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Assessment of the properties of asphalt mixtures modified with LDPE and HDPE polymers

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ABSTRACT

The performance of asphalt pavements is crucial due to heavy traffic loads from civil and industrial developments. Various additives and modifiers are used in flexible roads to improve their resistance to deterioration caused by climatic changes. From this context, modifying the asphalt binder with polymers is popular in asphalt pavement construction. The present research investigates the effect of Polyethylene (PE) polymers in powder form on the characteristics of asphalt mixtures since these polymers are composed of hydrocarbons. It is similar to asphalt binders, making them very effective in enhancing the performance of neat asphalt produced from the oil refinery. To confirm this, two types of PE, High-Density PE (HDPE) and Low-Density PE (LDPE), were blended with neat asphalt binder at different dosages of 0%, 2%, 4%, and 6% by the weight of asphalt binder. The physical tests, including penetration, ductility, softening point, and weight loss on heat, were conducted to examine neat and PE-modified binders' rheological properties, durability, and temperature sensitivity. Marshall stability, stiffness index, tensile strength, and Scanning Electron Microscope (SEM) were also employed to assess the performance of PE-modified asphalt mixtures. The findings reveal that incorporating PE into asphalt mixtures significantly improves their mechanical properties, and the most optimal results are achieved when using 6% of both HDPE and LDPE. Specifically, modifying the asphalt binder with the inclusion of 6% HDPE and LDPE presents a remarkable increase in stability of 167.6% and 150.9%, respectively, compared to conventional mixtures. The stiffness index is improved for HDPE and LDPE-modified mixtures, which offers these mixtures superior resistance to permanent deformation. The moisture damage resistance can be enhanced by modification of the asphalt binder with HDPE and LDPE, especially at the inclusion of 6%. SEM images of asphalt pavement demonstrate HDPE's superiority in terms of distribution and dispersion in asphalt binder. In conclusion, the properties of HDPE-modified mixtures are better than those of LDPE-modified and untreated mixtures.

Keywords: Marshall properties, Moisture damage, Polyethylene polymer, SEM, Wet mixing.

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1. INTRODUCTION

Improving the performance of asphalt binders is significantly effective in enhancing performance and increasing the service life of asphalt pavement. As a result, asphalt pavement can withstand heavy traffic and difficult service conditions, all while keeping prices down and reducing environmental damage. To achieve this, pavement researchers used polymers and fibers to modify the asphalt binder to improve flexible pavement performance at a reasonable cost. In the last decades, polymer-modified asphalt has been the greatest paving material available (Abed and Latief, 2024; Yan et al., 2024; Dalhat and Al-Adham, 2023).

Asphalt pavement is already defective due to visible flaws. However, problems like fatigue cracking and permanent deformation could emerge from moisture-induced degradation (Mohammed et al., 2024; Latief, 2019). Developing polymer-modified asphalt is a unique technology and is highly recommended for pavement construction

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since the lifespan of flexible pavement will increase by improving the mechanical qualities and resistance against moisture damage of asphalt mixture. Consequently, the maintenance and repair of polymer-modified flexible pavements are avoided and minimized. Modern studies have examined the modification of asphalt binders with polymers. These studies used many types of polymers, especially polyethylene, polypropylene, crumb rubber, styrene-butadiene rubber, and styrene-butadiene-styrene (Arif et al., 2023; Alnaqib and Bazuhair, 2023; Ghani et al., 2022; Mushtaq et al., 2022; Kakar et al., 2021; Al-Azawee and Latief, 2020).

Asphalt engineers must assess polymer efficacy to attain the best modification for asphalt. These pavements' mechanical properties must be assessed to choose polymers for more durable and adaptable pavements (Deef-Allah and Mohamady, 2014). Asphalt alteration is one of the possible applications for PE polymer, which has recently become a popular material in asphalt modification owing to its eco-friendliness and cost-cutting properties. Additionally, applying waste PE in pavement materials as a modifier or additive will help reduce the earth's pollution and enhance the environmental impact (Roja et al., 2021).

Polymers can be categorized into two groups: elastomers and plastomers. Plastomer polymers, such as PE, stiffen in moderate climates with average temperatures. However, these polymers failed to improve asphalt flexibility during sudden temperature fluctuations (Ahmadinia et al., 2011). Since asphalt and plastic are composed of hydrocarbons and share the same chemical composition, they act as modifiers when mixed with plastic polymers. The asphalt component disperses, absorbs these modifiers, and reacts chemically with the base asphalt. Therefore, the modifiers must be compatible with the basic asphalt to be homogeneous and free of stratification, cohesiveness, and separation (Wu and Montalvo, 2021).

From an economic interest, modifying the asphalt mixture or asphalt binder by incorporating the recycled PE polymer derived from plastic wastes provides a solution for waste management challenges. Therefore, Al-Haydari et al. (2021) modified the asphalt mixture with waste sheets of LDPE. The pavement performance is improved based on the experimental tests, and the cost savings are increased by including 6% recycled LDPE. In addition, Al-gurah et al. (2023) studied the effect of using LDPE waste on the physical properties of asphalt. By conducting penetration, elongation, and softening point tests, it was reported that the penetration and elongation values decreased with increasing the concentration of the additive while the softening point increased. Thus, waste LDPE significantly improved the physical properties and performance of asphalt binder.

The inclusion of 4% HDPE by weight to the asphalt binder enhanced the stiffness of asphalt. It increased the resistance to moisture deterioration, as reported by Abdel-Wahed et al. (2020). Furthermore, HDPE is a distinctive polymer that improves the mechanical qualities of asphalt mixtures and enhances the adhesion between the asphalt binder and aggregates.

Bilal et al. (2013) used waste HDPE in the form of pieces with sizes less than 4.75 mm to specify the optimal method for adding this polymer to the asphalt mixture. Two additional methods were utilized: the wet method and the dry method. The outcomes indicated that using the wet method leads to the formation of an inhomogeneous mixture due to the irregular distribution of the PE pieces deposited within the asphalt. Accordingly, the dry method was adopted, which includes adding PE to the hot aggregate, as PE works to coat the aggregate granules, which contributes to improving the mechanical properties of the asphalt mixture. In addition, the optimal percentage for the addition of HDPE is 8%, as this percentage achieved the best results in improving the performance of the mixture.

The main challenge in developing PE-modified asphalt to achieve the best performance during the service life of road pavement is to effectively disperse PE particles into the asphalt binder structure. Accordingly, PE particles must be crushed before being mixed with asphalt binder to ensure uniformity and avoid the formation of PE polymer agglomerations that usually occur when using uncrushed PE (Kakar et al., 2021).

Previous studies have focused on individual PE polymer modifications in asphalt binders. This research expands upon these studies by examining two types of PE polymer, namely HDPE and LDPE, at different ratios (0%, 2%, 4%, and 6% by weight of the asphalt cement). Furthermore, a wet mixing technique was used to combine PE with asphalt to achieve better dispersion of PE in the asphalt binder and prevent agglomeration. For better dispersion in asphalt binders, unlike in other studies, PE granules were crushed before being added to the asphalt. Consequently, crushed PE polymer has a larger surface area and is expected to dissolve more easily in asphalt than PE polymer in granular form. It requires a higher temperature to dissolve in asphalt, which must be avoided to prevent accelerated aging of asphalt when heated to higher than permissible temperatures. To demonstrate this, the distribution and shape of PE in the asphalt mixture were evaluated using scanning Electron Microscopy (SEM) testing. The performance of the modified asphalt binder was evaluated by investigating the physical properties to identify the changes that occurred in the binder material when PE polymer was added. In addition, the volumetric properties, mechanical properties, stiffness index, indirect tensile strength (ITS), and resistance to water damage were examined, and the morphology of asphalt mixtures modified with PE polymer was studied.

2. MATERIALS

2.1 Asphalt Cement

In this research, asphalt cement Type AC (40-50) was used. This asphalt type was brought from the Al-Duarah refinery. The physical properties of asphalt cement Type AC (40-50) are examined based on ASTM specifications and evaluated to meet the local standard requirements

(SORB/R9, 2003).

2.2 Combination of Aggregate

The crushed aggregate, which included coarse and fine aggregates and limestone filler material, was obtained from nearby sources. The physical properties of all aggregate components were scrutinized following the specifications outlined in the ASTM standard. In addition, these properties must comply with the criteria outlined in the local specification (SORB/R9, 2003). Table 1 and Fig. 1 present the selected gradation with the recommended limits of the local specification (SORB/R9, 2003). Table 2 presents the physical properties of coarse and fine aggregates and limestone filler.

Table 1. Aggregate grading for wearing course

Sieve size	Sieve opening, mm	% Passing by weight		
		Requirements		Mid-range (selected)
		Lower limit	Upper limit	
3/4"	19	100	100	100
1/2"	12.5	90	100	95
3/8"	9.5	76	90	83
No. 4	4.75	44	74	59
No. 8	2.36	28	58	43
No. 50	0.3	5	21	13
No. 200	0.075	4	10	7

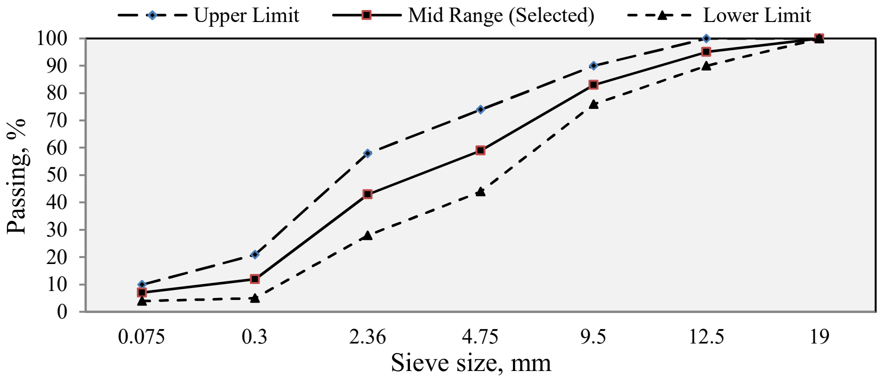

Fig. 1. Grain size distribution

Table 2. Physical properties of aggregate components

Property	Test method	Results	Specification limits
Coarse aggregate			
Bulk specific gravity	ASTM C-127	2.58	-
Percent wear by Los Angeles abrasion, %	ASTM C-131	17.18	30 Maximum
Passing sieve no. 200, %	ASTM C-117	0.46	-
Fine aggregate			
Bulk specific gravity	ASTM C-128	2.6	-
Passing sieve no. 200, %	ASTM C-117	0.9	-
Mineral filler			
Bulk specific gravity	-	2.71	-
Passing sieve no. 200, %	-	87	70-100

2.3 Polyethylene Polymer

This work utilizes two types of polymers, namely HDPE and LDPE, in a crushed form (powder). The polymers were acquired from a manufacturing facility in the Karbala province. The density of PE polymer is 0.954 gm/cm^3 for HDPE, and it has a melting point of 131°C. Meanwhile, LDPE density is 0.924 gm/cm^3 with a melting point of 114°C. Fig. 2 depicts the pulverized PE polymer.

Fig. 2. Crushed PE polymer

3. EXPERIMENTAL METHODS

3.1 PE-Modified Asphalt Preparation

In the current research, traditional asphalt binder (40-50) was utilized and mixed with crushed PE polymer, which had a particle size of less than 0.3 mm. The PE particles were added at concentrations of 2%, 4%, and 6% by weight of the asphalt binder. The asphalt binder is initially heated to a specific temperature of 163°C. Subsequently, the polymer is introduced incrementally into the heated asphalt. Notably, special attention must be paid to preparing PE-modified asphalt binders. Therefore, the mixing bowl is shielded with aluminum foil to mitigate oxidation resulting from the elevated temperature. The mixing procedure is conducted at a temperature of 165°C, using a high-speed stirrer moving at 3,000 rpm for 30 minutes, resulting in a uniformly mixed binder (Attaelmanan et al., 2011; Al-Hadidy and Yi-qiu, 2009). Fig. 3 illustrates the mixing of PE polymer and asphalt binder.

Fig. 3. Mixing PE polymer and asphalt binder

3.2 Physical Tests of Asphalt binder

The crucial tests performed to evaluate the performance of bitumen are penetration test per ASTM D5, ductility per ASTM D113, weight loss on heat percentage per ASTM D1754, and softening point per ASTM D36. In addition, the temperature sensitivity measure penetration index (PI) was determined based on penetration and softening point results.

3.3 Marshall Test

Hot Mix Asphalt (HMA) formulations were optimized using the Marshall mix design procedure outlined in ASTM D6927-15. Five asphalt content levels ranging from 4.0% to 6.0% were investigated. Through the determination of the theoretical maximum specific gravity as per ASTM D-2041-03, alongside the assessment of Marshall sample density as per ASTM D-2726-08 and the percentage of air voids (AVs) as per ASTM D-3203-05, it determines the volumetric properties of the Marshall sample. Employing the Asphalt Institute Procedure, the optimal asphalt content was determined to be 4.9% using optimum stability, maximum density, and 4% AVs. Specimens were compacted using 75 Marshall blows on each face and subsequently allowed to cure in the mold under ambient conditions for 24 hrs.

The PE-modified asphalt binder was prepared at the optimal asphalt content to ensure uniformity. As the PE content in the binder increased, mixing and compaction temperatures increased for the PE-modified asphalt mixture to enhance the ability of PE polymer to melt more easily and sufficiently blend into the asphalt binder (Attaelmanan et al., 2010). Specifically, mixing temperatures ranged from 160 to 170°C, with compaction temperatures set 10°C lower than the mixing temperatures determined by conducting a viscosity test based on ASTM D 4402. Marshall specimen testing is demonstrated in Fig. 4.

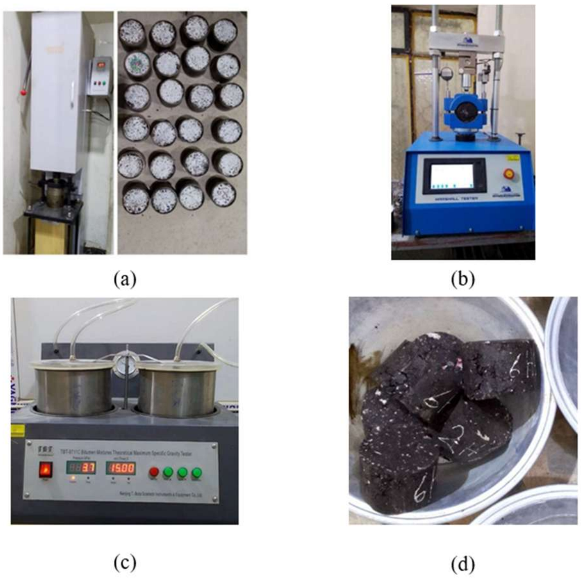

Fig. 4. Marshall specimen testing, (a) Marshall compactor and compacted specimens, (b) Marshall device, (c) Theoretical maximum specific gravity tester, (d) Fractured specimens

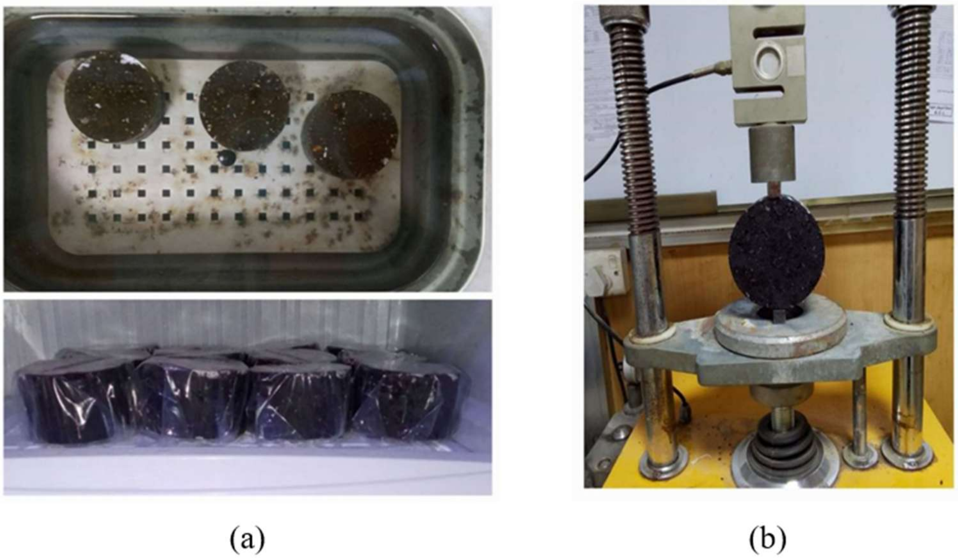

Fig. 5. Moisture damage test, (a) Freezing and thawing cycle, (b) Specimen testing

3.5 Scanning Electron Microscopy

SEM is an advanced method used to generate high-resolution images of the microstructure of materials. SEM techniques generate images of an object's surface morphology by subjecting it to electron radiation in a vacuum environment. As such, Tescan MIRA3 SEM was used in this study to capture high-resolution microstructure images to describe the specimens' structure. SEM analysis was conducted for samples of modified asphalt with PE polymer. In addition, fractured samples obtained from the asphalt mixture were analyzed using SEM to determine the presence and distribution of PE polymer.

4. RESULTS AND DISCUSSION

4.1 Evaluation of the Physical Properties of PE-Modified Asphalt Binder

Table 3 summarizes the results of physical tests for modified asphalt and their comparison with neat asphalt. Neat bitumen is denoted by NB, while bitumen modified with HDPE and LDPE is denoted by HB and LB, respectively.

Table 3. Physical properties of the neat and PE-modified asphalt

Property		Penetration (25°C, 100 g, and 5 sec)	Softening point (ring and ball)	Ductility, (25°C and 5 cm/min)	Weight loss on heat	Penetration index
Units		1/10 mm	°C	cm	%	-
Test method		ASTM D-5	ASTM D-36	ASTM D-113	ASTM D-1754	-
Specification limits		40-50	-	≥100	≤ 0.5	-
Bitumen type	NB	45	51	105	0.025	-1.17
	2%-HB	38.5	55.4	39	0.023	-0.52
	4%-HB	30	61.5	22	0.017	+0.169
	6%-HB	21	70.2	14.5	0.011	+0.928
	2%-LB	41.5	54.2	66	0.024	-0.625
	4%-LB	35.3	57.4	35.5	0.020	-0.291
	6%-LB	26	65.1	24.5	0.012	+0.507

According to the laboratory results, the penetration value decreases, the elongation decreases, and the heat loss decreases with the addition of PE. The penetration test can determine the degree of softness and consistency of the asphalt binder. The results indicate that PE enhances the cohesion and strength of the modified asphalt binder. Note that increasing the hardness may improve the mixture's resistance to abrasion. However, it may also reduce the flexibility of the asphalt binder by making it stiffer, which reduces its resistance to fatigue cracking. The softening point test was conducted to determine the softening degree by measuring the temperature of the asphalt binder. In addition, PE raises the softening temperature as its percentage increases, which increases the hardness of the asphalt binder. The PI was calculated based on the penetration results at 25°C and the softening point temperature. A higher PI value indicates a lower effect of temperature on the asphalt binder, which enhances its resistance to cracking and rutting. One of the advantages of using PE-modified asphalt binder is its low susceptibility to temperature. In general, higher softening point temperatures indicate better resistance to high temperatures, making it a preferred choice in hot climates.

4.2 Marshall Properties

The outcomes in Figs. 6 and 7 illustrate the impact of PE polymer as an asphalt modifier on Marshall stability and flow. All mixtures incorporating both HDPE and LDPE polymers exhibit a noticeable enhancement in stability and a decrease in flow compared to the conventional mixture. Specifically, the inclusion of 6% HDPE causes a remarkable stability increase of 167.6%, whereas 6% LDPE yields a stability enhancement of 150.9% relative to the conventional mixture. This phenomenon is ascribed to the lower specific gravity of PE polymer compared to virgin asphalt. This characteristic facilitates its infiltration amidst particles, thereby augmenting the interlocking of aggregates, resulting in heightened stability and reduced flow (Al-Hadidy and Yi-qiu, 2009). This improvement may be attributed to the bonding ability of the PE polymer, which acts like a glue and improves the interconnectedness between the aggregate particles (Singh et al., 2017). Additionally, the high viscosity of the PE-modified asphalt enhances the bitumen's cohesion and increases the bond with aggregate particles. The outcomes presented before are consistent with those of previous studies (Al-Haydari et al., 2021; Al-Hadidy and Yi-qiu, 2009). For simplicity, the terms of asphalt mixture modified with HDPE and LDPE are next referred to in the text, tables, and figures as displayed in Table 4.

Table 4. Symbols for asphalt mixtures

Mixture designation	Mixture type
NB	Neat Bitumen
2HMB	2% HDPE-Modified Bitumen
4HMB	4% HDPE-Modified Bitumen
6HMB	6% HDPE-Modified Bitumen
2LMB	2% LDPE-Modified Bitumen
4LMB	4% LDPE-Modified Bitumen
6LMB	6% LDPE-Modified Bitumen

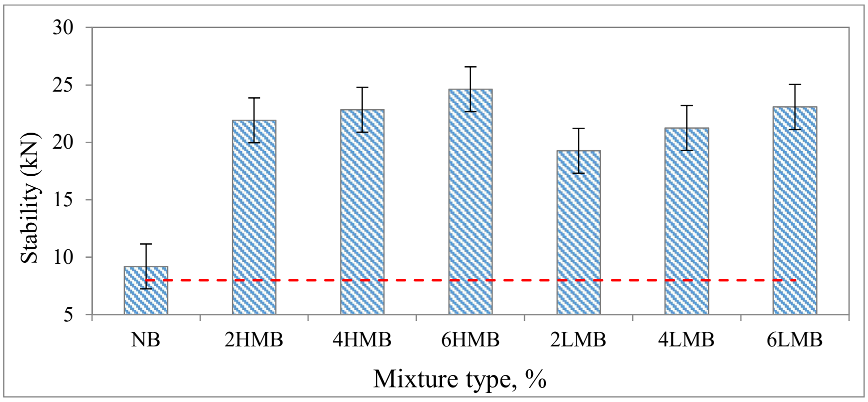

Fig. 6. Effect of PE on Marshall stability

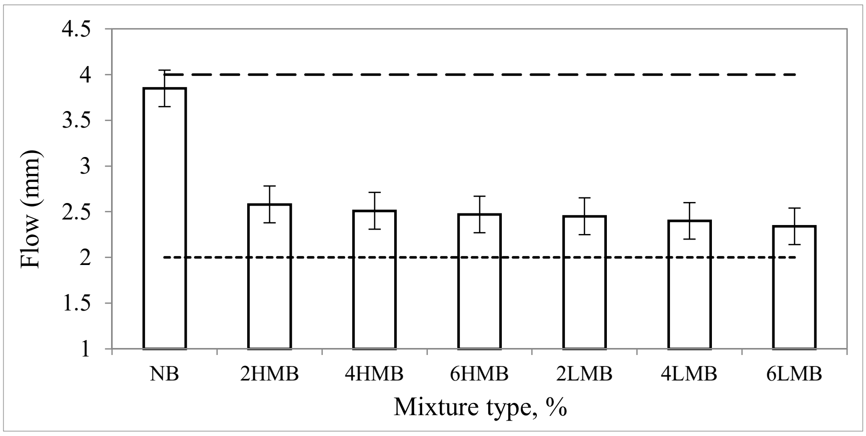

Fig. 7. Effect of PE on Marshall flow

Fig. 8 illustrates the correlation between the PE concentration and Marshall Stiffness (MS). The mixtures containing 2%, 4%, and 6% PE for both types of HDPE and LDPE recorded a higher MS than the conventional mixtures. However, the mixture with a higher percentage of PE has higher stiffness and more durability. This leads to the production of mixtures that are more durable and resistant to the action of permanent deformations that can occur as a result of high temperatures. This is attributed to the fact that PE polymer is considered one of the polymers suitable for use in climates with high temperatures since it is a plastic material. The outcomes reported in the previous study (Al-Haydari et al., 2021) support these findings.

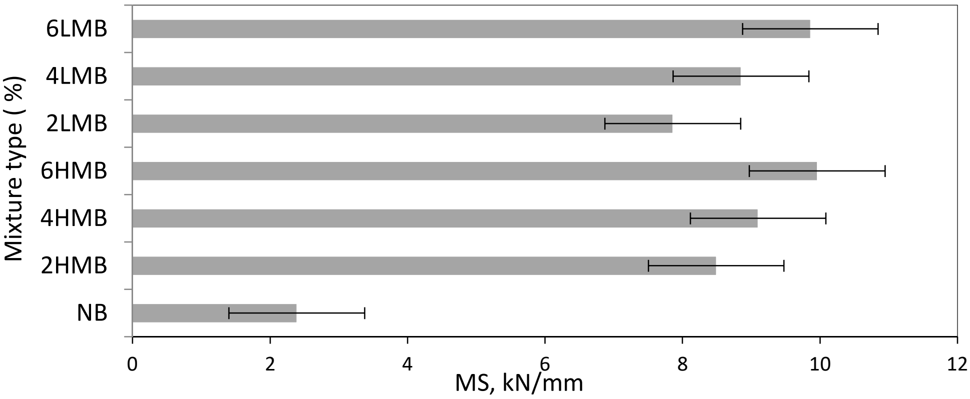

Fig. 8. Effect of PE on Marshall stiffness

According to the data in Table 5, the volumetric properties of all mixtures fulfilled the specification limit (SORB/R9, 2003). Furthermore, the bulk density of the PE mixture will be lower in comparison to the conventional mixture for both types, HDPE and LDPE. Subsequently, raising the ratio of PE polymer causes a decline in the bulk density of the mixture. This reduction in density is typically attributed to the disparity in specific gravity between the PE and the mineral aggregates and modified asphalt. Furthermore, the incorporation of PE polymers has also increased the AVs and voids of the mineral aggregate (VMA). VMA facilitates the accommodation of binder films on the aggregate particles. The strength of the mixture is enhanced by increasing the thickness of the coating on the aggregate particles. To provide the demanding strength of the mixture, it is advisable to satisfy the minimum VMA in local standards (SORB/R9, 2003). VMA values rise as the parentage of PE in the asphalt binder structure grows. The VMA values for PE-modified asphalt mixtures were also more than those of the conventional mixture. Additionally, the PE-modified mixtures have higher AV contrast to the conventional mixture, which had 3% AVs. Indeed, this value represents the minimum required by local specifications and is considered a critical percentage. Thus, it is vital to measure the AVs since they significantly influence the durability of asphalt pavement. According to the specification requirements (SORB/R9, 2003), AV limits are between 3-5% since the AVs must be more than 3% to effectively prevent the bleeding of asphalt binder and less than 5% to increase the resistance of asphalt pavement against moisture damage and fatigue (Ahmed et al., 2024). The results reported in the previous studies (Ghani et al., 2022; Ahmadinia et al., 2011) support these findings.

Table 5. Volumetric properties for conventional and PE-modified mixtures

Mixture type	Density (g/cm^3)	AV (%)	VMA (%)	VFA (%)
Specification limit	-	3-5	14 Minimum	-
NB	2.316	3.00	15.28	80.00
2HMB	2.313	3.20	15.39	79.14
4HMB	2.305	3.35	15.69	78.64
6HMB	2.286	3.62	16.38	77.89
2LMB	2.306	3.14	15.65	79.93
4LMB	2.294	3.53	16.09	78.06
6LMB	2.275	3.80	16.78	77.35

4.3 Indirect Tensile Strength

Fig. 9 illustrates the influence of PE additives on ITS for asphalt mixtures. Based on analytic findings, the asphalt mixture modified with HDPE polymer exhibits the highest ITS compared to LDPE polymer. The most notable enhancement in tensile properties is observed in mixtures modified with 6% HDPE and LDPE, where these polymers serve as strengthening agents since these polymers increase the viscosity of traditional asphalt binder when used as a results indicated that asphalt mixtures with high strength in dry and wet conditions and greater resistance to high loads can be obtained with HDPE polymer. The findings of ITS modifier for asphalt and significantly improve ITS. The ITS are compatible with the results stated in the previous study (Al-Hadidy and Yi-qiu, 2009).

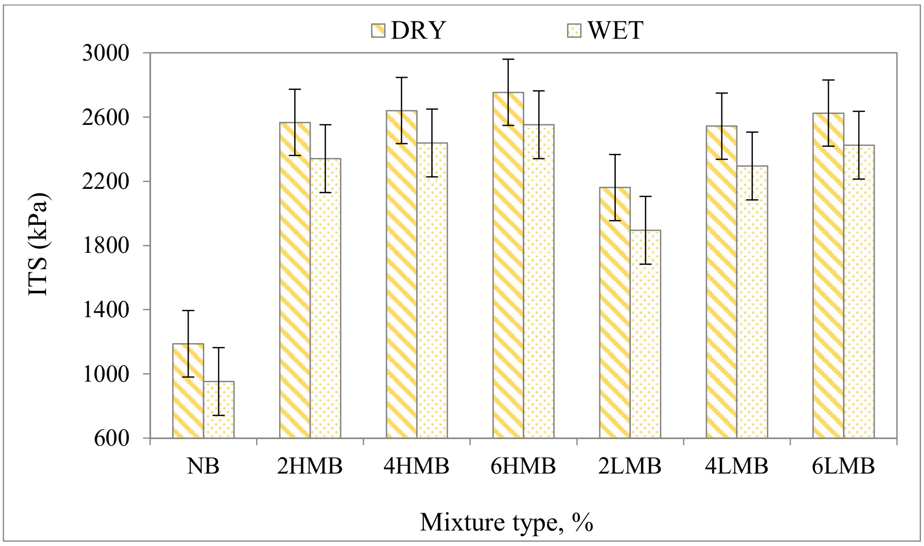

Fig. 9. Effect of polyethylene on ITS

4.4 Moisture Damage Assessment

Fig. 10 presents the TSR results for the specimens following ASTM D-4867 M-96 standards. TSR evaluates moisture-induced deterioration in HMA by computing the ratio of strength under wet conditions to dry conditions. A higher TSR indicates greater resistance to strength degradation during water immersion, reflecting enhanced moisture resistance. Mixtures with TSR values below 80% are susceptible to moisture-induced damage, while values exceeding 80% indicate more resistance to such deterioration. Analysis of TSR results reveals that all specimens achieved TSR values above 80%. Overall, the findings indicate that incorporating PE polymers positively influenced the resistance to water damage, with higher PE content correlating with increased TSR values. Notably, the optimal TSR values were achieved with 6% HDPE, exhibiting a 16% improvement in water damage resistance compared to conventional asphalt mixtures. This enhancement is due to the increased viscosity of modified asphalt, increasing the strong bond and improved adherence between modified binder and aggregate. Accordingly, it reduces the occurrence of adhesive failure (stripping) within the HMA structure (Attaelmanan et al., 2010).

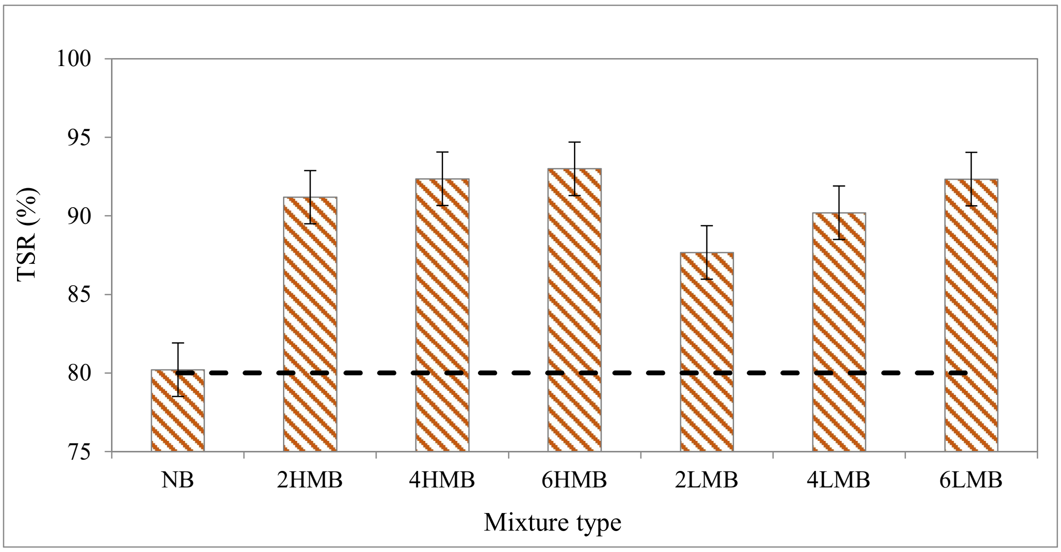

Fig. 10. Effect of polyethylene on TSR

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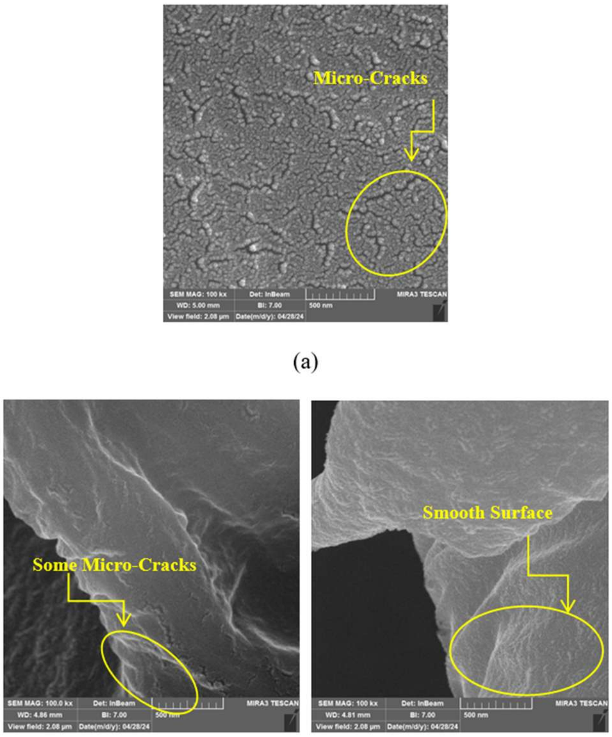
4.5 Scanning Electron Microscope Results

To evaluate the PE polymer's distribution, quality of dispersion in the bitumen, and morphology in asphalt mixes, the SEM test was employed. Two states are discussed: the first state when the PE polymer is applied as a modifier for binder and the second state after mixing the PE-modified asphalt with the aggregate to produce a PE-modified asphalt mixture.

In the first state, Fig. 11 displays the SEM images for the neat binder and modified asphalt binder with LDPE and HDPE. Micro-cracks can be observed on the surface of the neat binder, as illustrated in Fig. 11(a). Meanwhile, Fig. 11(b) illustrates that adding 6% of LDPE to the neat binder can strengthen the asphalt binder despite the fact that some micro-cracks are still visible on the surface of the LDPE-modified binder. On the other hand, adding 6% of HDPE is more effective since the molecular chains of HDPE and the binder material adequately interact. This leads to the production of an HDPE-modified asphalt binder with a smooth surface without any observable micro-cracks, as noted in Fig. 11(c). Consequently, HDPE-modified asphalt exhibits superior effectiveness compared to the LDPE-modified asphalt. This prevents the creation of cracks in the binder material, which could develop into permanent deformations in the road. This finding aligns with the outcomes of the previous studies (Ghani et al., 2022; Sengoz et al., 2009).

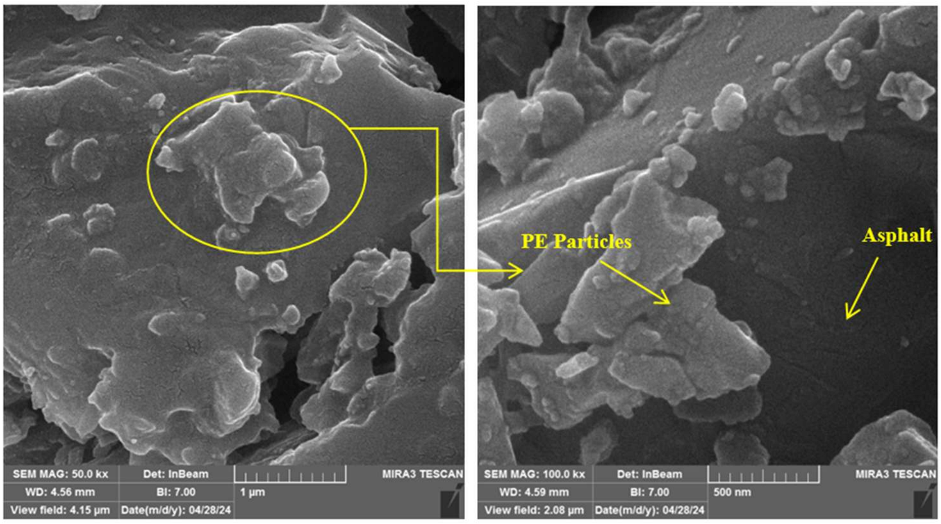
In the second state, SEM photos demonstrate that the PE remains observable in the mixture, exhibiting an elastic reaction when the binder's viscosity increases at elevated temperatures. The SEM image, as depicted in Fig. 12, differentiates the PE particles in light gray color from the asphalt mixture on the surface of the cut and polished specimen. The PE polymer partially melts during mixing, perhaps due to the elevated temperature of 170°C. Nevertheless, they did not fully liquefy. At elevated experimental temperatures, the binder undergoes softening and exhibits viscoelastic behavior, whereas the PE keeps its elasticity at these temperatures. The finding of the SEM test for PE-modified asphalt mixture aligns with the outcomes of the previous investigation (Kakar et al., 2022).



(a)

(b) (c)

Fig. 11. SEM images for asphalt binder, (a) Neat asphalt, (b) Modified asphalt with 6% LDPE, (c) Modified asphalt with 6% HDPE



(a) (b)

Fig. 12. SEM images for polyethylene polymer in the asphalt mixture at two scales, (a) 50 kx scale, (b) 100 kx scale

5. CONCLUSIONS

To determine the potential of PE polymer incorporation into flexible pavement production, this study provided a relatively comprehensive assessment of the influence of including HDPE and LDPE polymers in crushed form on neat asphalt binders. The motivation for using this form of PE polymer (crushed or powder) is to prevent the formation of lumps and avoid the early aging of asphalt binder when using PE polymer in granular form, as presented in previous studies. The major findings of the research are formulated as follows:

- Laboratory experiments have proven that PE can improve the physical properties of bitumen, as it enhances consistency and flexibility and reduces sensitivity to high temperatures. Furthermore, PE-modified binders have good resistance to high temperatures since PE polymers can reduce the weight loss of asphalt binders under heating conditions.
- Incorporating PE polymer into asphalt mixtures significantly enhances the mechanical characteristics of these mixtures. The Marshall stability is greatly enhanced by increasing the PE component in the mixture. A concentration of 6% yielded the maximum Marshall value for both polymer types, HDPE and LDPE, along with reduced flow values and increased VTM and VMA, in contrast to the conventional mixture. Furthermore, the mixture prepared with HDPE-modified asphalt exhibits higher stability and MS values than that of LDPE-modified asphalt.
- Mixtures treated with PE polymer reveal greater impedance to permanent deformations than conventional mixtures owing to their increased stiffness index. Meanwhile, asphalt mixtures treated with PE polymers exhibited TSR over 80%, indicating their capacity to resist degradation caused by moisture exposure.
- The enhancement observed in the mechanical characteristics and moisture resistance of mixtures modified with PE polymer is attributed to the vigorous bond formed between the aggregate and the polymer-modified asphalt. This bond improves as the proportion of polymer increases. HDPE is a more efficient additive than LDPE for bettering the strength and durability of asphalt mixtures. SEM images depict that adding HDPE polymer is more effective than LDPE due to the compatibility during mixing between the binder and HDPE. This contributes to preventing the occurrence of cracks in the modified asphalt, reducing the deterioration that occurs in the flexible roads.
- SEM images reveal that the PE polymer is still visible in the structure of the asphalt binder. PE particles do not melt completely during mixing. This is attributed to the fact that asphalt binder and PE polymer have different melting points. In other words, asphalt binder acts as a viscoelastic material at higher temperatures since the binder starts to soften at 51°C, representing the softening point of refinery asphalt. Meanwhile, the PE polymer remains elastic at these temperatures. However, it is also worth mentioning that both asphalt binder and PE polymer are elastic at lower temperatures.

Nevertheless, testing storage stability at high temperatures and fatigue cracking behavior at low temperatures for modified asphalt binders with PE polymer needs more attention, and it is recommended that these indicators be evaluated in future studies.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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