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INVESTIGATING THE MOISTURE SUSCEPTIBILITY OF ASPHALT MIXTURES MODIFIED WITH HIGH-DENSITY POLYETHYLENE

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ABSTRACT

Flexible pavements are susceptible to the damaging effects of moisture, causing various kinds of problems for asphalt such as stripping. That reduces the durability and serviceability life of pavements and consequently increases the construction and maintenance cost. The aim of this research is to study the moisture sensitivity of the hot asphalt mixture with high-density polyethylene as an asphalt binder modifier. Asphalt 60/70 was mixed with several concentrations of high-density polyethylene (HDPE) ranging from 2% to 8% by bitumen weight using a high shear mixer at a temperature of 180 0C and a speed of 4000 rpm for 60 minutes. Penetration depth, softening point, rotational viscosity (RV), and scanning electron microscopy (SEM) tests were performed on both the conventional and HDPE-modified binders. Asphalt mixtures were designed according to the Egyptian specifications using the Marshall method. Conventional and HDPE-modified asphalt mixtures' moisture susceptibilities were evaluated through indirect tensile strength (IDT) and loss of stability tests. Results of scanning electron microscopy (SEM) showed that HDPE was homogeneously dispersed through the binder with no polymer cluster formations. Testing results revealed that adding high-density polyethylene at a concentration of 4% gives superior performance in most tests. Adding HDPE significantly improved the properties of asphalt binder, increased the hardness of the asphalt mixture, and reduced the effect of moisture damage.

KEYWORDS: High density polyethylene, Polymer modified binder, Moisture susceptibility, Indirect tensile strength, Loss of stability.

1. Introduction

The low adhesion between the binder and aggregates in asphalt mixes is one of the main reasons for distresses like moisture sensitivity and fatigue cracking in HMA [1]. Currently, some kinds of polymers are used as additives to improve the performance of asphalt mixtures by increasing the adhesion between aggregates and binder [2]. At hot climates, polyethylene increases the stiffness of the asphalt mixture, which leads to a reduced strain under the influence of traffic loads [3]. HDPE is a type of polymer that is characterized by durability, toughness, and resistance to hot climates [4]. Sinan Hinislioğlu et al. studied adding HDPE to the asphalt at rates ranging from 4 to 8%. Their results showed an improvement in Marshall stability with an increase in the deformation resistance [5]. Ahmed, L.A. et al. investigated the effect of HDPE using six concentrations ranging from 2% to 10%. He concluded that HDPE improved Marshall stability of the modified asphalt mixtures [6]. Zahra Kalantar et al. modified bitumen (80/100) using HDPE with rates (0.5%-4%) at a temperature of 180° C and mixing time for 60 minutes. The findings appeared that high HDPE improved the resistance of modified binder to temperature changes [7]. NZ Habib et al. prepared the polymer modified binder (PMB) by adding ratios of polyethylene ranging from (0.5% to 5%) by weight of the binder, using a mixer at a speed of 120 rpm at a temperature of 170° C for 60 minutes. The results showed that HDPE increased the mixture's hardness and reduced permanent deformation [8]. Moghadas Nejad et al. concluded that the adhesion between the binder and aggregates in HDPE-modified asphalt mixtures increased even in the presence of moisture [9]. Nahla Yassoub et al. used the wet process to mix HDPE with dosages of (2, 5, and 7%) by weight of bitumen (40/50) and for a mixing period of 90 minutes at a temperature of 180° C. They reported that HDPE increased the Marshall stability of the mixture and improves the rutting depth as well [10]. Moghadas Nejad et al. evaluated the effect of HDPE on asphalt mixtures at high temperatures. Where the polymer was added at concentrations 3% and 7% to the bitumen (85/100) using a high shear mixer at a speed of 5500 rpm for 60 minutes at a temperature of 180°

C. They reported a significant improvement in rutting parameters (G*/sinδ) [11]. HAA Gibreil et al. studied the effect of HDPE and reclaimed asphalt pavement (RAP) on the binder and asphalt mixture. The outcomes showed an improvement in the physical properties of binder and less sensitivity to temperature [12]. AK Sarka et al. Compared high-density polyethylene (HDPE) and low-density polyethylene (LDPE) performance as bitumen additives using polymer concentrations ranging from 1% to 4% by the bitumen weight. They concluded that HDPE was more effective than LDPE in improving bitumen properties and mixture properties as well [13]. LuZhou et al. concluded that the utilization of HDPE at dosages ranging from (2% to 8%) enhanced the self-healing properties of asphalt binder [14].

Although several studies have considered employing HDPE as a binder modifier, a few of them have investigated its effect on the asphalt mixture's moisture susceptibility, especially in the case of adding HDPE to bitumen using the wet mixing method. Therefore, the main objective of this research is to investigate the impact of incorporating HDPE as a binder additive on the moisture damage tendency of the modified asphalt mixture. Moisture damage tendency is investigated through two experimental tests: the indirect tensile strength (IDT) and loss of stability. For capturing the quality of the dispersion of HDPE in the asphalt binder after the wet mixing process, the scanning electron microscope (SEM) is conducted.

2. Materials

2.1 Binder

In this study, AC 60/70 asphalt binder is used as the conventional binder, which is commonly used in Egypt, and its main properties are presented in Table 1.

2.2 Aggregates

Coarse and fine aggregates utilized in this study are crushed dolomite stone, but the sand and mineral filler are natural siliceous sand and limestone dust, respectively. The utilized aggregates physical properties are presented in Table 2.

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2.3 High-density polyethylene (HDPE)

High-density polyethylene (HDPE) has been used as a binder additive to improve the properties of bitumen and asphalt mixture as well. Table 3 presents the physical properties of HDPE.

Table 1. Physical properties of the conventional asphalt binder

Test	Standard	AC 60/70
Penetration (0.1mm, 25◦C, 5 sec.)	ASTM D5	62
Ductility (25◦C, 5 cm/min), cm	ASTM D113	+100
Softening Point (ring and ball), °C	ASTM D36	45.4
Rotational viscosity (135 °C), mpa.s Rotational viscosity (165 °C), mpa.s	ASTM D 2170	376 83
Flash point (°C)	ASTM D92	+250
Specific gravity at 25 ºC	ASTM-D70	1.01
Penetration index (PI)		-1.95

Table 2. Physical Properties of Aggregates

Test	Results				Standard Test Method
	Agg. #1	Agg. #2	Sand	Filler	
Bulk Specific Gravity	2.583	2.576	2.514	---	ASTM C127 [15] ASTM C128 [16] ASTM D854 [17]
SSD Specific Gravity	2.624	2.622	2.531	---	
Apparent Specific Gravity	2.650	2.705	2.603	2.701	
Water Absorption (%)	1.95	2.04	2.89	---	
Disintegration in Water (%)	0.0	0.0	---	---	ASTM C88 [18]
Los Angeles	27.9	33.3	---	---	ASTM C131 [19]

Table 3. Physical and mechanical properties of HDPE

Property	Value	Standard Test Method
Density	0.956 g/cm³	ASTM D4883
Melt Index (190°C/2.16 kg)	20 g/10 min	ASTM D1238
Peak Melting Temperature	130 °C	AST M D3418
Tensile Stress at Yield	23 M Pa	ISO 527-2/1A/50
Tensile Strain at Yield	10 %	ISO 527-2/1A/50
Tensile Strain at Break	> 100 %	ISO 527-2/1A/50
Flexural Modulus	920 M Pa	ISO 178
Notched Izod Impact Strength	4.3 kJ/m²	ISO 180/1A

3. Experimental work

3.1. Preparation of the HDPE- modified binder

To prepare the modified binder, the bitumen was mixed with high-density polyethylene via a wet mixing process using a high shear mixer at a temperature of 180 ^{0}C and a speed of 4000 rpm for 60 minutes. HDPE was added to the pure binder at concentrations 2%, 4%, 6% and 8% of the binder weight [7].

3.2. Physical properties of binders

To characterize the properties of the modified binder and the conventional binder, three physical tests were performed: penetration test (ASTM D5), softening point test (ASTM D36), and rotational viscosity test at 135 ^{0}C (ASTM D 4402). Each test was replicated three times for each percentage of HDPE.

3.3. Scanning electron microscope (SEM)

The Scanning electron microscopy (SEM) was conducted to examine the microstructure and the dispersion of the HDPE additive in the binder. The sample of asphalt binder is prepared by cutting it into small pieces with dimensions of (20x20x10) mm. To increase the hardness of the sample surface, without affecting its morphology, as well as obtaining electrical conductivity, the sample was painted with a gold [20, 21].

3.4 Asphalt mixture design

3.4.1 Conventional asphalt mixture

According to the Marshall method [22], the asphalt wearing surface (4C) was designed. Mixing and compaction temperatures for base asphalt binder were estimated using rotational viscosity at 135^{o}C and 165^{o}C. The ranges of mixing and compaction temperatures for binder were (154.1-158.16) ^{o}C and (141.83-147.95) ^{o}C, respectively. The mixing proportions of coarse aggregate, fine aggregate, and filler were given in Table 4. Grading curves of the mixture and the minimum and maximum limits are depicted in Fig. 1. Hot aggregates were blended individually with five different percentages of pure bitumen (4%, 4.5%, 5%, 5.5%, and 6%) until homogeneity is reached. Three samples were prepared for each bitumen percentage. The homogeneous mixture was poured into a Marshall mold and each sample received 75 blows on each face. After at least 24 hours, the samples were placed in a water bath for 30 minutes at a temperature of 60° C. Samples were loaded using the Marshall device at a loading rate of 50.8 mm/minute until the failure occurred. The failure load is Marshall stability and its corresponding deformation is the flow. After analyzing the test results, the conventional asphalt mixture's properties were obtained as presented in Table 5.

Table 4. Final proportion of each used aggregate

Aggregate Type	Proportions of the proposed mix (%)
Aggregate #2	24
Aggregate #1	27
Sand	42
Filler	7

Table 5. Marshall Mix Design Properties

Parameter	Value	Design Egyptian limitations	
		Minimum	Maximum
Marshall bulk density (t/m3)	2.35	----	----
Stability (kg)	979.5	900	
Flow (mm)	3.83	2	4
Air voids (AV) (%)	4.32	3	5
Voids in mineral aggregates (VMA) (%)	15.83	13	----
Voids filled with binder (VFB) (%)	72.7	-----	----
Asphalt cement (%)	5	----	----

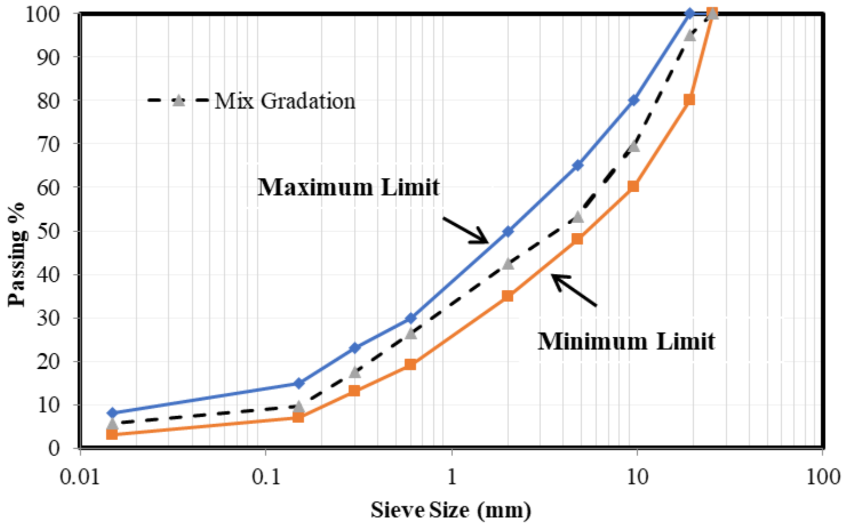

Fig. 1. Grading Curve of conventional asphalt mixture

3.4.2 Polymer modified asphalt mixtures

To prepare the HDPE-modified mixtures, both aggregates and HDPE-modified bitumen were heated at 180° C. The hot aggregates were blended with the HDPE-modified bitumen at the same optimum asphalt content (OAC) of the control mixture (5%).

3.5. Moisture Susceptibility

Moisture susceptibility of the conventional and HDPE-modified mixtures is assessed via two tests: the indirect tensile strength (IDT) and loss of stability tests. As will be discussed in the following sections:

3.5.1 Indirect tensile strength test (IDT)

IDT test was conducted on samples of the conventional and HDPE-modified mixtures to investigate the effect of moisture on the asphalt mixture's tensile strength in accordance with AASHTO T283-14 [23]. In which, six samples were prepared with the same dimensions of Marshall samples for each concentration of HDPE. The air void ratios of specimens were from 6% to 8%. Several trails were conducted to determine the blows numbers which sustain this range. Samples are divided into two sets. For the first set, the samples were tested in a dry state at a temperature of 25^{o} C with a loading rate of 50.8 mm/minute until the occurrence of the collapse with recording the failure load. For the second set, the samples are processed as in the following steps:

- First, the percentage of saturation in the samples increased to reach (55% to 80%) using the vacuums according to (AASHTO T283-14) [23] .
- Second, samples are placed in a water tank at a temperature of 60^{o} C for a period of 24 hours and then 2 hrs, at 25 ^{o}C.
- Third, samples are charged on the loading machine with a loading rate of 50.8 mm/minute and the breakdown load is measured.

Indirect tensile strength (ITS) can be inferred from Equation 1. Moreover, the tensile strength ratio (TSR), which gives an indication of moisture susceptibility, can be defined as the ratio of the tensile strength of wet samples to that of dry samples. And can be estimated using Equation 2.

$$\text{ITS} = \frac{2\text{P}}{\pi\text{HD}} \qquad \text{............... (1)}$$

$$\text{TSR\%} = 100\left(\frac{\text{ITS}_{\text{wet}}}{\text{ITS}_{\text{dry}}}\right) \qquad \text{............... (2)}$$

Where,
P= failure load, KN
H= thickness of the sample, mm
D= diameter of the sample, mm

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ITS_{dry} = average indirect tensile strength for the first group samples, kPa.
ITS_{wet} = average indirect tensile strength for the second group samples, kPa.

3.5.2 Loss of stability test

The loss of stability test, also known as immersion Marshall test, was carried out to evaluate the moisture damage resistance of the asphalt mixtures according to [24-26]. In which, six samples of the conventional and HDPE-modified mixtures were prepared. The samples are divided into two groups, the first group is tested in a Marshall apparatus after being placed in a water bath for 30 minutes at a temperature of 60^{o} C. While the second group is tested after being immersed in a water container for 48 hours at a temperature of 60^{o} C. Loss of stability (LOS) expresses the percentage decrease in Marshall stability (Ms) between the first group and the second group samples (reduction in Marshall stability). The value of LOS can be calculated from Equation 3.

$$\mathrm{LOS\%} = 100\left(1 - \frac{\mathrm{Ms}_1}{\mathrm{Ms}_2}\right) \qquad \text{.................. (3)}$$

Where,
Ms_1 = average Marshall stability of the second group samples.
Ms_2 = average Marshall stability of the first group samples.

4. Results

4.1. Physical properties of Binder

Physical tests conducted on the conventional and HDPE-modified binders containing various HDPE content involved penetration, softening point, and rotational viscosity tests. Fig.2 presents the results of the penetration tests for the modified asphalt cement with different percentages of HDPE. A relatively linear relationship between the HDPE percentage and penetration (0.1mm) was noticed. As shown in Fig. 2, a significant improvement in the penetration occurred with the increase in the modifier concentration. On the other hand, the softening point increased with increasing HDPE contents as shown in Fig. 3.

To evaluate the effects of HDPE as additives on the temperature sensitivity of the asphalt binder, the penetration index (PI) was determined. The acceptable PI for asphalt of road construction has been standard to be between +1 and -1 for normal bitumen [27]. However, PI for polymer modified bitumen ranged from -3 to +7 at low and high temperature respectively [28]. Fig. 4 shows the relationship between the HDPE contents and the penetration index of modified asphalt.

The PI values were determined for binders and varied from -1.95 for the conventional binder to +0.072, +0.411, +1.718, and +1.972 for the 2%, 4%, 6%, and 8% HDPE-modified binders, respectively. This reveals that the asphalt became considerably less sensitive to temperature due to this modification (a higher penetration index indicates a lower temperature sensitivity).

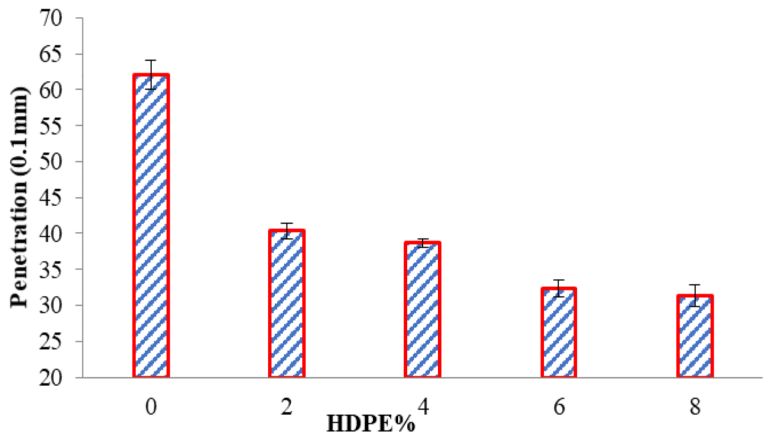

Fig. 2. Penetration of modified binder

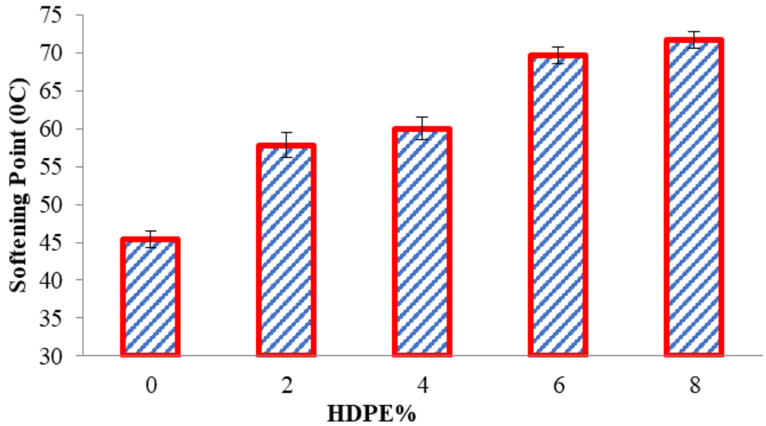

Fig. 3 Softening point of modified binder

The results of the Brookfield RV tests presented in Fig. 5 show that the binder viscosity increases almost by a polynomial relation with the increasing of HDPE. A significant improvement in the viscosity was observed with the increase of HDPE concentration. However, in the extreme cases of adding 6% HDPE and 8% HDPE, the viscosity increased to 4991 MPa and 9647

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mPa.s, respectively which do not satisfy (ASTM D6373) criterion for asphalt binder workability (3000 mPa.s).

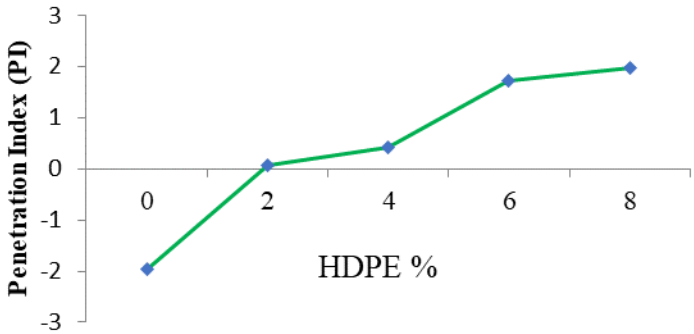


Fig. 4. Penetration Index of modified binder

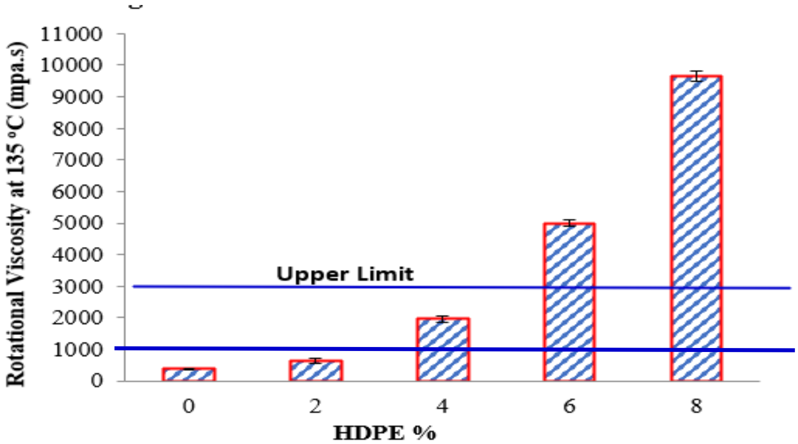


Fig. 5. Rotational Viscosity of modified binder

4.2. Scanning electron microscope (SEM)

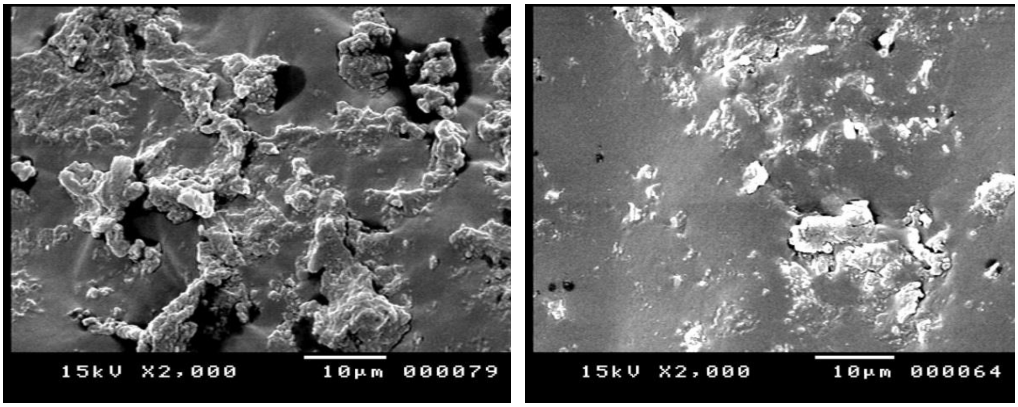
From the SEM tests, images of the conventional asphalt and HDPE-modified asphalt (at 4% of HDPE) are shown in Fig. 6. It can be noticed from the Figure that HDPE was well dispersed in the binder and no polymer cluster formations.

4.3. Marshall test

It was found that the addition of HDPE enhanced the stability of AC mixtures as shown in Fig. 7. The AC mixture modified with 4% HDPE (by asphalt weight) attained the maximum stability with an increase of 41% than the conventional mix. Increasing Marshall stability improves the mixture stability as it can sustain more traffic volume requirements with a higher rutting resistance. The remarkable increase in Marshall stability can be due to the significant improvement in the asphalt stiffness when adding HDPE.

From Fig. 8, the flow values of asphalt mixtures were not affected significantly by adding HPDE with different percentages. This may be attributed to the physical properties of asphalt binder. It can be observed from the Fig. that all flow values are within the limits set by the Egyptian Code [25] except the mix with 8% HDPE which had a flow value slightly higher than the maximum limit.

The variation of bulk density values with different HDPE contents was given in Fig. 9. It was observed that the 2.0% HDPE modified mixture yielded the highest bulk density value. Fig. 10 provides the effect of using different percentages of HDPE on the volumetric properties of the conventional and HDPE-modified asphalt mixtures. Which include the percentage of air voids (AV%), the percentage of voids in mineral aggregate (VMA%), and the percentage of voids filled with aggregate (VFA%) values. Generally, the air voids content was within the range of 3% to 5% for all samples except the samples containing 6% and 8% of the HDPE which were higher than the upper limits. The addition of HDPE to the mixture slightly increased the VMA% compared to the conventional mixture except the sample containing 2% HDPE. The increase in the VMA% indicates thicker AC film thickness and hence better durability and resistance to environmental effects. The percentage of voids filled with aggregates (VFA %) for modified asphalt mixtures was within the asphalt institute specifications except sample modified by 2% HDPE it was higher than the upper limits [25].



(a) (b)

Fig.6. SEM fracture micrographs of AC (a) conventional, (b) HDPE-modified

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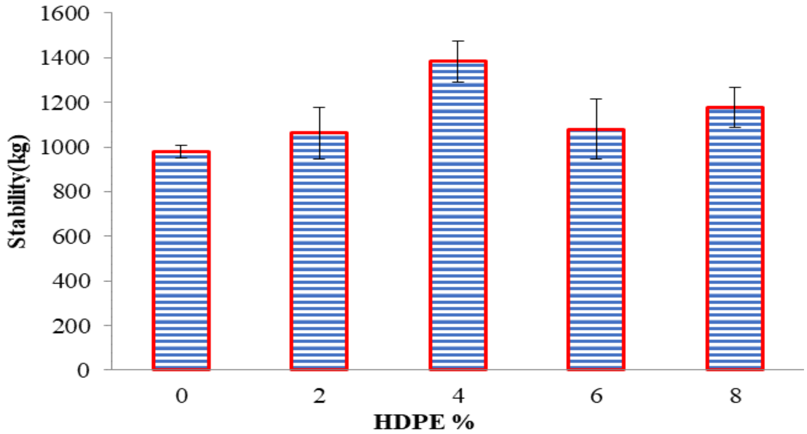

Fig. 7. Stability of HDPE- modified mixtures

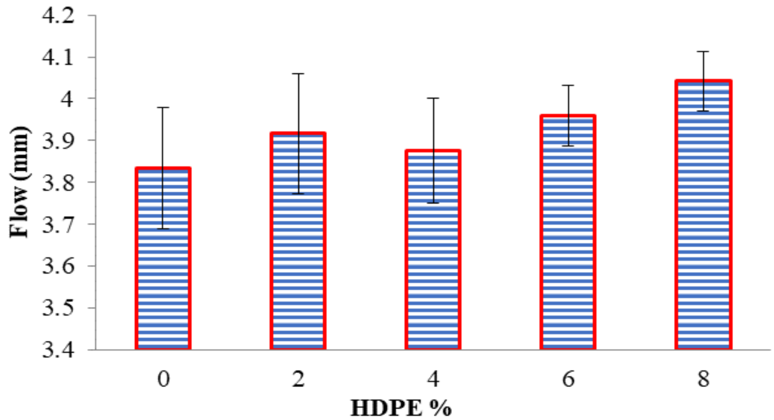

Fig. 8. Flow of HDPE-modified mixtures

In addition to the stability, flow, and volumetric properties, the Marshall test can give an indication of the resistance of mixtures against rutting. In which, Marshall Quotient (MQ) calculated from dividing the stability over the flow can be used as an indication of the mixture's tendency for rutting. The higher MQ values indicate higher mixtures' stiffness and consequently higher resistance to permanent deformation i.e. rutting [29]**.** As shown in Fig. 11, it can be observed that using HDPE increased the mixture rigidity that reveals higher resistance to AC rutting, especially in hot climatic areas. The 4.0% HDPE-modified mixture had the highest rigidity value with an increase of up to 39% than the conventional mixture.

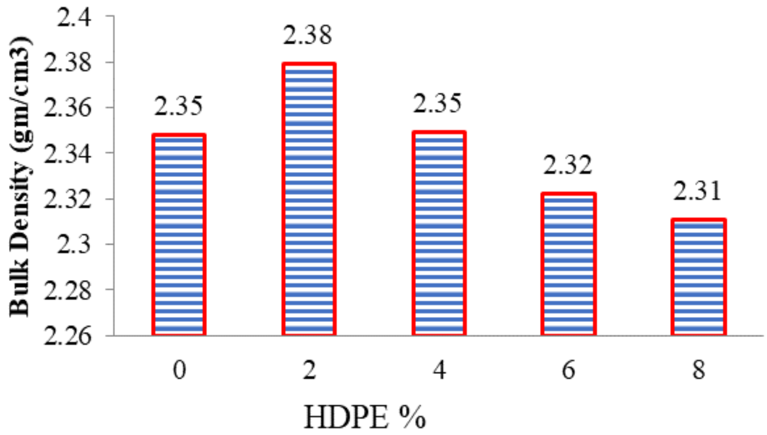

Fig. 9. Bulk density of control and HDPE-modified mixtures

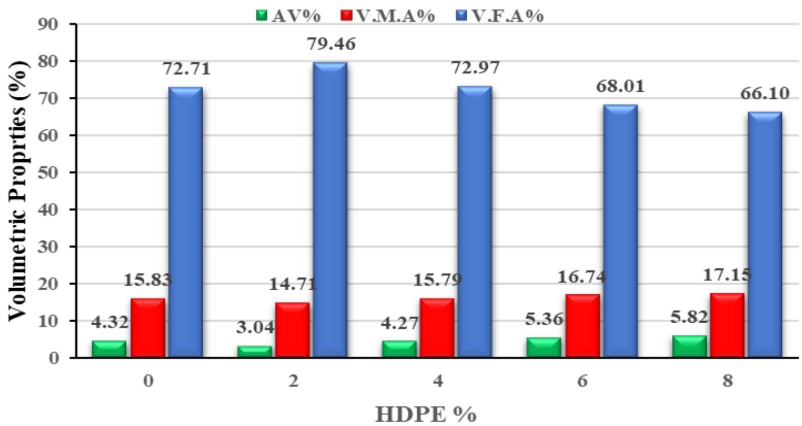

Fig. 10. Volumetric properties of control and HDPE-modified mixtures

4.4. Indirect tensile strength

The indirect tensile strength (ITS) values of the conventional and HDPE-modified mixtures are presented in Fig. 12. Results indicated that in general, the average tensile strength values of all modified dry subsets (at 25 °C) were higher than those of the conventional mixture, which can be considered as an improvement in mixture stiffness. The 6% HDPE-modified mix attained the highest ITS_{dry} value with an increase of about 46% than the conventional mixture. The 6% HDPE-modified mixture gave the highest ITS_{wet} value with an increase of about 100% than the conventional mixture. Moreover, the tensile strength ratios (TSR) of the conventional and modified mixtures are depicted in Fig. 13. It can be noticed from Fig. 13 that HDPE-modified asphalt mixtures achieved higher values of TSR than the conventional asphalt mixture. Therefore, using HDPE as an additive improved the TSR values, i.e. improved the binder-aggregates bonding and consequently higher moisture resistance was gained. However, all mixtures did not satisfy the TSR minimum value of 80%, as required by the Egyptian code of practice, except the mixtures modified by 6% and 8% of HDPE [25].

4.5. Loss of stability (LOS)

Fig. 14 shows the percentage of the average loss of stability values for the conventional and HDPE-modified mixtures. It can be observed that the increasing proportion of HDPE leads to a decrease in the loss of stability percentage and the 6% HDPE-modified mixture achieved the lowest loss of stability.

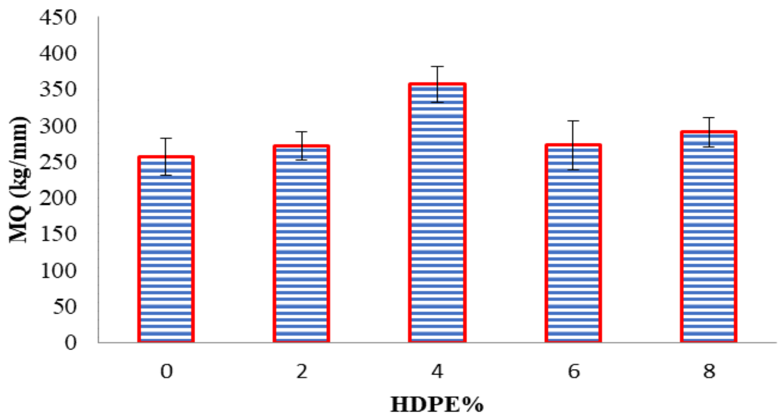

Fig. 11. Marshall Quotient for the control and HDPE-modified mixtures

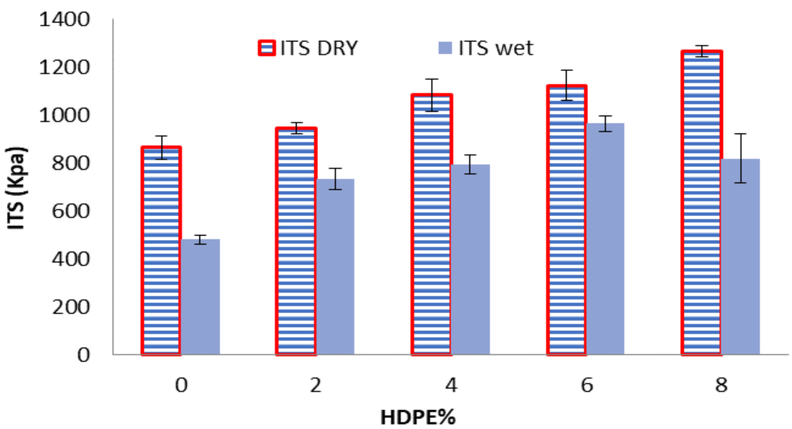

Figure 12. Indirect tensile strength for control and modified mixtures

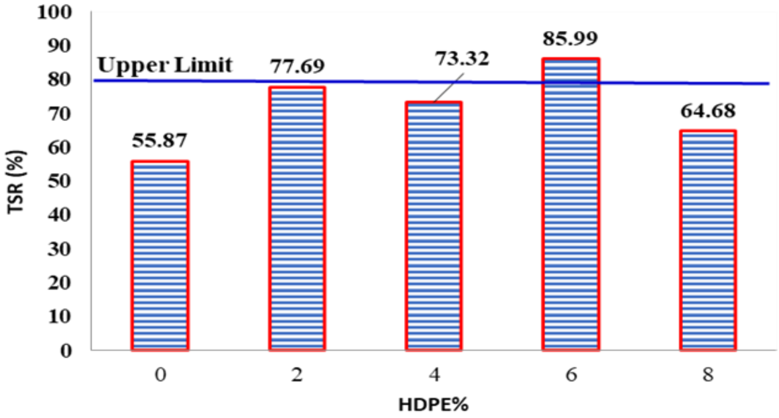

Figure 13. Tensile strength ratio for control and modified mixtures

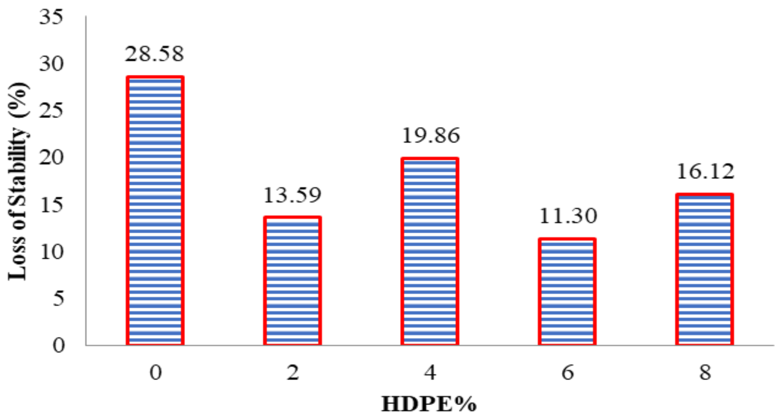

Fig. 14. Loss of Stability for control and HDPE-modified mixture

5. Conclusions

In this paper, high-density polyethylene (HDPE) was employed as an additive to bitumen (60/70). HDPE was added at concentrations ranging from 2% to 8% by bitumen weight. The general outcomes from this research were as follow:

- Results revealed an improvement in physical properties of the HDPE-modified binder with a reduction in its sensitivity to temperature compared with the conventional binder.
- SEM microstructural investigation showed a good dispersion of HDPE within the modified binder.

- The best performance of modified asphalt mixture was achieved at 4% of high-density polyethylene (HDPE), by bitumen weight.
- Implementing HDPE as a binder-additive enhanced mixture stiffness and consequently its tendency to permanent deformation.
- Also, it improved the binder-aggregates bonding and consequently higher moisture resistance was gained. Therefore, incorporating HDPE enhanced mechanical properties and moisture damage resistance of the asphalt mixtures.

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التحقق من حساسية الرطوبة للمخلوطات الأسفلتية المعدلة بالبولي إيثيلين عالي الكثافة

الملخص العربي:

الأرصفة المرنة تكون عرضة للتأثيرات الضارة للرطوبة، مما يتسبب في أنواع مختلفة من الأضرار، بما في ذلك التشريخ، والتجريد، والتشكل الدائم. وهذا ما يقلل من متانة وأداء الخدمة للأرصفة وبالتالي يزيد من تكلفة الإنشاء والصيانة. الهدف من هذا البحث هو دراسة حساسية الرطوبة لخليط الإسفلت مع إضافة البولي إيثيلين عالي الكثافة كمعدِّل للأسفلت حيث تم خلط أسفلت (٦٠/٧٠) مع عدة تركيزات من البولي إيثيلين عالي الكثافة (HDPE) تتراوح من ٢٪ إلى ٨٪ من وزن البيتومين باستخدام خلاط عالي القص عند درجة حرارة ١٨٠ درجة مئوية وسرعة ٤٠٠٠ دورة في الدقيقة لمدة ٦٠ دقيقة. تم إجراء اختبار الاختراق واختبار التطرية واختبار اللزوجة الدوارة (RV) واختبار الفحص المجهري الإلكتروني (SEM) على كل من الاسفلت التقليدي والمعدل بالبوليمر. تم تصميم مخاليط الأسفلت حسب المواصفات المصرية باستخدام طريقة مارشال وتم تقييم حساسية الرطوبة لمخاليط الأسفلت التقليدية والمعدلة بالبوليمر من خلال اختبار الشد غير المباشرة (IDT) واختبار النقص في الثبات. أظهرت نتائج الفحص المجهري الإلكتروني (SEM) أن البولي إيثيلين عالي الكثافة كان منتشرًا بشكل متجانس خلال البيتومين مع عدم وجود تكتلات للبوليمر كما أظهرت نتائج الاختبارات أن إضافة البولي إيثيلين عالي الكثافة بتركيز ٤٪ يعطي أداءً مقبولا في معظم الاختبارات. مما سبق يمكن أن نخلص إلى أن إضافة البولي إيثيلين عالي الكثافة أدى إلى تحسن كبير في خصائص الأسفلت، وزيادة صلابة خليط الأسفلت.