility, and viscosity. This makes it an ideal choice for applications that require improved flexibility, durability, and thermal resistance. Additionally, it has a slightly higher density and moderate viscosity, which enhances its adaptability to various environmental conditions. These properties contribute to the potential for improved road lifespan and performance, particularly in flexible pavements.

3.3. The effect of adding maleic rosin ester on the chemical changes of modified asphalt

The impact of adding maleic rosin ester on the chemical properties of modified asphalt is shown in Figure 1. The figure presents the FTIR spectra for base asphalt, maleic rosin ester, and maleic rosin ester-modified asphalt. The analysis covers the wavenumber range from 400 to 3,900 cm^{-1}, typical for identifying functional groups and bonds in materials. In the asphalt spectrum, the stretching vibration of its functional groups shows that the main substances existing in base asphalt are long-chain alkanes, aliphatic hydrocarbons, aromatic compounds, and various derivatives. It has peaks at 2,920 and 2,851 cm^{-1}, corresponding to CH_3 stretching and C-H stretching, respectively, indicating aliphatic bonds and methylene groups in hydrocarbon chains, a major component in asphalt. The peak at 1,457 cm^{-1} indicates the presence of aromatic C=C bonds, representing the aromatic fraction in asphalt and C-H bending vibrations. The spectrum shows a relatively simple structure, mainly suggesting saturated hydrocarbons with fewer modifications or additives. The maleic rosin ester peaks at 2927 and 2868 cm^{-1} also indicate CH_3 stretching and aliphatic C-H stretching vibration.

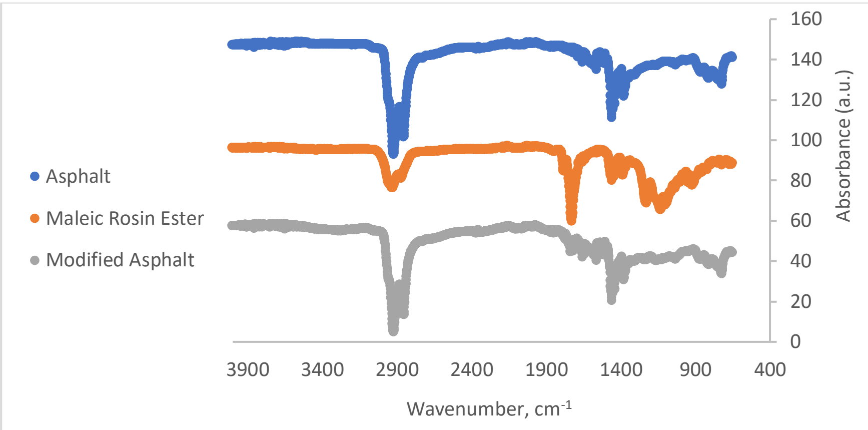


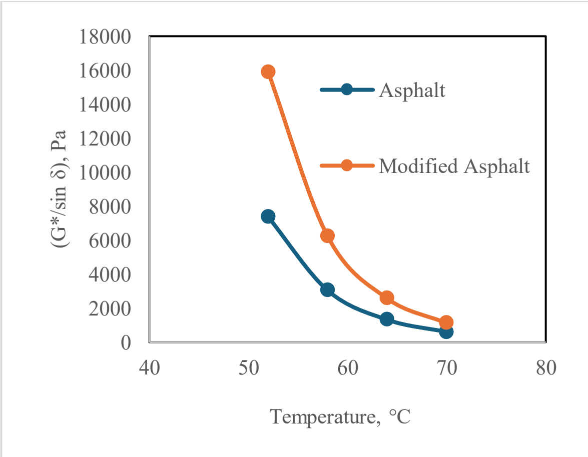
Figure 1. FTIR spectrum analysis of asphalt, maleic rosin ester, and modified asphalt

Furthermore, the peaks at 1,848, 1,749, 1,727, and 1,036 cm^{-1} are attributed to C=O stretching (both symmetric and asymmetric), typical of ester groups, indicating the presence of the maleic rosin ester. The modified asphalt shows similar features to the maleic rosin ester but with more distinct differences in the fingerprint region (under 1,500 cm^{-1}). The absorption peak at 1,025.91 cm^{-1} represents the stretching vibration of aliphatic sulfoxide and benzyl sulfoxide. The S-O group is polar. After depolarization occurs, the group will interact with other dipole groups in the matrix asphalt, improving the viscosity of the asphalt. Meanwhile, the peak at 1,127 cm^{-1} characterizes C-C stretching. Lastly, the C-O-C structure is denoted by peaks at 905 cm^{-1}. The appearance of new peaks or shifts in existing ones indicates that the modification has significantly altered the chemical structure, possibly involving the introduction of various chemical groups that affect the asphalt's performance.

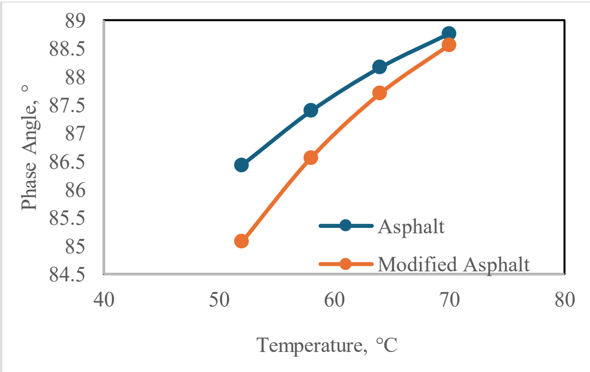
3.4. Dynamic shear rheometer analysis

Figure 2 describes the variations in the rutting factor and phase angle for both base and modified asphalt as temperature changes. Figure 2(a) shows that the rutting factor for both types of asphalt decreases as the temperature increases. This indicates that the material becomes softer and more fluid as it warms up. However, this decrease becomes more gradual over time, highlighting the significant influence of temperature on the asphalt's rutting resistance. Compared to the base asphalt, the modified form exhibits a much higher rutting factor, signifying superior resistance to rutting. The modification improves the stiffness and resistance to deformation at higher temperatures. A higher value of the rutting factor indicates better resistance to rutting. It has an advantage in anti-rutting performance under high traffic and temperature conditions. Furthermore, studies on other modified asphalts, such as those incorporating SBS polymers, have demonstrated improvements in high-temperature performance. For instance, research has shown that adding SBS to asphalt increases the complex shear modulus (G^*) and decreases the phase angle (δ), indicating enhanced stiffness and reduced viscosity. However, the specific quantitative DSR results vary depending on the SBS content and testing conditions [33].

In Figure 2(b), it is evident that as the temperature increases, the phase angle of each asphalt gradually increases. The phase angle of the base asphalt is more significant than that of the modified asphalt, indicating that the base asphalt exhibits more liquid-like behavior and has viscous properties. This implies that the base asphalt may be more susceptible to deformation or rutting under load. On the other hand, the phase angle of the modified asphalt decreases, suggesting that the modifier and the matrix asphalt create a more stable internal structure after blending, leading to improved resistance to permanent deformation. The temperature-sensing performance of modified asphalt has been improved. It shows better viscoelastic properties, the most vigorous resistance to permanent deformation, and the lowest sensitivity to temperature. In summary, the performance of asphalt in terms of temperature sensitivity has been enhanced. The DSR results from this study, which involves maleic rosin ester-modified asphalt, are consistent with existing literature, demonstrating that rosin modification effectively enhances the stiffness and high-temperature performance of asphalt binders.



(a)



(b)

Figure 2. Rheological performance of base and maleic-modified rosin ester asphalt binder evaluated using DSR testing of (a) the high temperature rutting resistance and (b) the viscoelastic and elasticity behavior

4. CONCLUSION

This study demonstrates that maleic-modified rosin ester is a practical, sustainable, and cost-efficient asphalt modifier. It significantly improves key properties of pen 60/70 base asphalt, including penetration resistance, softening point, viscosity, and thermal stability, while maintaining acceptable ductility and density. The modified asphalt meets and exceeds technical specifications for synthetic elastomer-modified asphalts, enhancing high-temperature performance and resistance to rutting and deformation. The results align with existing literature, showing that maleic-modified rosin ester provides a promising alternative to synthetic polymers, offering improved durability and sustainability at a lower cost. Optimal performance is achieved with 4-10% rosin ester content, making it suitable for large-scale applications.

FUNDING INFORMATION

This research was financially supported by the Indonesian Ministry of Education, Culture, Research, and Technology through the Fundamental Research Scheme for Higher Education Excellence under contract numbers 109/E5/PG.02.00.PL/2024 and 004/SP2H/PT/LL7/2024.

AUTHOR CONTRIBUTIONS STATEMENT

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Yosafat Gary Tegar Harijono		✓			✓	✓	✓		✓		✓			

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author, [ES], upon reasonable request.

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