



Characterizing The Properties of Polymer-Modified Bitumen with a Mix of Sasobit and LDPE To Be Used in Warm Mix Asphalt

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Abstract

The use of polymers to modify asphalt binder properties in road paving has been increased over the past few decades, producing asphalt mixes that can withstand the growth in traffic load concurrent with development. Therefore, the use of modified asphalt binders has become increasingly popular in recent years to enhance the properties of pavement roads by incorporating various materials, including sustainable ones. This study was conducted as part of a larger study for enhancing asphalt binder properties by using 1%, 2%, 3%, and 4% of sasobit (S) as a warm mix asphalt additive and 1%, 2%, 3%, and 4% of low-density polyethylene (L) as sustainable materials and the mix combination (MC) of both of them. The performance of the treated bitumen was evaluated using conventional tests, including penetration, softening point, and ductility, to assess the physical properties of the mixtures. More advanced tests, including a dynamic shear rheometer (DSR) and a rolling thin film oven test (RTFOT), were conducted. The results show that 4% of Sasobit and 1% of LDPE achieved the optimal values, which significantly enhances the performance of asphalt binders, offering a synergistic blend of sustainability and functionality. LDPE improves the binder's elasticity and resistance to deformation, while Sasobit lowers mixing and compaction temperatures, boosting workability and energy efficiency. Their combination increases the softening point and reduces penetration and ductility, indicating better high-temperature performance. Viscosity is notably reduced, facilitating easier handling and mixing. Moreover, Sasobit enhances the binder's resistance to thermo-oxidative aging, with improved ductility retention and thermal stability. The study concluded that using Sasobit and LDPE results in high-performance and durable asphalt mixes that may be highly resistant to permanent deformation and temperature susceptibility.

Keywords: *Asphalt Modified, Sasobit, LDPE, Penetration Index, Temperature Sensitivity, Warm Mix Asphalt.*

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1. Introduction

Asphalt is the main component in asphalt mixtures and is primarily responsible for binding the elements together to form a stable and robust mixture that can withstand traffic loads. Asphalt binder, aggregate, filler, all these ingredients are tied together to create what is called an asphalt concrete mix[1]. The development of asphalt mixtures has gone through a series of development stages, including the creation of other types of asphalt mixtures by reducing the production and application temperature to produce the following types: Warm Mix Asphalt (WMA), Cold Mix Asphalt (CMA), Half Warm Mix Asphalt (HWMA)[2]. Each type is produced for one or more of these reasons: to lower production temperature, reduce emissions, decrease fuel consumption, and minimize environmental pollution[3]. Some researchers were working on developing the asphalt binder by using many materials to produce an asphalt mix with more resistance to the population and urban development that have

occurred over the last years, leading to an increase in traffic loads, which makes it an urgent necessity to develop and modify the properties of asphalt to become capable of bearing and handling these loads[4]. To reduce resource consumption and achieve a clean environment, it is essential to address the issue of large quantities of waste materials, which are considered the world's worst problems due to their pollution-causing nature and difficulty in disposal[5].

Some researchers around the world have turned to reusing these materials as an alternative to certain materials used in daily life. Using recycled waste in asphalt mixtures as additives or a partial or complete substitute for certain materials, such as aggregate or fillers, is one of the most common ways to utilize this waste. In this approach, some researchers used crumb rubber from tire waste [6, 7] to evaluate their effect on the modified binder combined with other sustainable modifiers such as waste-LDPE. Their results showed that all additives improved binder performance in the

presence of SBS and significantly enhanced viscosity and softening point, while CR demonstrated strong aging resistance. The study concludes that using 6% of each additive yields optimal improvements, and incorporating these waste-derived materials enhances environmental sustainability in addition to improved performance and conservation of natural resources. Reclaimed asphalt pavement (RAP), sourced from pavement waste, has also been utilized as an aggregate replacement[6]. Al-Ghurabi and Al-Humeidawi [7] investigated the effect of the RAP particle size on the properties of hot-mix asphalt (HMA), including the volumetric and mechanical properties. Researchers replaced fine and coarse aggregates in HMA with RAP at varying percentages (up to 40%). Results showed that replacing coarse aggregates with RAP up to 40% yielded better mechanical performance and met all volumetric criteria. In comparison, fine aggregate replacement was optimal only up to 20% due to limitations in voids in mineral aggregate (VMA). The study also found that RAP-enhanced mixes demonstrated satisfactory moisture resistance and significantly reduced material cost up to 34% for coarse aggregate replacement. Different types of fly ash can serve as partial or full replacements for fillers[8, 9]. Al-Gurah and Al-Humeidawi [10] also discussed the effect of using different types of fillers, including Rice Husk Ash (RHA) as sustainable materials, to replace the mineral filler with different percentages, including (25%, 50%, 75%, and 100%). Overall, the result showed that incorporating RHA can improve the durability and performance of HMA while promoting sustainable material practices.

In the construction aspect, Al-Nawasir and Al-Humeidawi [11] investigated the impact of using ceramic waste powder (CWP) as a sustainable grout material in semi-flexible pavement (SFP) to enhance moisture resistance and rutting performance. SFP consists of a porous asphalt skeleton injected with cementitious grout. This study explored partial replacement of cement with CWP at ratios of 15–50%. The performance revealed that mixes with 20% and 30% CWP replacement showed significant improvements in moisture resistance and rutting reduction, up to 76% in comparison to the control mixture. The study concludes that 20% CWP replacement is optimal for achieving superior mechanical properties and environmental benefits, offering a sustainable solution for pavement construction by reducing cement usage and recycling ceramic waste.

The modification of bitumen properties by using waste plastic in different aspects, such as elastomers or plastomers, is also used, which significantly affects the rheological properties and influences viscosity by adding elastomers or plastomers at a weight percentage of 2% to 6% of the bitumen. The wet process was used to add these polymers to modify bitumen[12]. Using plastic waste can improve many properties and reduce deformations resulting from high temperatures and traffic loads, such as rutting, fatigue life, and moisture damage. Plastic materials increase the hardness of asphalt, resulting in greater resistance to high temperatures. These improvements depend on the correct mixing process of the plastic materials with the bitumen, which depends on the nature, size, and type of equipment used[13]. Recent studies have increasingly focused on sustainable modifiers such as LDPE and Sasobit to enhance asphalt binder performance while addressing

environmental concerns. Studies on LDPE consistently demonstrate its ability to improve stiffness, tensile strength, and resistance to rutting and fatigue, while also offering economic feasibility and significant waste reduction benefits. Singh and Gupta [14] reported that LDPE mixtures achieved up to 171% higher stiffness and repurposed approximately 750 kg of plastic waste per kilometer of roadway, whereas Kovács, et al. [15] identified 6% LDPE as the optimal dosage and validated its mechanical performance in field trials without requiring additional plant investment. Complementing these findings, Ghani, et al. [16] provided a comprehensive evaluation of waste HDPE and LDPE binders, confirming improved rheological properties and durability under diverse climatic conditions. Sudibyo [17] further distinguished between recycled and virgin LDPE, showing that recycled LDPE can deliver comparable performance, thereby reinforcing its role in circular economy strategies. These findings highlight LDPE's major role in advancing pavement durability and supporting circular economy principles and Sustainability.

In parallel, Sasobit has emerged as the most widely adopted warm mix asphalt (WMA) additive, valued for its viscosity-reducing and workability-enhancing properties. Gong, et al. [18] demonstrated that Sasobit-modified epoxy asphalt retained high strength and durability at reduced production temperatures, thereby improving sustainability without compromising structural integrity. Similarly, Yang, et al. [19] showed that Sasobit significantly lowered binder viscosity and enhanced rutting resistance compared to Deurex, though excessive dosages risked reducing low-temperature flexibility. Xu, et al. [20] further advanced understanding by modelling Sasobit's behavior, revealing its crystalline network formation and transition between gel- and sol-asphalt phases. More recently, Kushwaha, et al. [21] reported that Sasobit combined with Zycotherm improved rutting resistance and moisture durability in WMA mixtures, while Feng, et al. [22] demonstrated that Sasobit, when blended with SBS, enhanced low-temperature performance, thereby broadening its applicability in cold regions. Regional studies, such as study provided by Sukkari, et al. [23] conducted under UAE conditions, also confirmed that Sasobit at 2–4% dosage improves penetration, softening point, and high-temperature stability. Collectively, these studies confirm Sasobit's effectiveness in lowering construction temperatures and improving high-temperature performance, while also underscoring the need for dosage optimization and advanced rheological modelling.

Taken together, LDPE and Sasobit represent complementary approaches; LDPE provides mechanical reinforcement and sustainability by utilizing plastic waste, while Sasobit enhances workability and thermal efficiency in WMA. However, existing studies largely examine these additives in isolation, with limited exploration of their combined effects under aging conditions. Addressing this gap, the present study investigates the synergistic performance of LDPE-Sasobit blends, aiming to establish a more comprehensive framework for sustainable, high-performance asphalt modification by studying the physical and rheological properties of asphalt modified with the mix of both materials to reduce the temperature of asphalt used to prepare WMA and to achieve sustainable principles. The study adopted 1%, 2%, 3%, and 4% of both materials. The performance evaluation involves many

tests, including conventional tests such as penetration, softening point, and ductility. The rheological properties were assessed by viscosity test, rolling thin film oven test (RTFOT) to evaluate the aging properties of asphalt before and after aging, and viscoelastic properties using a dynamic shear rheometer (DSR).

2. Materials

2.1 Bitumen

A 40-50 penetration grade of asphalt binder was used in this research. Table 1 summarizes the common traditional properties of this binder according to the standard specifications.

Table1. characteristics of neat asphalt binder.

Property	ASTM specification	Measured value	Standards Limit SCRB / R9, 2003
Penetration (25C°, 0.1mm, 5sec, 100g)	ASTM D5[24]	47	40-50
Melting point (R&B), C°	ASTM [25] D 36	47.5	----
Elongation at 25 C°, cm	ASTM [26] D113	112.5	>100
viscosity at 135C°, Pa · s	ASTMD4402 [27]	0.6425	----
Flash& Fire points, C°	ASTM D92 [28]	Flash	298 °C
		Fire	356 °C
			>232 °C

2.2 Additives

2.2.1 Sasobit

Sasobit is a widely recognized additive used in WMA organic technology. It is a synthetic wax derived from paraffin, manufactured by Sasol through the Fischer-Tropsch process, which involves coal gasification. The compound consists of long-chain aliphatic hydrocarbons that contribute to lowering the viscosity of asphalt binder at reduced temperatures. This property enables asphalt mixtures to be produced and compacted at temperatures approximately 20-40°C lower than those required for traditional HMA, resulting in less emissions, enhanced aggregate coating, and improved energy efficiency. Upon cooling, Sasobit transitions into crystalline form, leading to an improved mixture's resistance to rutting[29]. Table 2 presents the physical and rheological characteristics of Sasobit[30]. While Figure 1: (A) shows the granular structure of it.

Table 2. Features of Sasobit[30].

Characteristic	Description
Chemical group	<i>Alpha-polyethylene hydrocarbons</i>
Melting point °C	<i>100-124 °C</i>
Fire point °C	<i>287</i>
Water dissolution	<i>Non-dissolvable</i>
Relative density gr/cm3	<i>0.619 g/cm³</i>
Colour	<i>White</i>
State	<i>Solid</i>

2.2.2 Polyethylene

In this study, the low-density polyethylene (LDPE) modifier was utilized in the form of a white, granular substance commonly

employed as a base material in the production of various plastic industries. The physical characteristics are detailed in Table 3[31-33]. While Figure 1:(B) illustrates its visual appearance. LDPE is a thermoplastic polymer distinguished by its relatively low density and melting point range of approximately 110-115C°. Compared to other polyethylene variants, LDPE exhibits a highly branched molecular structure, resulting in reduced crystallinity and enhanced flexibility[34].



Figure 1. (A)Sasobit, (B)LDPE

Table 3. Common Physical and rheological features of LDPE [31].

Feature	Value
Density, g/cm3	<i>0.919</i>
Tensile stress, MPA	<i>14</i>
Melting temperature, C°	<i>105-115</i>
Modulus of bending, MPA	<i>95</i>
Functional group	<i>(-CH2-CH2-) n</i>

3. Laboratory Design

3.1 Polymer Modified Bitumen

The asphalt treatment process goes through two stages. The first stage is modifying the asphalt binder using each additive separately. The second stage involves modifying the asphalt binder by gradually adding the two materials to the mixture. Four dosages of Sasobit were used (1%, 2%, 3%, and 4%) by weight of the asphalt binder, as suggested by the production company and previous studies. Also, four dosages of LDPE were used (1%, 2%, 3%, 4%) by weight of asphalt binder. These dosages were adopted throughout the trial method to study the effect of the material on binder properties, as seen in previous studies. The modifier blending method begins by heating the asphalt binder in an oven at 165 °C for 2 hours until it becomes fluid. The fluid asphalt binder was then placed in the shear mixer. After that, the modifier agent was added at a temperature that did not exceed 125C° to 60 minutes for Sasobit [35] and 145 °C for LDPE for two hours, at a mixing rate of 2500 rpm, then it is cured in the oven for another two hours, and mixed in the shear mixer for another two hours. The same LDPE mixing procedure was adopted when both modifiers were added to the binder. Figure 2 illustrates the shear machine used to mix the modifiers.



Figure 2. Shear mixer machine used in the preparation of the modified binder.

3.2 PMB Evaluation

The PMB with both LDPE, sasobit, and the blend of two materials was evaluated by the main conventional tests: penetration (mm), ductility (cm), and softening point (°C) to evaluate the physical properties of virgin binder and PMB according to ASTM specifications recommended by ASTM D5-D5M, ASTM D 113, and ASTM D36, respectively. Moreover, temperature sensitivity was determined by penetration index (PI) depending on penetration and softening point, and by using equation (1) as recommended by Dr Robert N. Hunter, [36], Jun et al [37], and Ameri et al [38].

$$PI = \frac{1952 - 500 \log_{10} pen - 20SP}{50 \log_{10} pen - SP - 120} \quad (1)$$

Where:

PI: penetration index, Pen: penetration value (mm), SP: softening point (°C).

Additionally, a rotational viscosity test was conducted to determine the viscosity of neat and PMB according to ASTM D4402. The aging properties were conducted using a thin-film oven test (RTFOT) according to AASHTO T240 for neat and PMB. Finally, the viscoelastic properties of the MC (4+1) mix of both materials were determined according to AASHTO T315 before and after aging at 76°C. Figure 3 illustrates the laboratory work of the modified binder.



Figure 3. Modified binder tests.

3.3 Optimum Additives Content

Both additives were used at dosages of 1%, 2%, 3%, and 4% by weight of asphalt binder. The optimum of both materials was adopted by the effect of both materials on the physical properties of the modified binder, including penetration (mm), softening point (°C), and ductility (cm), as recommended by ASTM D5-D5M, ASTM D36, and ASTM D 113, respectively. For heavy-duty applications, 4% Sasobit was adopted, as reported by the manufacturer and previous studies, and 1% LDPE was added due to LDPE's significant impact on the asphalt binder's physical properties. Whenever the dosage of the modifier increased, the binder stiffness increased, and the materials became more brittle [35]. The optimal combination of both materials was MC (4+1), due to the significant effect of both materials on the tested physical properties, in which PMB with MC becomes stiffer and more brittle. Where increased for unacceptable limit with mixed temperature of WMA, and indicated that the materials are more subject to cracking under high traffic loads. This may be attributed to the fact that the lower dosage of LDPE reinforced the crystalline network of sasobit wax, promoting stiffness, elasticity, and balanced synergistic system of both modifiers, while this dosage increased to reach (4+3)%, the performance was disrupted, weakening the synergistic effect.

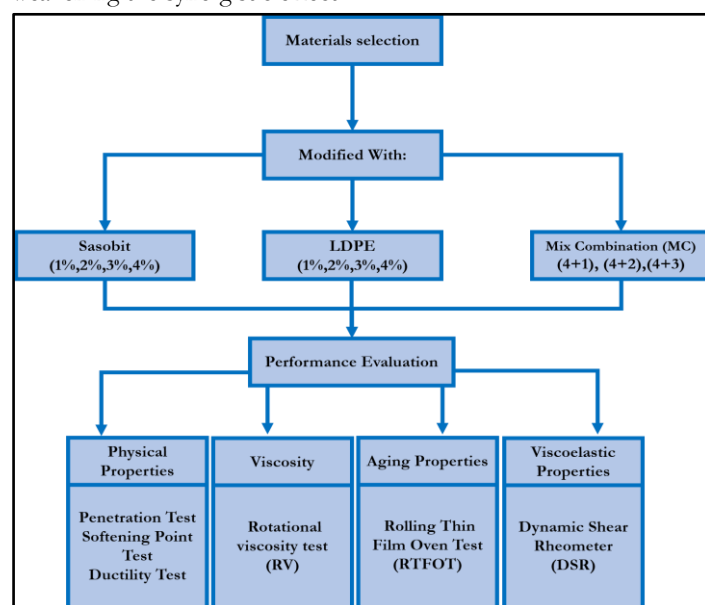


Figure 4. Asphalt modified methodology flow chart.

4. Results and Discussion

4.1 Penetration

The penetration test assesses the binder's consistency and indicates its hardness. The penetration results for the virgin binder, Sasobit, LDPE, and the mix of both are illustrated in Figure 5. The figure shows that as the amount of modifier increased, the penetration decreased until it reached 14.2 dmm at (4+3), which means a decrease of 73.16% as compared to the neat binder, where the addition of (4%) of Sasobit results in a reduction of 44.61%. Rezaeizadeh Herozi, et al. [39] explain this reduction is a result of Sasobit being an organic material that reduces viscosity. Therefore, when mixed with the binder configuration, lattice formation. Consequently, it will stiffen the binder and alter its flexibility, reducing penetration.

The reduction in LDPE PMB penetration by 9.45% when 1% LDPE is added due to the polymer network formed by the connection of asphalt molecules to the polymer, which hardens the binder and decreases its penetration. The same result was indicated by Zhao, et al. [40]. The penetration values for the mix combination decreased as the LDPE value increased, reaching 14.2mm for MC (4+3). This decrease is attributed to the composite structure effect of both materials on the binder molecules, reflecting the impact of Sasobit crystallinity and LDPE flexibility.

4.2 Softening Point

The softening point test measures the resistance of the asphalt binder to flow and deformation at elevated temperatures. It is crucial for evaluating binder performance in hot climates or heavy traffic conditions. The softening point (SP) results are presented in Figure 6. The Sasobit PMB shows an increase in softening point as the percent of Sasobit increased, compared to neat binder, the softening value increased by 21%, 23.2%, 65.3%, and 68.4% for 1%, 2%, 3%, and 4% of Sasobit, respectively, which reflects the enhanced performance of asphalt thermal resistance for high-temperature effects[23]. This increment is attributed to the lattice structure of Sasobit, which alters the asphalt binder's structure and enhances the asphalt's resistance to permanent deformation [41]. Similarly, LDPE PMB shows an increment in SP of (11.5%, 14.5%, 33.7%, and 35.8%) for (1, 2, 3, and 4) % of LDPE, respectively. The increment in SP indicates that LDPE increases the stiffness of the binder, which means enhanced LDPE resistance to deformation due to the polymer network that interacts with the asphalt molecules, which agrees with results in the literature [42]. The MC exhibits a reduction in SP as the LDPE content increases, with the (4+1) percent showing the highest SP, achieving 89°C. While achieving 83.5°C for MC (4+3). However, the SP value remains higher than that of the neat binder. This reflects the composite structure of both materials, which enhances the binder's thermal resistance.

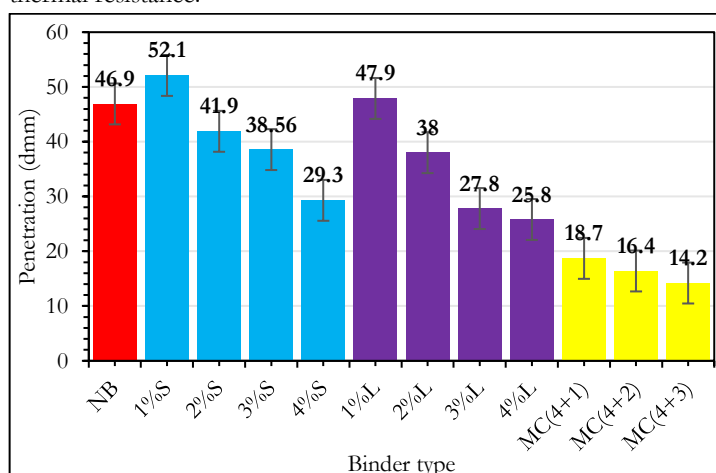


Figure 5. The result of the penetration test for pure and PMB

4.3 Penetration Index

The binder's susceptibility to temperature was evaluated using the penetration index, as illustrated in Figure 7. According to Dr Robert N. Hunter, [36] The PI range is (-3 to +7), where negative values indicate a sensitive binder and positive values indicate a less sensitive or more temperature-resistant binder. Generally, the

results show an improvement in the sensitivity of the binder to temperature after using a modifier, which means the development of the resistance ability of asphalt to rutting and temperature cracking, as indicated by Hawesah, et al. [43]. The Sasobit modifier results in greater improvement in temperature susceptibility compared to the neat binder. The PI values were +0.616, +0.299, +3.449, and +3.012 for 1%, 2%, 3%, and 4% percentages of Sasobit, respectively. A similar finding was indicated by Zhang, et al. [44]. Where they attributed this enhancement to the sasobit lattice structure, which results in the binder's enhanced ability to withstand temperature-induced susceptibility.

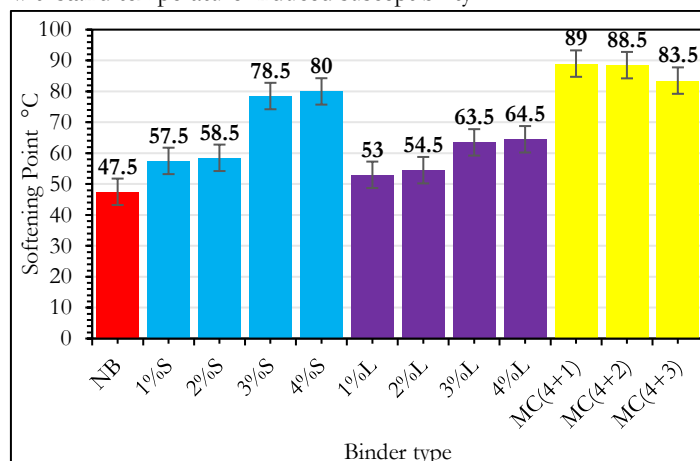


Figure 6. The result of the softening point test of pure and PMB.

LDPE results show less improvement as compared with Sasobit but better than neat binder, where the PI values were -0.582, -0.755, +0.360, and +0.385 for 1% 2%, 3%, and 4% percentage respectively, as compared with neat binder, which means better resistance to temperature susceptibility, the same result observed by Geçkil, et al. [45] where their results showed that 5% of LDPE samples achieved a PI of +1.20, indicating a polyethylene network that enhanced the binder's resistance to thermal stresses.

The MC results show the best moisture-sensitivity development compared to neat binder, Sasobit, and LDPE separately. The PI for MC reaches +3.190 and +2.879, +2016 for MC (4+1, 4+2, 4+3), respectively, reflecting higher development of temperature sensitivity provided by the MC PMB. As shown in Figure 7, the MC (4+1) shows the best improvement in moisture sensitivity. This development in temperature sensitivity reflects the strong structure formed by the mixture of the two materials.

4.4 Ductility Test

A ductility test was used to describe the elongation of the binder. The ductility results of all types of PMB were illustrated in Figure 8. The elongation of Sasobit-PMB modification exceeded 100 cm due to the elastic behavior of the wax materials, which increases stiffness without causing brittleness. The same result was indicated by Joni and Alkhafaji [35] Where all dosages of Sasobit used passed 100 cm. While for LDPE-PMB, as the LDPE dosage increases, ductility decreases, reaching 16.5% at a 4% LDPE dosage, representing an 85.3% reduction. This reduction is due to the polymer network that interfaces with asphalt molecules. The same results were observed by Mustafa, et al. [46]. The MC showed a reduction in ductility value as the LDPE dosage increased, where the reduction of 89% for the MC of (4% Sasobit

+3 % LDPE), while this reduction was 52% for (4% Sasobit +1% LDPE), which means that the asphalt binder becomes more brittle as the percentage of LDPE increased due to the combined effect of both polymer materials on the physical properties of virgin binder. As shown in Figure 8, the MC (4+1) achieved the lowest reduction in ductility. As the LDPE content increased, the material became more brittle, increasing the likelihood of cracking and fracture under traffic loads.

4.5 Rotational Viscosity Test

A viscosity test was conducted on both the neat binder and PMB, as illustrated in Figure 9. SHARP recommended that the viscosity should not exceed 3000 centistokes at 135 °C to achieve a range of application conditions, from workability to pumpability [47]. Figure 9 shows that Sasobit reduces the viscosity of PMB compared with neat. On the other hand, the LDPE causes a significant increase in viscosity. MC (4+1) can provide a suitable viscosity of PMB to be used in WMA, in addition to improving the cohesion of PMB by using LDPE. 4% Sasobit reduced the PMB viscosity by 7.79% and 2.83% at 135 °C and 165 °C, respectively, compared to the neat binder. The lattice structure of sasobit is mainly responsible for this reduction. Zhang, et al. [48] indicated the same result.

While the use of 1% of LDPE resulted in a 80.23%, and 64.17% at 135°C and a increase at 135 °C, and 165°C respectively compared to the neat binder, this change is due to the reasons mentioned above, as the addition of LDPE causes the creation of a polymer network, which leads to a change in the asphalt structure from sol-gel, leading to increased bonding between the asphalt components and increased asphalt hardness, which leads to an increase in its viscosity, these results are congruent with Al-Gurah, et al. [49]. The mix combination (MC) of the two additives (Sasobit, LDPE) shows a reduction in the viscosity values by 3.7%, and 25% at 135°C, and 165°C respectively compared to neat binder, which reflects the effect of Sasobit on the reducing viscosity of LDPE to produce an integrated structure as a result of the interface between the network of both materials and their impact on the viscosity of binder.

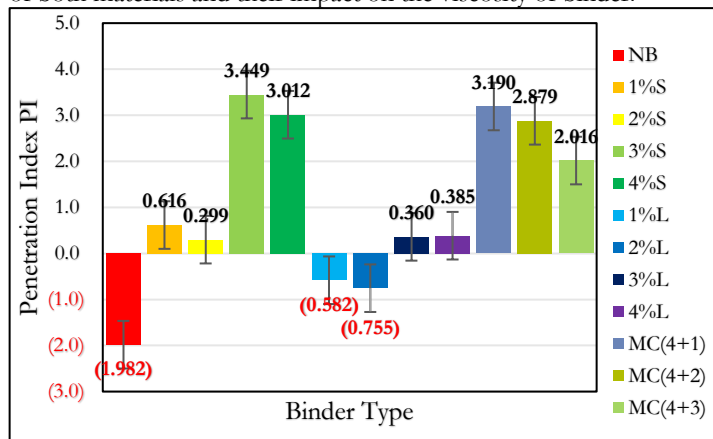


Figure 7. The result of the Penetration index for pure binder and PMB

4.6 Rolling thin film oven test (RTFOT)

The results of the RTFOT test are illustrated in Figure 10, according to AASHTO T240, to simulate the aging properties of modified and neat binders. The ASTM D2872 standard states that the change in mass of the RTFOT result should be limited to ± 1 . As illustrated in Figure 10, the neat binder exhibits a mass loss of -0.070%, indicating that temperature affects its properties. While the sasobit shows a loss in mass of -0.052%, it is a synthetic wax that improves workability and reduces viscosity, that attributes to long

hydrocarbons chains of sasobit, also the melting point of sasobit that ranging between 85-120°C make the sasobit became liquid when the temperature higher than temperature of melting point resulting in a more compact structure and reducing temperature susceptibility and mass change. The same result was indicated by Tembe, et al. [50].

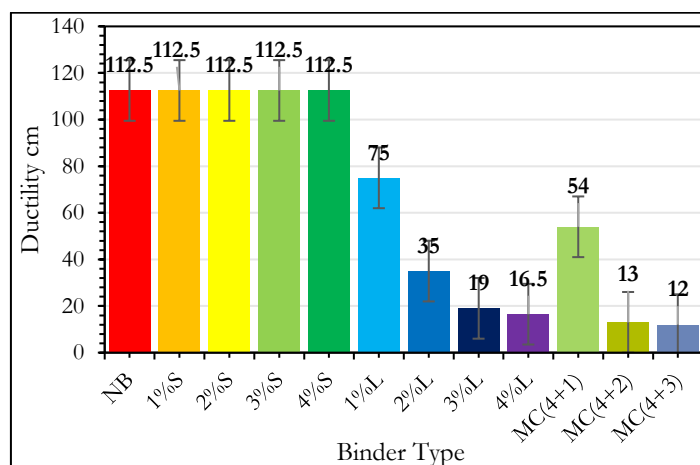


Figure 8. The result of the Ductility test for pure binder and PMB

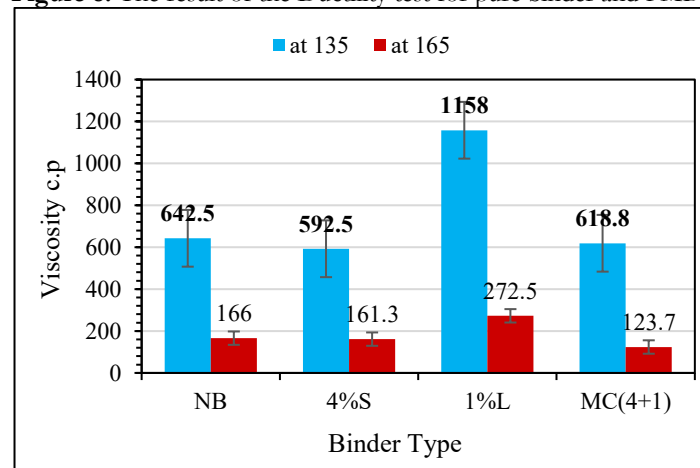


Figure 9. Viscosity test for neat binder and PMB.

The LDPE shows the most significant change in mass. LDPE can improve stiffness and rutting resistance because it contains short-chain hydrocarbons or unreacted monomers. Under high-temperature conditions, these lighter components volatilize easily, resulting in higher mass loss[51]. Additionally, LDPE has a relatively low melting point, ranging from 105 to 115°C, and begins to degrade at around 200 °C degradation releases small, volatile molecules, such as alkanes and alkenes, which escape during the aging process, thermal degradation can cause volatilization or loss of lighter fractions, explaining the sharp decrease in mass[52]. Without proper blending or the use of compatibilizers, LDPE may remain poorly dispersed within the binder matrix. This can lead to micro-phase separation, making volatiles more likely to concentrate and evaporate[53]. LDPE may also dilute or suppress the natural stabilizing compounds in bitumen. This can accelerate oxidation reactions during RTFOT, indirectly leading to mass loss through chemical changes and volatilization. Poor dispersion or incompatibility with the base binder can further increase this effect[54].

The MC (4+1) of both modifiers shows a positive value, indicating an increase in mass of 0.013%. It could be due to enhanced oxidative crosslinking, resulting in an increase in binder weight. Reduced evaporation through mutual stabilization of the matrix. Sasobit may

be compensating for LDPE's volatility due to its waxy structure and high crystallinity, thereby reducing thermal losses from LDPE and acting as a volatility buffer, thereby retaining heavier fractions or absorbing volatiles.

4.7 Dynamic shear rheometer (DSR)

The DSR test was conducted according to AASHTO T315 for MC₍₄₊₁₎ at 76°C to evaluate the viscoelastic properties of the mixture of both modifiers, in accordance with the local country's temperature. According to AASHTO M320, the $G^*/\sin \delta$ for unaged binder should exceed 1 kPa, and after aging, should exceed 2.2 kPa. As shown in Figure 11, both test results before and after aging meet the minimum requirements of AASHTO M320, where the increased value of $G^*/\sin \delta$ from 3.66 kPa before aging to 5.2 kPa after aging revealed that the MC₍₄₊₁₎ blend retained higher stiffness and elasticity after aging, which reflects improved rutting resistance. This suggests that the blend not only enhances binder performance initially but also mitigates the negative effects of aging, thereby extending pavement service life, indicating MC's resistance to permanent deformation and thermal cracking in hot areas such as Iraq. This showed the enhancement achieved by the combined structure of the two modifiers. Sedaghat, et al. [55] explain that the melting point of Sasobit is around 100°C, and below this temperature, Sasobit crystallizes, reinforcing the binder structure, resulting in increased stiffness. The polymer network of LDPE enhances the binder's elasticity, resulting in an integrated structure that resists permanent deformation and high-temperature distress.

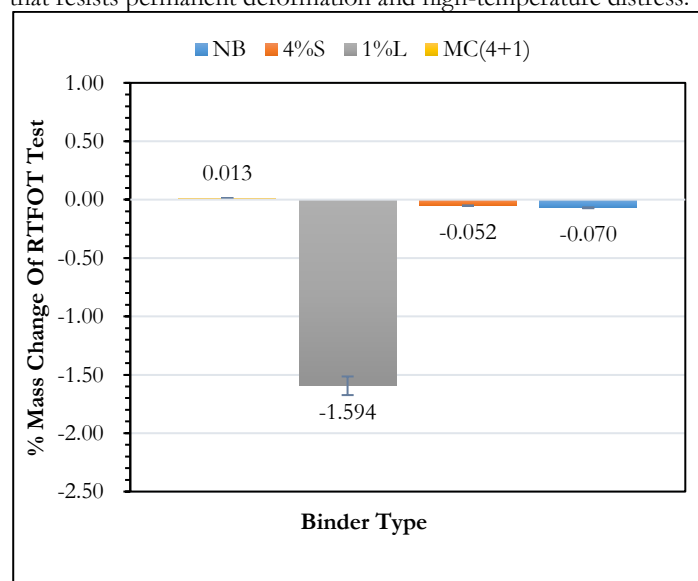


Figure 10. Result of the RTFOT test.

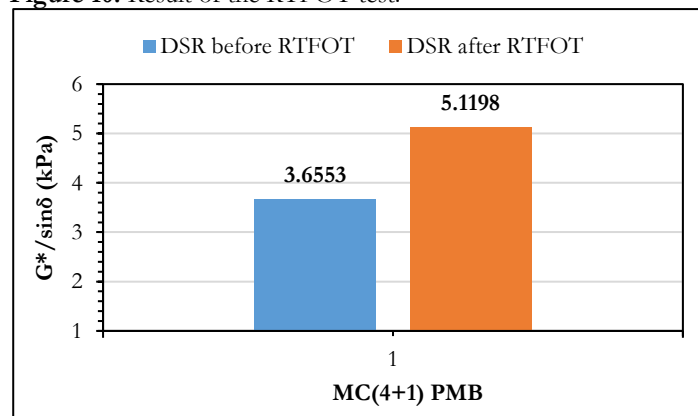


Figure 11.: DSR test for PMB with MC₍₄₊₁₎

5. Conclusion

This study was conducted to investigate the influence of Sasobit wax, LDPE, and a mix of both on the asphalt binder characteristics and reached the following conclusion:

1. The incorporation of Sasobit into asphalt binder significantly enhances its performance across multiple domains, making it a valuable additive for warm mix asphalt (WMA) systems, particularly in hot climate regions. Sasobit acts as a reinforcing agent by forming a crystalline wax matrix within the binder. This causes a reduction in penetration values (up to 30%), indicating increased stiffness. For all types of PMB investigated here, an increase in softening point (up to 71%) was observed, enhancing thermal resistance, and minimal impact on ductility at optimal dosages.
2. Sasobit significantly reduces binder viscosity at high temperatures, up to 8% reduction in viscosity at 135°C and 3% at 165°C. Improves workability and compaction, enabling lower production temperatures. Facilitates uniform dispersion of other modifiers like LDPE. At the same time, it improves the binder's viscoelastic behavior, enhances short-term aging resistance during mixing and laying.
3. The modification of asphalt binder with LDPE introduces significant improvements in mechanical and thermal performance, particularly in enhancing stiffness, deformation resistance, and durability under traffic and environmental stress. LDPE modifies the binder through physical blending, forming a semi-interpenetrating polymer network that reduces penetration values, indicating increased binder hardness, elevates the softening point by 15%, and improves high-temperature stability. Ductility reduction depends on the LDPE dosage.
4. LDPE increases asphalt binder viscosity due to its polymeric structure. Higher viscosity requires higher mixing temperatures during production.
5. LDPE contributes to aging resistance through structural reinforcement, improves short-term aging performance under RTFOT by reducing volatility loss, and enhances long-term durability when carefully dosages used fully dissolved.
6. The mixed modification of asphalt binder using Sasobit and LDPE yields a congruent enhancement in performance across physical, rheological, and aging domains. This dual-modifier strategy helps to benefit from the strengths of each additive. The blend significantly reduces penetration and ductility, indicating increased stiffness and reduced elongation capacity. The softening point increases by 20%, reflecting improved thermal resistance. The penetration index (PI) becomes more positive, indicating reduced temperature susceptibility and enhanced high-temperature performance.
7. MC(4+1) improves rutting resistance, as evidenced by increased $G^*/\sin \delta$ value, indicating a more elastic binder response where LDPE contributes to fatigue resistance while Sasobit enhances dispersion and reduces viscosity, resulting in a binder with a balance of stiffness and elasticity.
8. The combined use of Sasobit and LDPE creates a thermomechanical optimized binder that is stiffer, more elastic, and more resistant to aging than either modifier alone. This blend is particularly effective for warm mix asphalt (WMA) applications in hot climate regions, where both thermal resistance and construction efficiency are critical.

6. Recommendations

The experimental findings confirm that the synergistic system enhances binder stiffness, rutting resistance, and thermal stability, while also contributing to eco-friendly, energy-efficient asphalt production. Based on these outcomes, the study is recommended for further application in pavement design and construction

projects, particularly in regions with high-temperature climates where improved durability is critical. The results also provide a foundation for extending research into fatigue performance, moisture susceptibility, and long-term field validation, ensuring that the environmental and mechanical benefits observed in the laboratory can be translated into practical infrastructure solutions. Future work should extend these findings by evaluating fatigue resistance under repeated loading, validating performance through long-term field trials, and conducting life-cycle sustainability assessments. Such studies will provide a more comprehensive understanding of the durability and environmental benefits of Sasobit-LDPE-modified asphalt under real-world conditions.

7. References

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