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Improving the mechanical properties and performance of asphalt mixtures using high density polyethylene and crumb rubber powder

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ABSTRACT

Asphalt cement is considered a necessary bonding material for asphalt mixture manufacturing; nowadays, in Egypt, there is a lack of the amount of asphalt cement due to the rapid progress in highways construction which is necessary for development. The main objective of this research is to use waxy asphalt as a compensatory material to address the shortage of asphalt in Egypt. After modifying its properties by adding polymer (HDPE) and crumb rubber powder (CRP) together because of waxy asphalt may have a harmful effect on road construction, and to obtain the best method of adding polymer and CRP to the asphalt mixture. The experimental program consists of six stages. In the first stage, a control mix M0 was designed without additives, followed by the second stage, in which six asphalt mixtures from M1 to M6 were designed, with varying ratios of HDPE and CRP, both applied through a wet process. The third stage also consists of six asphalt mixtures from M7 to M12, incorporating different ratios of HDPE in a wet process and CRP in a dry process. The fourth stage, included six asphalt mixes from M13 to M18, employing various ratios of CRP in a wet process and HDPE in a dry process. All mixes were designed using Marshall Test. From the prescribed three stages, the optimum asphalt mixtures were identified as M6, M8, and M17, respectively. In the fifth stage, the moisture sensitivity was measured as well as rutting characteristics for the control mix and the three optimum mixes. In the last stage, a Scanning Electron Microscope analysis was conducted. In conclusion, the results indicate that the waxy asphalt can be used by adding HDPE (Wet Process) and CRP (Dry Process) which significantly enhance the Marshall properties, as well as improving resistance to moisture damage and permanent deformation.

1. Introduction

Asphalt is commonly utilized for road paving due to its strong adhesive properties with aggregates. However, it is highly sensitive to temperature differences, which can result in various forms of pavement distress, including fatigue cracking, permanent deformation, and rutting. [1]. Enhancing the properties of traditional asphalt binders is crucial for increasing their resistance to permanent

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deformation and cracking. The mechanical performance of asphalt binders can be significantly improved by incorporating suitable materials. [2]. The composition of bitumen is complex and remains incompletely understood, mainly due to the variety of chemical compounds it contains. During the distillation process in bitumen production, waxes inherent in crude oils can remain in the finished product. These waxes typically include paraffin wax and microcrystalline wax. Paraffin wax is characterized by its n-alkanes with few branches, while microcrystalline wax mainly comprises naphthens and iso-paraffins. The presence of these waxes in bitumen is generally considered undesirable. As a result, countries such as Germany, France, and China have implemented limits on the wax content in binder specifications, primarily based on the belief that wax melting at high temperatures reduces the rutting resistance of asphalt mixtures, and that crystallization of wax at lower temperatures can lead to cracking. Furthermore, issues like physical hardening (due to molecular structuring) and impaired binder adhesion to aggregates have also been associated with wax content [3].

To improve the engineering properties of bitumen, modification is essential. This can be accomplished using various commercial modifiers, such as fillers, extenders, polymers, and antioxidants. While these modifiers have the potential to enhance bitumen's properties, their use can significantly increase the cost of bituminous mixtures. To address this issue, polymers for asphalt modification can be categorized into three main types: thermoplastic elastomers, plastomers, and reactive polymers. Thermoplastic elastomers provide excellent elasticity to the modified binder, whereas plastomers and reactive polymers are used to enhance rigidity and minimize deformation under load. Commonly studied polymers for asphalt modification include polyethylene (PE), ethylene-vinyl acetate (EVA), and ethylene-butylene-styrene (EBA) random copolymers. [4]. Asphalts modified with polymers from multiphase systems typically feature one phase that is rich in polymer and another that is abundant in asphaltenes, which remain unabsorbed by the polymer. The characteristics of asphalt-polymer blends are influenced by both the concentration and type of polymer utilized. Generally, the polymer is incorporated at concentrations of approximately 4–6% of the total weight of the asphalt. [4]. Higher concentrations of polymers are often deemed economically unfeasible and can also lead to various issues concerning the material's properties. Polyethylene is a widely used plastic globally, and when employed as a modifier for asphalt, it can significantly increase the rigidity of asphalt pavements. This enhancement effectively reduces deformation of the pavement when subjected to heavy traffic loads at elevated temperatures. [5]. Hassani et al. replaced asphalt aggregate with waste polyethylene terephthalate, resulting in Marshall stability and quotient values similar to those of standard asphalt mixtures. Dalhat et al. determined that substituting No. 8 (2.36 mm) plastic particles provided improved moisture susceptibility compared to replacing aggregates from No. 40 (0.42 mm) to No. 8 (2.36 mm) in dense-graded pavement designs. Sarang et al. explored the incorporation of waste plastic as fine aggregates to enhance stiffness in stone matrix asphalt pavements. Ranieri et al. [5] compared the recycling of plastic through wet and dry processes, concluding that rutting and moisture resistance were similar for both methods [6].

Sinan and Emine investigated the possibility of using different plastic wastes containing (HDPE) as polymer additives to asphalt concrete mixture. They investigated the effect of HDPE-modified binder obtained by different mixing times, mixing temperatures and HDPE content on the Marshall Stability, flow and Marshall Quotient (Stability to flow ratio).The hot mix asphalt (HMA) binders were prepared with HDPE incorporated at concentrations of 4–6% and 8% (relative to the weight of the optimum bitumen content) at temperatures of 145–155 °C and 165 °C, using mixing times of 5, 15, and 30 min. They concluded that the HDPE-modified asphalt concrete resulted in a considerable rise in the Marshall Stability value and MQ (resistance to deformation). Four percent HDPE, 165 °C of mixing temperature and 30 min of mixing time were determined as optimum conditions for Marshall Stability, flow and Marshall Quotient (MQ). MQ increased by 50% compared to the control mix. It can be said that waste HDPE-modified bituminous binders provide better resistance against permanent deformations due to their high stability and high MQ and they provide protection for the environment by recirculation of plastic wastes [7].

Pérez- Lepe et al. studied asphalt binders modified with (HDPE) at contents of 1–5 wt%. Their test results noted that although HDPE improved high temperature performance, severe storage instability occurred which made this type of modification inefficient for pavement application. Additionally, the use of plastomeric polymer to bump binder performance grade can yield binders that are more sensitive to oxidative aging and, consequently, decrease cracking performance [8]. Moatasim et al. observed that adding high-density polyethylene to asphalt improves the deformation resistance under high and moderate temperatures, in addition to its shear resistance. Further, it also improves the Marshall Quotient (MQ) and indirect tensile strength of bituminous mixtures [9]. Ahmed, L.A. et al. investigated the influence of HDPE using six ratios from 2% to 10%. He concluded that HDPE improved Marshall Stability of the modified bituminous mixtures [10].

Zahra Kalantar et al. modified bitumen (80/100) using HDPE with percentages ranging from (0.5%-4%) at a temperature of 180°C and mixing time for 60 min. The results showed that HDPE enhanced the resistance of modified binder to temperature changes [11]. NZ Habib et al. reported that the polymer-modified binder (PMB) was created by incorporating varying ratios of polyethylene, from 0.5% to 5% by weight of the binder. This was achieved using a mixer operating at 120 rpm and a temperature of 170°C for 60 min. The results indicated that the addition of HDPE enhanced the hardness of the mixture and decreased permanent deformation. [12]. 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 [13]. 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 min at a temperature of 180°C. They noted that HDPE increased the Marshall stability of the asphalt mixture and improved the rutting depth as well [14].

Mohamady et al. studied the effect of using polymers on bituminous mixtures characteristics in Egypt. The study presented the effect of polymers on the stability and flow values for all HMA samples. The results reported that adding polymers to asphalt mixes significantly improved stability, flow and density of HMA up to 4% polymer ratio [15].

The increasing number of vehicles results in the overproduction of tires, which in turn contributes to the build-up of waste materials such as ground tire rubber (GTR) and tire fibers [16]. If not managed appropriately, these materials can pose a threat to the environment. One effective approach to address this issue is to incorporate ground tire rubber (GTR) and tire fabric in road construction, which allows for the recycling of these waste products and minimizes their potential as environmental pollutants [16].

In general, there are three main technologies for incorporating crumb rubber into asphalt pavements: the on-site dry process, the on-site wet process, and terminal blending. These approaches vary significantly in how the rubber particles interact with the other materials. In the dry process, rubber acts as a polymer modifier for the base asphalt, achieving either full or partial integration. In contrast, the wet process involves minimal interaction between the rubber and asphalt binder, while the dry method partially replaces the aggregate structure with rubber particles. Terminal blending, similar to the production of polymer-modified asphalt, offers a stable shelf life. Meanwhile, the wet process requires merging rubber with asphalt at high temperatures (approximately 180°C) and using mechanical mixing to ensure that the oily components of the asphalt penetrate the rubber's polymer matrix [16] [17].

The wet mixing method enhances the viscosity of hot mix asphalt (HMA). For asphalt modified with rubber through the wet process, both storage stability and the rubber modification significantly elevate the viscosity of the material, resulting in greater challenges during mixing and application [17].

Nguyen [18] indicated that rubber modified asphalt (RMA) produced through the dry process demonstrated comparable road performance to that of polymer-modified hot mix asphalt (HMA). Additionally, Moreno et al. [18] reported that dry process RMA enhances rutting resistance and anti-stripping properties when compared to HMA that does not contain rubber.

Many asphalt modifications have been proposed to enhance the characteristics of asphalt pavement to minimise cost and pollution [19]. The use of crumb rubber (CR) in the asphalt mixture is one of the many examples. The advantages of CR application included the enhancement of the overall performance of asphalt pavement, reduced life cycle cost of asphalt pavements, and the ability to obtain hardened asphalt mixtures at high service temperature [20].

Kim et al. studied the effect of using crumb rubber on asphalt mixture properties. The results indicated that the use of crumb rubber as a modifier seemed to improve the penetration resistance of the asphalt binder because of increasing viscosity at 60ºC. Additionally, its advantage was more apparent at lower loading frequencies, and the asphalt binder with higher crumb rubber contents was observed to have better resistance to permanent deformation at higher temperatures and greater elasticity at lower temperatures [21]. Xiao et al. concluded that increasing the rubber content improved the aging resistance of the binder and prolonged the fatigue life of the mixtures, while it caused a decrease in both the Indirect Tensile Strength (ITS) and the resilient modulus (Mr). Therefore, rubber was used to enhance the flexibility of HMA to improve cracking resistance, [22]. Xu et al. developed a novel method for preparing activated CR, and after comparing the performance of the activated CR asphalt mixtures with that of ordinary CR asphalt mixtures, they concluded that the activated CR mixtures were superior, [23]. Dias et al. illustrated the mechanical response of two gap-graded CR asphalt mixtures produced by the dry process, compared their performance with that of a mixture devoid of rubber granulate, and concluded that the rubber-blended mixtures performed better than their counterparts, [24].

Al-Khateeb and Ramadan investigated the effect of rubber additives on the following rheological properties of asphalt binders: Super pave rutting parameter, fatigue parameter, and storage modulus at various percentages. The authors found that the addition of rubber yielded increases in rutting resistance and fatigue resistance, [25]. Ge Xuanrui [26] showed that the fatigue life of the asphalt rubber mixture increased as the crumb rubber content increasing, but only to a certain point before it started to decrease again, meaning that there was an optimal crumb rubber content.

Hussein A.A. Gibreil and Cheng Pei Feng found that as the amounts of (HDPE) and (CRP) increased, the rutting-depth decreased. Conversely, the asphalt mixture dynamic stability improved with the incorporation of HDPE and CRP. Additionally, the permanent deformation resistance, or rutting resistance, was enhanced by the addition of these materials. The optimal concentrations of the additives were determined to be 5% for HDPE and 10% for CRP, based on bitumen weight. [27]. The main objective of this research is to use the waxy asphalt as compensation for the shortage of asphalt in Egypt, after modifying its properties by adding polymer (HDPE) and crumb rubber powder (CRP) together, because waxy asphalt may have a harmful effect on road construction, and to obtain the best method of adding polymer and CRP to the asphalt mixture while reducing initial costs.

2. Experimental program

The practical program consists of six stages. The main purpose of the first stage is to describe the material characteristics used in the

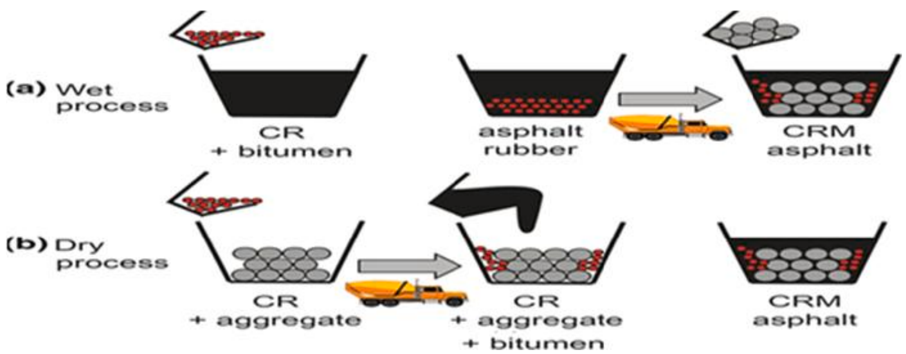

Fig. (1). The different methods are [28,29]. (a) Wet Process (b) Dry process.

research and to obtain the optimum bitumen content for control mix. The stages from two to four is to define the optimal HDPE and crumb rubber dosage at the different mixing methods (wet and dry process). Fifth stage discusses the results of two performance tests (Hamburg Wheel Tracking Test and Indirect Tensile Strength Test) depending upon the optimum results of the previous four stages. Finally, sixth stage for the inspection of Scanning Electron Microscopy. Figs. (1),(2) shows the experimental program of this research.

3. Materials

3.1. Asphalt

Alexandria Bitumen was used for this research; a variety of physical tests were conducted to characterize the bitumen properties, including the penetration test, softening point test, ductility test, Flash point test, and kinematic viscosity test. The tests were conducted at the General Authority for Roads, Bridges and Land Transport (GARBLT). Table (1) presents the engineering properties of Waxy Alex Bitumen according to specifications limits of the Egyptian code [30].

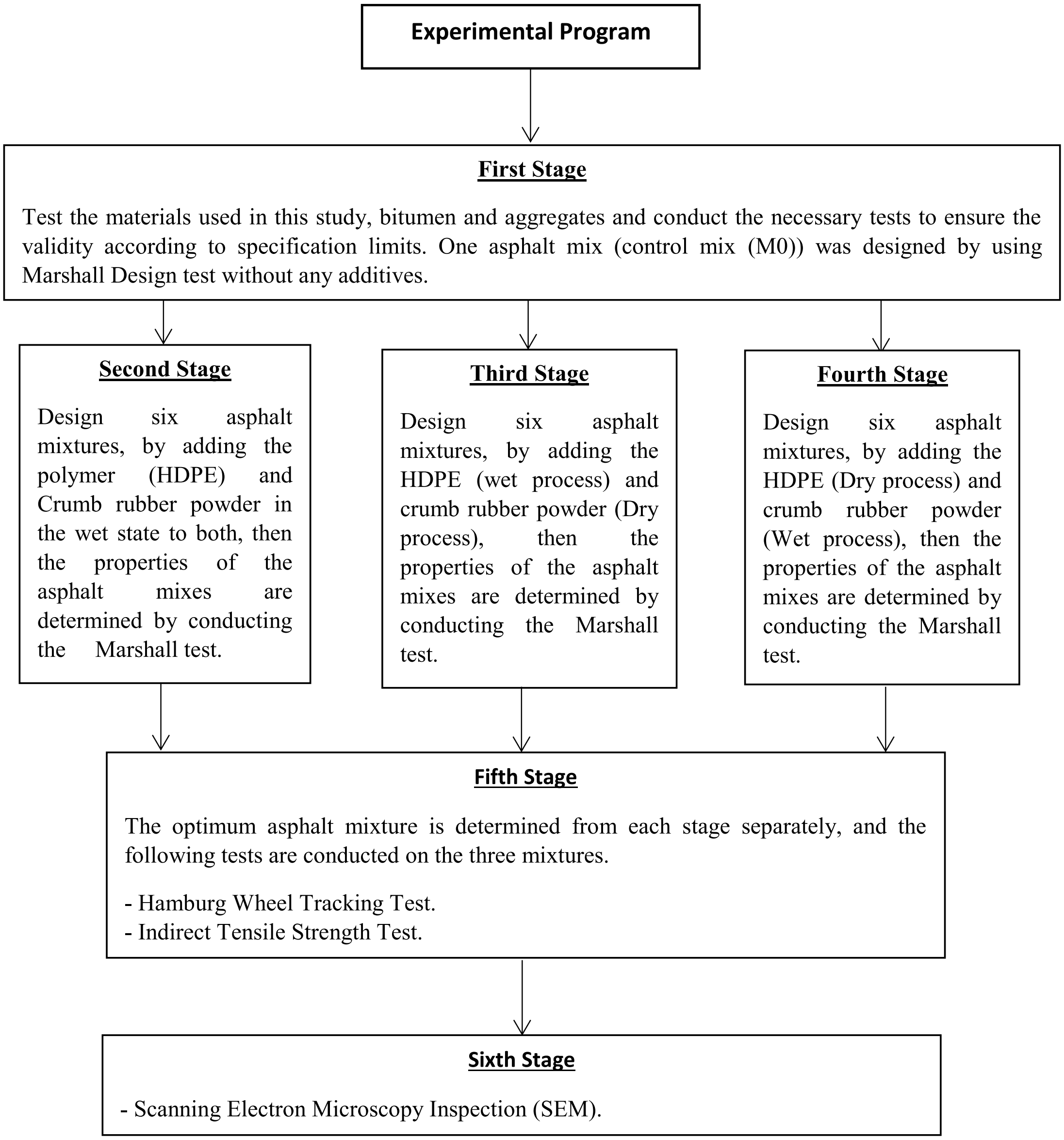

Fig. (2). The experimental program of the research study.

Table (1)
Properties of used bitumen.

Test No.	Test	AASHTO Designation No.	Results	Specification Limits
1	Penetration (0.1 mm)	T- 49	65	60–70
2	Softening point (°c)	T-53	48	45–55
3	Flash point (°c)	T-48	+ 270	+ 250
4	Kinematic viscosity (cSt)	T-201	435	+ 320
5	Ductility (cm)	T-51	+ 100	+ 90

3.2. *Aggregate*

3.2.1. *Coarse aggregate*

The coarse aggregate used in this study is crushed stone obtained from "ATTAKA" quarry, Suez Governorate, Egypt. Its bulk specific gravity is 2.52. Table (2) illustrates the characteristics of the coarse aggregates.

3.2.2. *Fine aggregate*

The fine aggregate of the investigated asphalt mixes was crushed sand obtained from "ATTAKA" quarry, Suez Governorate, Egypt. Its bulk specific gravity is 2.49 and its gradation is shown in Table (3).

3.2.3. *Mineral filler*

The mineral filler used for asphalt mixtures design is dust of limestone gradation with 2.75 bulk specific gravity. Table (4) illustrates the limestone dust gradation.

3.2.4. *Mix gradation*

One gradation is used in this study. This gradation meets the dense gradation (4 C) according to Egyptian specifications of surface course layer as shown in Table (5).

3.3. *Additives used*

3.3.1. *High density polyethylene (PE100)*

High density polyethylene was used for this study to improve asphalt mixture properties. The physical and mechanical properties of the HDPE sample used are recorded in Table (6), which shows the high-density polyethylene (PE100) properties. The HDPE was passed through sieve #4 and retained on sieve #8. Fig. (3) shows the specimen of HDPE.

3.3.2. *Crumb rubber powder*

Crumb rubber powder was used for this study to enhance asphalt mixture properties. Table (7) illustrates the crumb rubber powder characteristics. Fig. (4) Shows the crumb rubber powder specimen.

4. Marshall test design

The Marshall Test can calculate the bituminous mixture resistance to plastic flow by obtaining stability value (kg) and the flow value (mm) by using the Marshall mix design method which was conducted for the wearing surface mix as illustrated in Fig. (5). The test was performed on a cylindrical sample with a diameter of 4 in. and the sample height was 2.5 in. A total of 50 blows were made on each face of the specimens. Samples were immersed in the water bath at temperature 60°C for a period of 45 min before the test began. Samples were loaded using the Marshall device at a loading rate of 50.8 mm/minute until the failure occurred. Asphalt was used with different concentrations ranging from (4–6%) to prepare the HMA [31].

For the first stage, all Marshall samples were prepared according to the standard procedure. For stages 2, 3, and 4, both HDPE and CRP were added to the mixture in two cases wet process and dry process. In case of wet process both were added as a percentage by weight of asphalt. In case of dry process both were added as a percentage by weight of sand according to their size.

Table (2)
The coarse aggregate characteristics.

Test No.	Test		Designation No.	Results	Specification Limits
1	Los Angles Abrasion	After 100 revolutions	T-96	5%	≤ 10%
		After washing After 500 revolutions		25%	≤ 40%
2	Water absorption (%)		T-85	2.1%	≤ 5%
3	Specific gravity	Bulk	T-85	2.516	-
		Saturated		2.59	-
		Apparent		2.676	-
4	Clay lumps and friable particles in aggregates		T-112	0.25	≤ 1%

Table (3)
Fine aggregate gradation.

Sieve size		Design gradation
Inches	mm	
1	25	100
3/4	19	100
1/2	12.5	100
3/8	9.5	100
No. 4	4.75	100
No. 8	2.36	80
No. 16	1.18	57
No. 30	0.6	38
No. 50	0.3	22
No. 100	0.15	11.8
No. 200	0.075	5.2

Table (4)
The gradation of the dust of limestone.

Sieve size		Design gradation	Specification limits
mm	Inch		
0.60	No.30	100	100
0.30	No.50	100	–
0.15	No.100	91	85% (min)
0.075	No.200	80	65% (min)

In the second stage, first, the asphalt was heated to 163 °C, then HDPE was added to it at a speed rate of 5000 rpm for a period of one hour at 180 °C. Next, the CRP was added to the binder at the same speed for another one hour. The aggregate was heated for one hour at 150 °C. Then the modified binder was added to the hot aggregates and mixed manually for about two minutes, the modified asphalt concrete mixture was heated at 150 °C for about one hour and half. In the third stage, the asphalt was heated to 163 °C, then HDPE was added to it at a speed rate of 5000 rpm for a period of two hours at 180 °C. The CRP was added to the aggregate and the mix was heated for one hour at 150 °C. Then, the modified binder was added to the hot mix of aggregates and CRP and mixed manually for about two minutes. The modified asphalt concrete mixture was heated at 150 °C for about one hour and half. Then the modified binder was added to the mix of CRP and hot aggregates.

In the Fourth stage, the asphalt was heated to 163 °C, then CRP was added to it at a speed rate of 5000 rpm for a period of one hour at 180 °C. The HDPE was added to the aggregate and the mix was heated for one hour at 150 °C, Then the modified binder was added to

Table (5)
Aggregate gradation job mix.

Sieve No.	Coarse Aggregate, Pin2		Coarse Aggregate, Pin1		Sand		Mineral Filler		Combined Aggregate Gradation	Specification Limits (4 C)
Sieve No.	Gradation	20%	Gradation	31%	Gradation	45	Gradation	4%		
"1	100	20	100	31	100	45	100	4	100	100–100
3/4"	94	18.8	100	31	100	45	100	4	98.8	80–100
1/2"	60	12	81	25.1	100	45	100	4	86.1	
3/8"	44	8.8	70	21.7	100	45	100	4	79.5	60–80
#4	11	2.2	3	0.9	100	45	100	4	52.1	48–65
#8	0	0	1.4	0.4	80	36	100	4	40.4	35–50
#16	0	0	1.1	0.3	57	25.7	100	4	30	
#30	0	0	0.9	0.3	38	17.1	100	4	21.4	19–30
#50	0	0	0.8	0.2	22	9.9	100	4	14.1	13–23
#100	0	0	0.7	0.2	11.8	5.3	91	3.6	9.2	7–15
#200	0	0	0.6	0.2	5.2	2.3	80	3.2	5.7	3–8

Table (6)
Physical and mechanical properties of HDPE (PE100).

Property	**Value**
Density (g/cm3)	0.97
Tensile Strength (MPa)	27
Flexural Modulus (MPa)	1372
Elongation at Break (%)	560

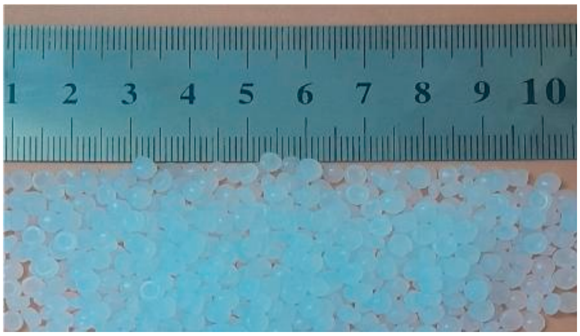

Fig. (3). High density polyethylene specimen.

Table (7)
The gradation of CRP sample used in this study.

Sieve No	8	30	50	200
Sieve (mm)	2.36	0.6	0.3	0.075
Passing (%)	100	90	4	0.4

the hot mix of aggregates and HDPE and mixed manually for about two minutes, the modified asphalt concrete mixture was heated at 150 °C for about one hour and half.

Table (8) presents the mixing ratios of HDPE and CRP for asphalt mixtures for the second, third, and fourth stages. The optimum asphalt mixture was selected from each stage based on its mechanical properties. Fig. (6) illustrates the samples of control mix (M0). It was found that the optimum bitumen content for control mix, comparison mix1, comparison mix2 and comparison mix3 was 5.19%, 4.95%, 4.77% and 4.77% respectively.

5. Performance tests

5.1. Indirect tensile strength test

The indirect tensile strength test was conducted on the investigated mixes. The main purpose of performing this test is to evaluate

Fig. (4). The crumb rubber powder specimen.

Fig. (5). The Marshall Device Test.

Table (8)
The mixing ratios of HDPE and CRP for asphalt mixtures for each stage.

Stage	Mix No	No of samples	State		Function	Crumb Rubber powder ratio added	High-density polyethylene (PE100) added
			HDPE	CRP			
1st	**Mix 0**	Twelve samples were conducted for each asphalt mix	**-**	**-**	**Control mix**	**0%**	**%0**
	Mix 1		Wet	Wet		5%	2%
	Mix 2		Wet	Wet		5%	4%
	Mix 3		Wet	Wet		5%	6%
2nd	Mix 4		Wet	Wet		10%	2%
	Mix 5		Wet	Wet		%10	%4
	Mix 6		**Wet**	**Wet**	**Comparison mix 1**	**%10**	**%6**
3rd	Mix 7		Wet	Dry		1%	2%
	Mix 8		**Wet**	**Dry**	**Comparison mix 2**	**1%**	**4%**
	Mix 9		Wet	Dry		1%	6%
	Mix 10		Wet	Dry		2%	2%
	Mix 11		Wet	Dry		2%	%4
	Mix 12		Wet	Dry		2%	%6
4th	Mix 13		Dry	Wet		5%	4%
	Mix 14		Dry	Wet		5%	5%
	Mix 15		Dry	Wet		5%	6%
	Mix 16		Dry	Wet		10%	4%
	Mix 17		**Dry**	**Wet**	**Comparison mix 3**	**%10**	**%5**
	Mix 18		Dry	Wet		%10	%6

Fig. (6). The samples of control mix (M0).

the cracking resistance and possible effects of water infiltration in the asphalt concrete mixtures; the indirect tensile strength (ITS) test was conducted according to AASHTO T-283 to measure the dry and wet strength and to estimate the tensile strength ratio (TSR %) [32].The samples were divided into two sets. For the first set, the samples were tested in a dry state at a temperature of 25 ºC with a loading rate of 50.8 mm/minute until the occurrence of failure, with recording the failure load. For the second set, the samples were then placed in the freezer at a temperature of -18 ºC for 16 h. After unwrapping the plastic bags, the samples were removed from the freezer and immediately placed in a 60 ºC water bath for 24 h. After this step, the samples were placed in a 25 ºC water bath for 2 h, the same as that used for AASHTO dry set, then they were ready to be tested.

$$ITS\ value = \frac{2P}{3.14HD}$$

Where:

P Represent the vertical load magnitude by (KN)
H Height of asphalt mixture specimen (mm)
D Diameter of asphalt mixture specimen (101.6 mm)

Table (9)
Marshal properties for the asphalt mixtures of the second stage.

Mix No	O.B.C	HDPE Ratio	CRP Ratio	Unit weight	Stability Kg	Flow mm	A.V %	VMA %
Requirement according to Egyptian code				-	Min. 900	2–4	3–5	> 14
M 0	5.19%	0	0	2.318	900	3.58	3.4%	14.45%
M 1	5.12%	2%	5%	2.315	910	3.5	3.6%	14.53%
M 2	4.90%	4%	5%	2.309	980	3.4	4.1%	14.6%
M 3	4.80%	6%	5%	2.304	1120	2.9	4.4%	14.7%
M 4	5.02%	2%	10%	2.314	1060	3.2	3.6%	14.5%
M 5	5.00%	%4	%10	2.308	1154	2.9	%4	%14.7
M 6	%4.95	%6	%10	2.303	1240	2.75	%4.2	%14.85

5.2. The hamburg wheel tracking test

This test method describes a procedure for testing the rutting and moisture-susceptibility of hot mix asphalt (HMA) pavement samples in the Hamburg Wheel-Tracking Device; the method also describes the testing of submerged, compacted HMA in a reciprocating rolling-wheel device. This test provides information about the rate of permanent deformation from a moving, concentrated load. A laboratory compactor has been designed to prepare slab specimens. In addition, the Superpave Gyratory Compactor (SGC) has been designed to compact specimens in the laboratory. Rut depth is expressed as a function of the number of wheel passes (AASHTO T324–14) [33].

6. Scanning electron microscope (SEM)

The Scanning Electron Microscopy test (SEM) was conducted to examine the microstructure and the dispersion of the HDPE and CRP additives in the binder. The asphalt sample was prepared by cutting it with dimensions of 20 × 20 x 10 mm. To increase the hardness of the sample surface, without affecting its morphology, the procedure described in [34,35] was followed.

7. Results and discussion

7.1. Marshal test design

7.1.1. Effect of HDPE and CRP content at wet process on marshal properties for asphalt mixtures

The results in Table (9) illustrate that the Marshall Mix stability for the first asphalt mixture **(M1)** is approximately the same as that the control mix **(M0)**. The stability of the following two mixes **(M2 and M3)** increased as the high-density polyethylene ratio was increased at constant ratio of crumb rubber powder equal to 5%, achieving a high value of 1120 kg at 6% HDPE **(M3)**, representing a 24.44% increase compared with the control mix **(M0)**. For the three subsequent mixes **(M4, M5, and M6)**, in which the HDPE ratio was increased from 2% to 6% at constant CRP ratio of 10%, the mix stability increased reaching the highest value 1240 kg at 6% HDPE and 10% CRP **(M6)**, representing a 37.77% increase compared with the control mix **(M0)**.

The inclusion of crumb rubber particles (CRP) enhances elasticity due to their ability to create interconnections. Additionally, high-density polyethylene (HDPE) may establish a partial network within the asphalt, resulting in reduced stiffness. Therefore, the combination of HDPE and CRP contributes to increased ductility of the asphalt [36].

According to these results, it can be concluded that adding high-density polyethylene at a percentage of 6% and crumb rubber powder at a ratio of 10%, both by bitumen weight in the wet state, had a pronounced effect on the mix stability.

The flow value of the mixes is presented in Table (9). The value of flow was 2.75 mm, corresponding to the highest value of stability at 6% HDPE and 10% CRP **(M6)**. This value represents a decrease in flow of 23.18% compared with the control mix **(M0)**. Figs. (7, 8 and 9) illustrate the change in marshal properties of each mixture.

7.1.2. Effect of HDPE (wet process) and CRP (dry process) content on marshal properties for asphalt mixtures

The results in Table (10) show that the Marshall mix stability for the first two mixes (M7 and M8) increased as the percentage of HDPE increased at a constant ratio of CRP equal to 1%, achieving the highest value of 1440 kg at 4% HDPE **(M8)**, representing a 60% increase compared with the control mix **(M0)**. For the following mix **(M9)**, in which the percentage of HDPE was increased, the mix stability decreased but remained higher than that of the control mix **(M0)**. For the three subsequent mixes **(M10, M11 and M12)**, the mix stability increased, achieving a high value for mix **(M10)** equal to 1400 kg at 2% HDPE and 2% CRP. After that the stability value decreased to achieve a value of approximately 1200 kg for mixes (**M11 and M12)**.

High-density polyethylene (HDPE) enhances bitumen via the wet process by creating a, reinforcing, and viscous binder-polymer network, increasing Marshall Stability. It improves binder adhesion to aggregates [37]. In the dry process, crumb rubber powder (CRP) functions as a flexible aggregate that absorbs lighter components from the bitumen, leading to swelling of the particles and the formation of a "mastic" that improves rutting resistance and fatigue life. This interaction is not as uniform as in the wet process, as bonding occurs primarily through physical adsorption rather than extensive chemical reactions. It typically necessitates the optimization of mixing temperatures (between 155°C and 180°C) to regulate swelling effectively [38].

According to these results, it can be concluded that adding high-density polyethylene at a percentage of 4% by bitumen weight (wet

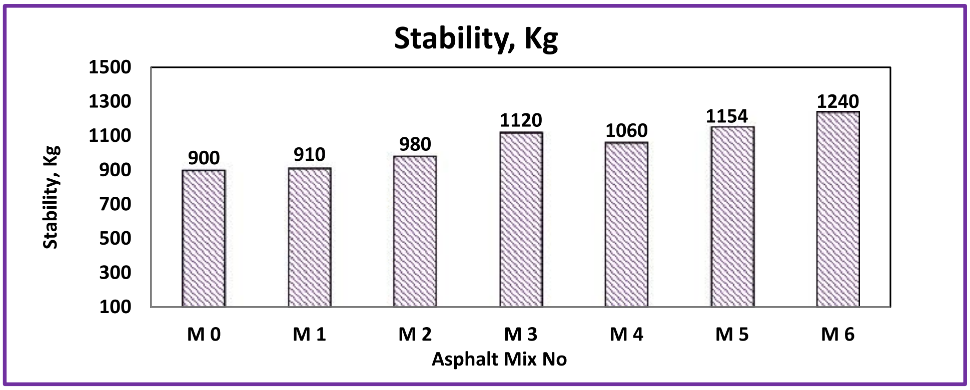

Fig. (7). Stability value for second stage.

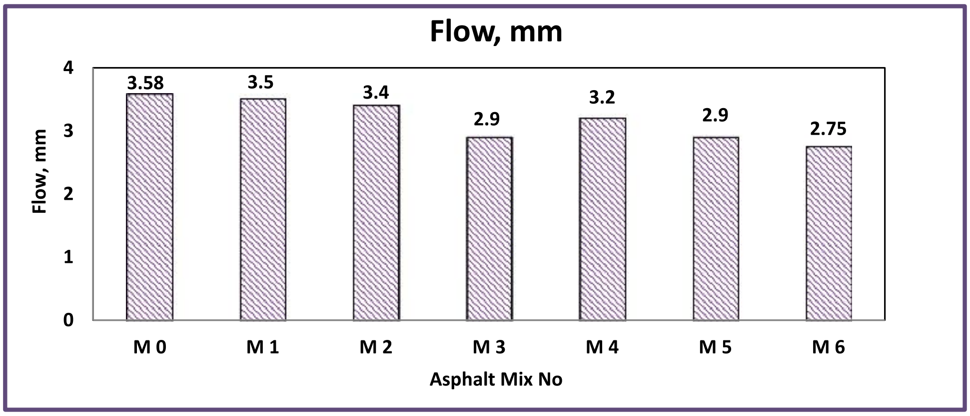

Fig. (8). Flow value for second stage.

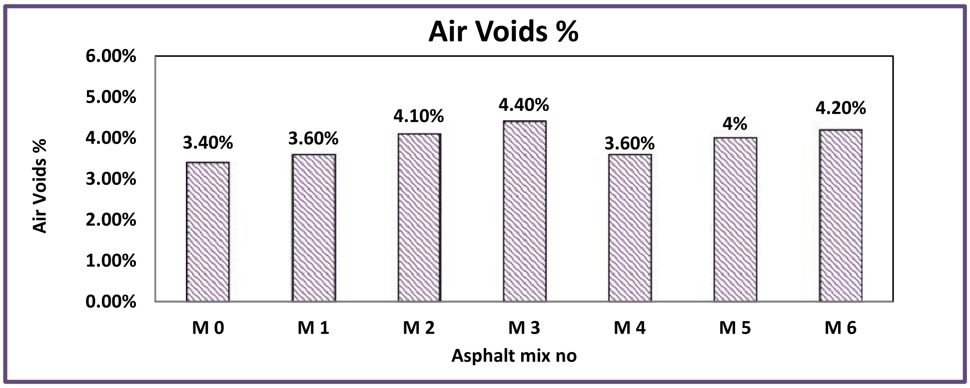

Fig. (9). Air voids % for second stage.

state) and crumb rubber powder at a ratio of 1% by fine aggregate weight (dry state) had the best effect on mix stability. The flow value of the mixes investigated is presented in Table (10). The value of flow was 2.8 mm, corresponding to the highest value of stability at 4% HDPE and 1% CRP **(M8)**. This value represents a decrease in flow of 21.78% compared with the control mix **(M0)**. Figs. (10, 11, and 12) illustrate the change in properties of each mixture.

7.1.3. Effect of HDPE at (dry process) and CRP content at (wet process) on marshal properties for asphalt mixtures

The results in Table (11) illustrate that the Marshall mix stability for the first three mixes **(M13, M14, and M15)** decreased as HDPE was increased at constant ratio of CRP equal to 5%, achieving a low value of 920 kg at a ratio of 6% HDPE **(M15)**, but remained

Table (10)
Marshal properties for the asphalt mixtures of the third stage.

Mix No	O.B.C	HDPE Ratio	CRP Ratio	Unit weight	Stability Kg	Flow mm	A.V %	VMA %
Requirement according to Egyptian code				-	**Min. 900**	2–4	3–5	> 14
M 0	5.19%	0	0	2.318	900	3.58	3.4%	14.45%
M 7	4.84%	2%	1%	2.325	1408	3.28	3.5%	%13.9
M 8	4.77%	4%	1%	2.318	1440	2.8	3.95%	%14.15
M 9	4.76%	6%	1%	2.309	1280	2.3	%4.3	%14.4
M10	4.82%	2%	2%	2.324	1400	2.8	%3.45	%14
M11	%4.74	%4	%2	2.316	1200	2.48	%3.8	%14.2
M12	%4.75	%6	%2	2.308	1190	2.2	%4.2	%14.5

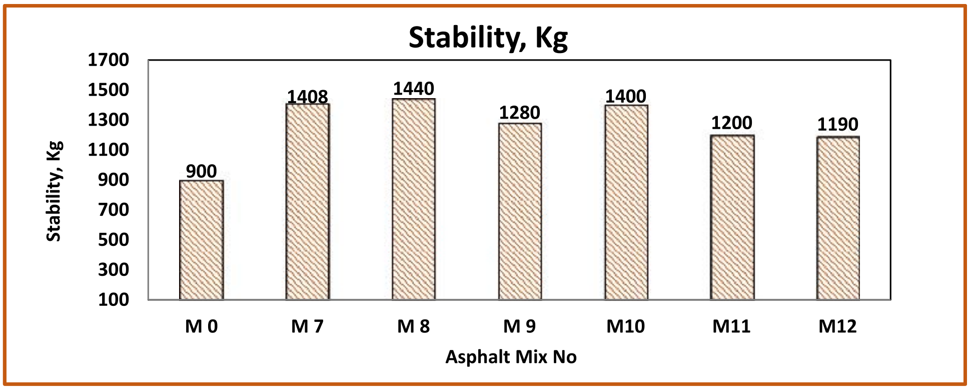

Fig. (10). Stability value for third stage.

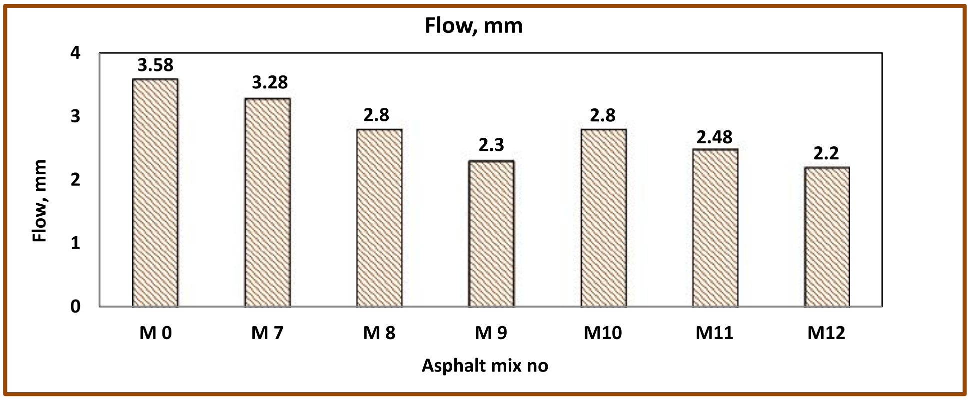

Fig. (11). Flow value for third stage.

approximately the same as that for the control mix (M0). For the following two mixes **(M16 and M17)**, in which the ratio of HDPE and CRP was increased, the Marshall mix stability increased, achieving the highest value of 1360 kg at 5% HDPE **(M17)** and 10% CRP content, representing a 51.11% increase compared with the control mix **(M0)**. For the final mixture **(M18)**, in which the percentage of HDPE was increased to 6%, the mix stability decreased but remained higher than that of the control mix (M0).

In the wet process, crumb rubber (CR) functions as a physical modifier by absorbing lighter components from the bitumen, which causes it to swell. This swelling results in an increase in the viscosity and stiffness of the binder, leading to marked improvements in Marshall Stability and a decrease in temperature susceptibility [39]. High-Density Polyethylene (HDPE) enhances bitumen through the dry process by coating aggregates and mixing with the binder at elevated temperatures. This process can improve asphalt stiffness and stability. HDPE serves as a filler, enhancing the adhesion between the binder and aggregates [40].

According to these results, it can be concluded that adding HDPE (dry process) at a percentage of 5% and crumb rubber powder at a

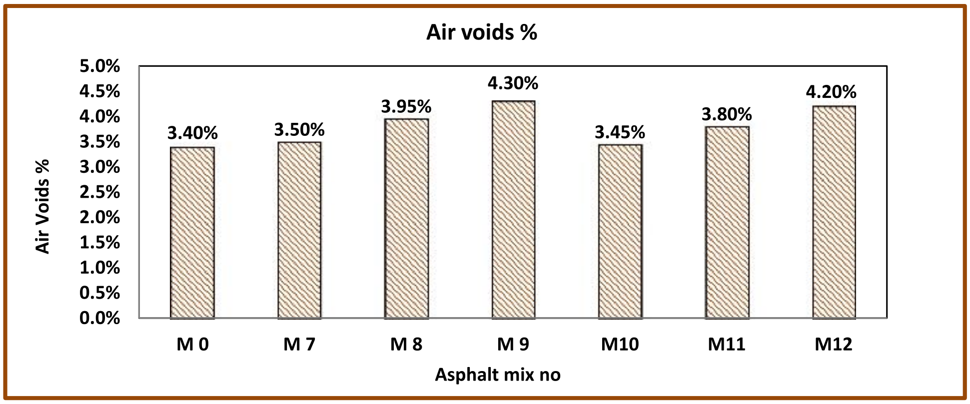

Fig. (12). Air voids % for third stage.

Table (11)
Marshal properties for the asphalt mixtures of the fourth stage.

Mix No	O.B.C	HDPE Ratio	CRP Ratio	Unit weight	Stability Kg	Flow mm	A.V %	VMA %
Requirement according to Egyptian code				-	**Min. 900**	**2–4**	**3–5**	> 14
M 0	5.19%	0	0	2.318	900	3.58	3.4%	14.45%
M 13	4.83%	4%	5%	2.313	1220	3.4	4%	%14.3
M 14	4.78%	5%	5%	2.31	1190	3.12	4.4%	%14.5
M 15	4.75%	6%	5%	2.308	920	3	%4.4	%14.55
M 16	4.80%	4%	10%	2.312	1240	3.24	%4.1	%14.5
M 17	%4.77	%5	%10	2.308	1360	3	%4.2	%14.6
M 18	4.80%	%6	%10	2.305	1200	2.84	%4.3	%14.65

ratio of 10% by bitumen weight in the wet state had the best effect on mix stability. The flow value of the investigated mixes is presented in Table (11). The value of flow was (3 mm), corresponding to the highest value of stability at 5% HDPE and 10% CRP **(M17)**. This value represents a decrease in flow of 16.2% compared with the control mix **(M0)**. Figs. (13, 14, and 15) illustrate the change in properties of each mixture.

7.1.4. Comparison of the mixtures' marshal properties

In this section, the properties of the three main mixtures, including stability, flow, percentage of air voids, and unit weight, were compared to get a partial evaluation of hot mix asphalt mixtures improved by high-density polyethylene and crumb rubber powder additives at different stages. The results in Table (12) show that the Marshall properties for the control mix (M0) and comparison mix1 (M6), comparison mix2 (M8), and comparison mix3 (M17).

The optimum binder content for M0 is higher than that of the other mixes and decreased by 4.6%, 8.1% and 8.1% for comparison mix1 (M6), comparison mix2 (M8) and comparison mix3 (M17) respectively compared with control mix M0. The stability of M8 is higher than that of M17, M6, and M0 by 5.6%, 13.9% and 37.5% respectively. The flow value of M0 is higher than that of the other mixes and decreased by 28.6%, 27.3% and 22.1% for M6, M8 and M17 respectively compared with control mix M0. The air voids percentage of M0 is lower than the others, The Air voids percentage increased by 23.5%, 16.2% and 23.5% for M6, M8 and M17

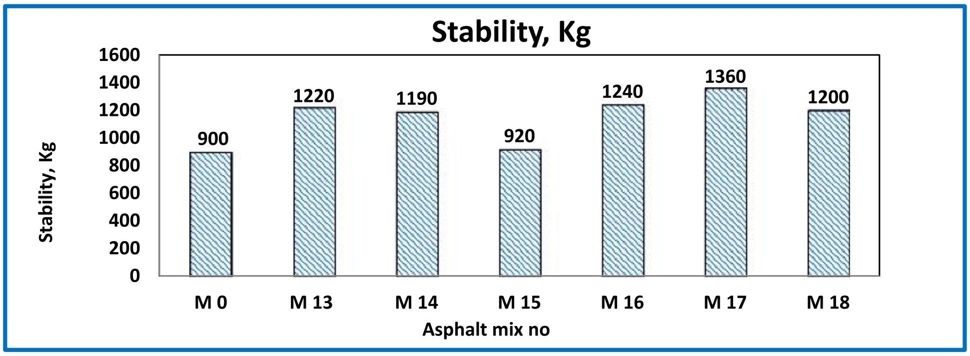

Fig. (13). Stability value for fourth stage.

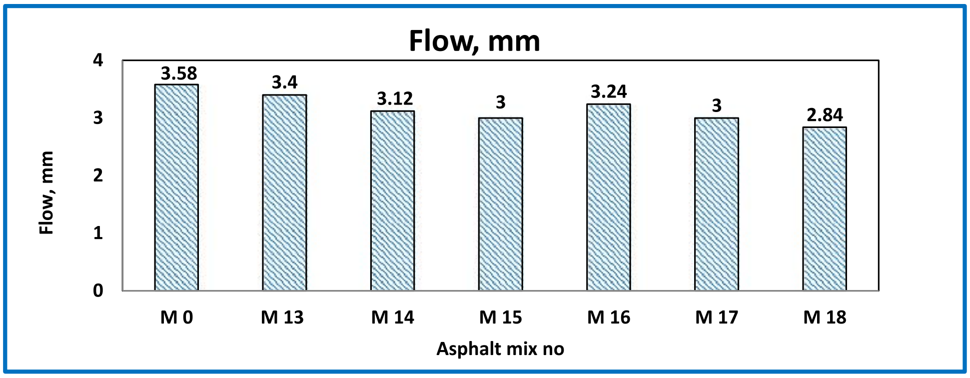

Fig. (14). Flow value for fourth stage.

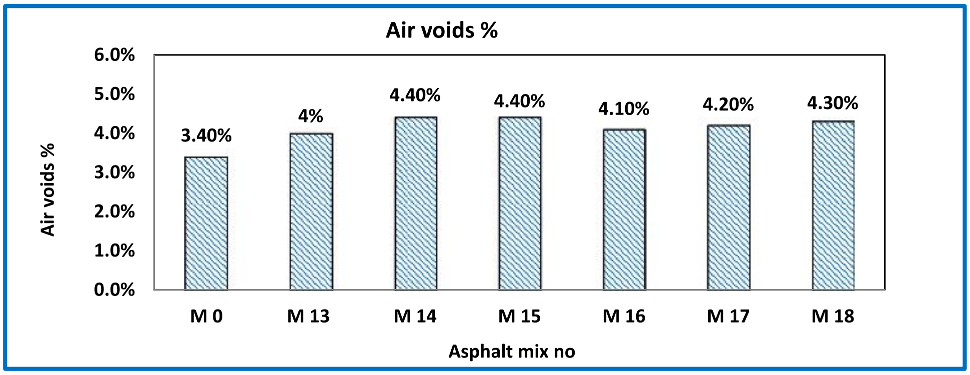

Fig. (15). Air voids % for fourth stage.

respectively compared with control mix M0. The unit weight values and VMA percentage are approximately the same for all mixes.

The control mix showed a lower stability value due to the use of Alexandria waxy asphalt and the presence of wax in the bitumen, which negatively impacted the stability value. The comparison mixes improved the stability values and reduced the flow value and

Table (12)
The marshal properties of control mix and comp. mixes.

Mix No	HDPE Ratio	CRP Ratio	O.B.C %	Stability Kg	Flow mm	A.V %	Unit weight	VMA %
Control mix (M 0)	0%	0%	5.19	900	3.58	3.4%	2.318	14.45%
Comp mix 1 (M 6)	6% (Wet)	10% (Wet)	4.95	1240	2.75	%4.2	2.303	%14.85
Comp mix 2 (M 8)	4% (Wet)	1% (Dry)	4.77	1440	2.8	3.95%	2.318	%14.15
Comp mix 3 (M17)	%5 (Dry)	%10 (Wet)	4.77	1360	3	%4.2	2.308	%14.60

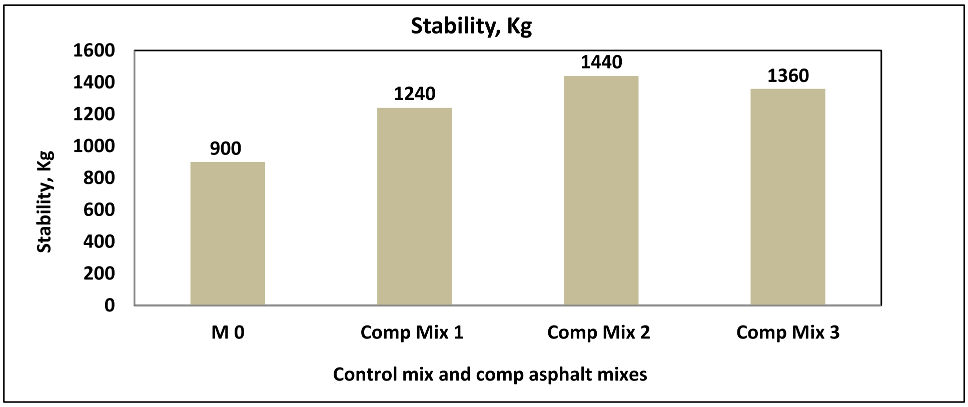

Fig. (16). Comparison of stability value between control Mix and comparison. Mixes.

increased the air voids ratios, bringing them closer to the mid- range. However, the most distinctive among them in terms of stability value was comparison mix 2, which confirms that the best mixing method is the third stage, followed by the fourth-stage comparison mix3, and finally the second-stage comparison mix1. This confirms that the combination of the wet and dry processes is better than the wet process only. Figs. (16, 17 and 18) illustrate the change in properties of control Mix and comparison mixes.

7.2. Moisture sensitivity tests

The variations in the ITS and TSR values with the addition of HDPE and CRP in different concentrations are shown in Table (13) and Figs. (19) and (20). The ITS of the unmodified mixture (control mix) was lower than those of the mixtures modified with HDPE and CRP for the three different stages. The test results also illustrated that the TSR ratios of the control mix, comparison mix1, comparison mix2, and comparison mix3 were 81.24%, 82.67%, 85.79% and 84.89% respectively. The ITS and TSR values increased with the addition of the modifiers at each testing temperature. For all comparison mixes, the indirect tensile strength (ITS) value improved under both dry and wet conditions. However, the highest ITS value was achieved by comparison Mix 2, with a TSR of 85.79%, followed by comparison Mix 3 (84.89%), and finally Comparison Mix 1 (82.67%). This confirms that the best mixing method was the third stage (Comparison Mix 2), followed by the fourth stage (Comparison Mix 3), and then the second stage (Comparison Mix 1). This is due to an increase in the degree of adhesion between the modified binder with HDPE and mixing CRP with aggregates. Thus, it can be said that the addition of HDPE and CRP increases the moisture resistance and tensile strength of HMA mixtures.

7.3. The hamburg wheel tracking test

The rut depth results, presented in Figs. (21) and (22), show the comparison of mixtures results. After 12000 cycles, the control mix M0 had the highest value of rut depth (1.71 mm). For comparison mix.1 (M6), the rut depth decreased achieved a value of (1.28 mm). This value represents a decrease in rut depth of 25.14% compared with the control mix. For comparison mix.2 (M8), the rut depth decreased, achieving a value of (1.02 mm). This value represents a decrease in rut depth by 40.35% compared with the control mix.

For comparison mix.3 (M17), the rut depth decreased, achieving the lowest value (0.95 mm). This value represents a decrease in rut depth of 44.44% compared with the control mix. Approximately, there is no significant difference in the results between M8 and M17. These mixtures were modified by HDPE and CRP, where one additive was applied using the wet process and other using the dry process, and vice versa. This confirms that the combination of the wet and dry processes leads to better results than using the wet process only. The high resistance to rutting indicated an increase in the ability of the asphalt mixture to resist accumulated deformations under traffic loads. Based on the previous discussion, the test results revealed that HDPE and CRP modified asphalt mixtures displayed superior resistance to rutting. This indicates that polymer-crump rubber-modified mixtures are suitable for road construction applications requiring stiff, low bitumen content pavements with improving deformation resistance.

7.4. Scanning electron microscope (SEM)

From the SEM Test, images of the control asphalt mixture (M0), as shown in Fig. (23); comparison mix 1 (at 6% HDPE and 10% CRP), as illustrated in Fig. (24); comparison mix 2 (at 4% HDPE in the wet state and 1% CRP in the dry state), as shown in Fig. (25); and comparison mix 3 (at 5% HDPE in the dry state and 10% CRP in the wet state) are presented in Fig. (26). It can be observed from the figures that HDPE and CRP were well dispersed in the binder, with no polymer cluster formation.

8. Economic study

The unit price of all materials used in this research is shown in Table (14) for July 2025, according to Egyptian market prices. In

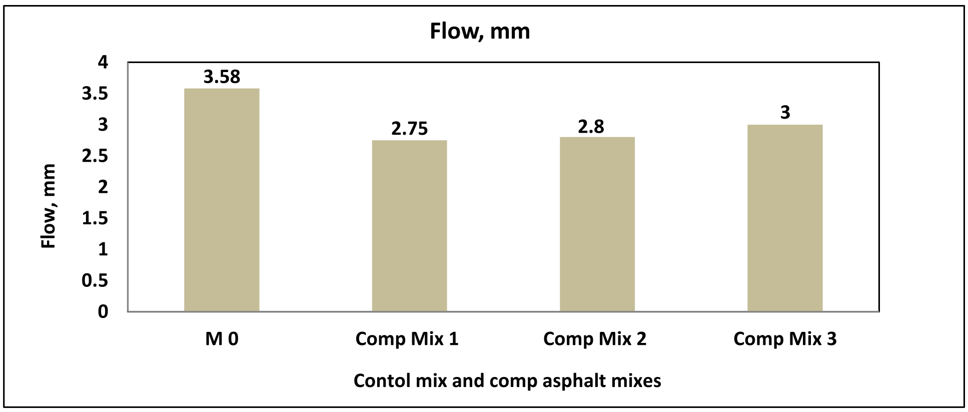

Fig. (17). Comparison of flow value between control Mix and comparison mixes.

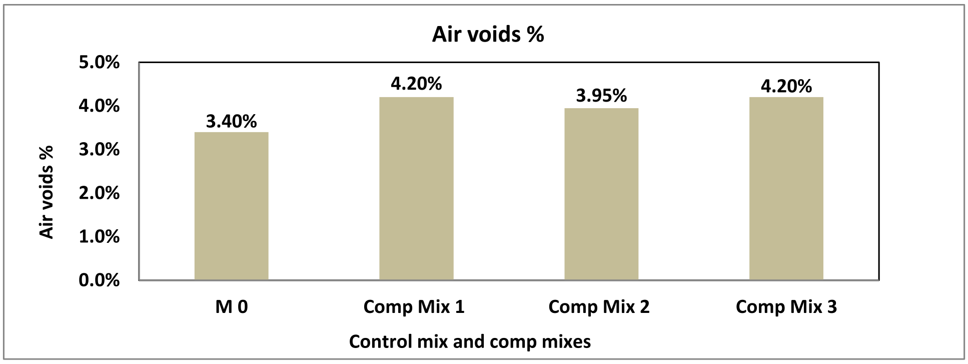

Fig. (18). Comparison of Air voids percent between control Mix and comparison mixes.

Table (13)
ITS value of the four main mixtures at dry and wet state.

Mixtures	Control Mix M0	Comparison.Mix.1 M6	Comparison.Mix.2 M8	Comparison.Mix.3 M17
ITS value at wet process	1022	1045	1292	1214
ITS value at dry process	1258	1264	1506	1430
TSR %	81.24%	82.67%	85.79%	84.89%

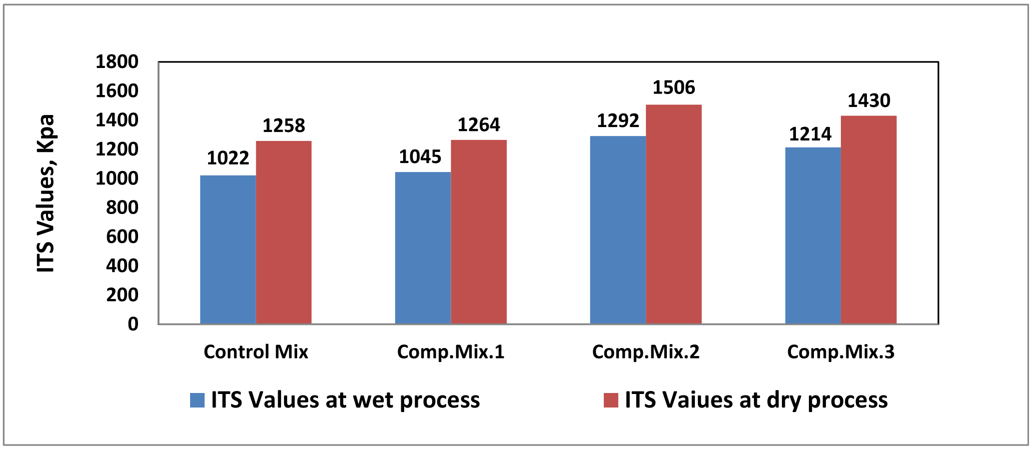

Fig. (19). Change in ITS value for control Mix and comparison mixes at different processes.

addition, the cost per ton for all mixes M0, comparison mix1 (M6), comparison mix2 (M8), and comparison mix3 (M17) is shown in Table (15). The cost for a 5 cm layer for mixes M0, comparison mix1, comparison mix2, and comparison mix3 is shown in Table (16) and Fig. (27). According to Table (16) and Fig. (27), the economic analysis for all mixes shows that the prices of mixes comparison mix1 (M6), comparison mix2 (M8), and comparison mix3 (M17) increased by 2.84%, 4.15%, and 108.24%, respectively, with respect to mix M0. As previously discussed, the best performance was obtained from comparison mix2 (M8), followed by comparison mix 3 (M17). According to the performance characteristics and economic analysis, comparison mix2 (M8) is considered the best alternative in this research.

9. Statistical analysis of the results

Table (17) shows the overall results for all mixes obtained from Marshall Test. Average, Standard Deviation (STDEV.S), and Coefficient of Variation (STDEV.S/Average) are included at the bottom of the table. The Average and Standard Deviation (STDEV.S) indicates the overall consistency of the laboratory program. The Coefficient of Variation (STDEV.S/Average) helps to identify which properties are most unstable.

The average value for Optimum Bitumen Content is 4.86%. The average value for Stability is 1179.58 kg; this metric shows the highest variability (STDEV of 166.29), this is because adding the modifiers to the mix contributes increasing stability from 900 kg at

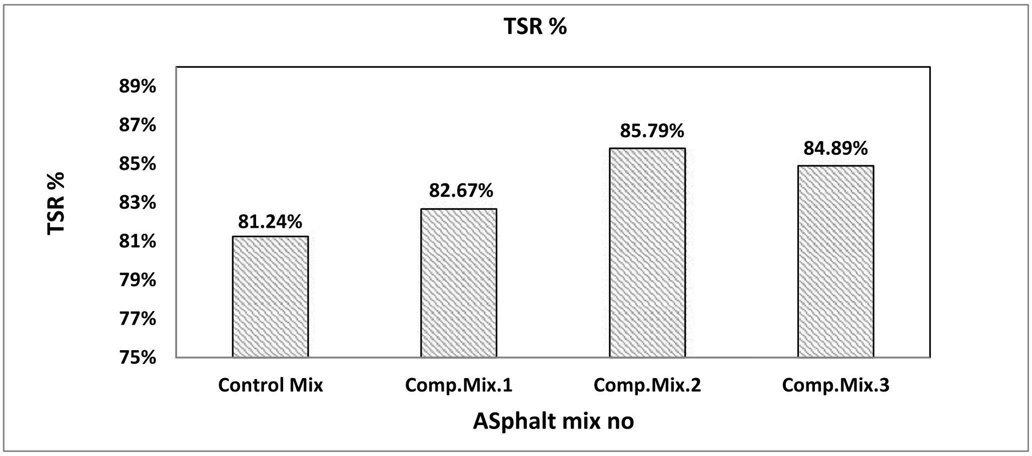

Fig. (20). Change in TSR % for control Mix and comparison mixes.

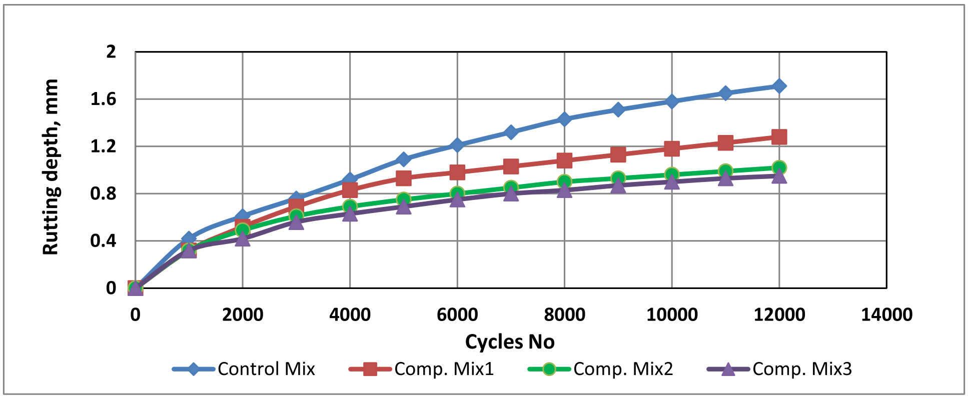

Fig. (21). Change in rutting depth for control Mix and comparison mixes and cycles no.

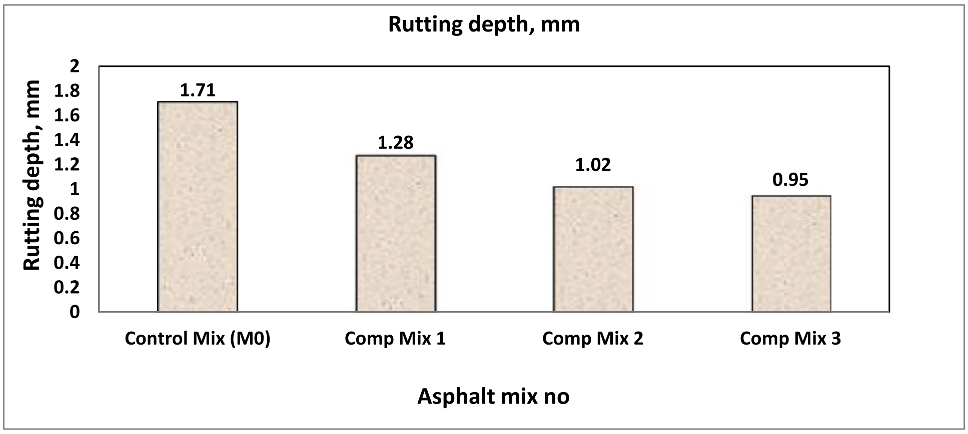

Fig. (22). Change in rutting depth for control Mix and comparison mixes.

M0–1440 kg at M8.

The average value for Flow is 2.98 mm. Most values stay within a tight range of 2.2–3.5 mm. Higher flow values M0 at 3.58 mm, often correlate with lower stability and higher bitumen content (5.19%). The average value for AV is 3.99%, this is right at the typical industry target of 4.0%.

The average value for VMA is 14.45%, this value is very consistent, ranging from 13.9% to 14.85%, ensuring enough space for the

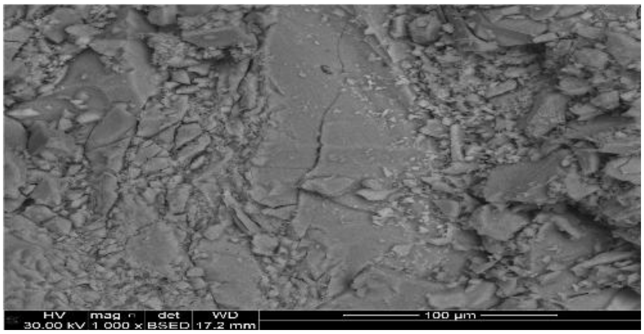

Fig. (23). SEM fracture micrographs of control mix (M0).

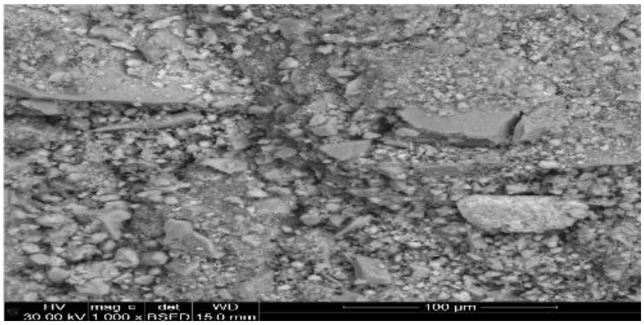

Fig. (24). SEM fracture micrographs of comparison mix1.

binder and air voids.

Unit Weight is the most consistent property (0.26% variation). Optimum Bitumen Content is a stable metric with a very low coefficient of variation (2.7%), whereas Stability (14.1% variation) and Flow (12.9% variation) are the most sensitive variables in this

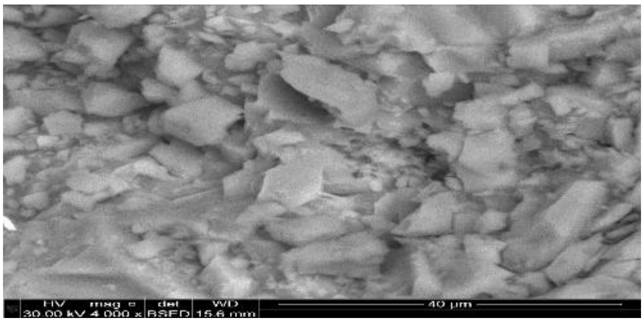

Fig. (25). SEM fracture micrographs of comparison mix2.

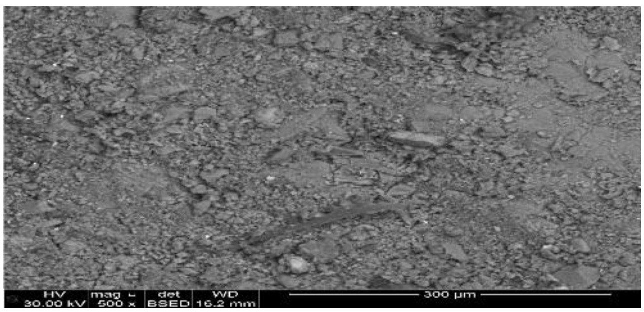

Fig. (26). SEM fracture micrographs of comparison mix3.

Table (14)
Unit price of materials in Egypt.

Material	Cost (LE)
Coarse aggregate (m^3)	390
Fine aggregate (m^3)	155
Fillers (m^3)	280
Bitumen (ton)	21500
HDPE (ton)	65000
CRP (ton)	12000

Table (15)
Cost for one ton for mixes M0, M6, M8, and M17.

	Control mix (M0)		Comparison mix1 (M6)		Comparison mix2 (M8)		Comparison mix (M17)	
	Weight, Kg	Price, LE	Weight, Kg	Price, LE	Weight, Kg	Price, LE	Weight, Kg	Price, LE
Coarse Aggregate	484.9	75.04	485.9	75.20	486.8	75.34	486.8	75.34
Fine Aggregate	427.8	26.63	428.8	26.69	425.2	26.47	408	25.40
Mineral Fillers	38	3.87	38.1	3.88	38.2	3.89	38.2	3.89
Bitumen	49.3	1059.95	39.7	853.55	43.7	939.55	41	881.50
HDPE	0	0.00	2.8	182.00	1.8	117.00	21.5	1397.50
CRP	0	0.00	4.7	56.40	4.3	51.60	4.5	54.00
Total	1000.00	1165.5	1000.00	1197.7	1000.0	1213.8	1000.0	2437.6

Table (16)
Cost for 5 cm layer for mixes M0, M6, M8, and M17.

	Control mix (M0)	Comparison mix1 (M6)	Comparison mix2 (M8)	Comparison mix3 (M17)
Density (ton/m^3)	2.318	2.303	2.318	2.308
Cost for 1.0 m^3 (LE)	2701.61	2758.35	2813.69	5626.04
Cost for 5 cm layer (LE)	135.08	137.92	140.68	281.30

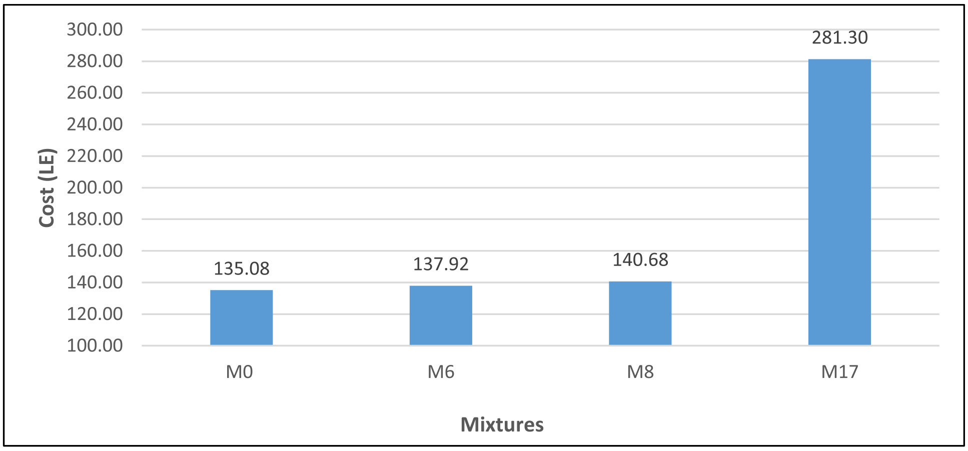

Fig. (27). Cost comparison of 5 cm layer for different Mixes.

study. This indicates that while the unit weight of the mixes is uniform, their structural performance varies significantly based on the changes in the mix composition.

10. Conclusions

Based on the results of this study, the following conclusions can be drawn:

1. Adding polymer (high-density polyethylene) and crumb rubber powder (CRP) to Alexandria waxy asphalt led to an increase in its hardness, as demonstrated by the results of the Marshall Tests.

Table (17)
statically analysis of the results.

MIX #	OBC, %	Stability, Kg	Flow, mm	AV, %	Unit weight	VMA, %
0	5.19	900	3.58	3.4	2.318	14.45
1	5.12	910	3.5	3.6	2.315	14.53
2	4.90	980	3.4	4.1	2.309	14.6
3	4.80	1120	2.9	4.4	2.304	14.7
4	5.02	1060	3.2	3.6	2.314	14.5
5	5.00	1154	2.9	4	2.308	14.7
6	4.95	1240	2.75	4.2	2.303	14.85
7	4.84	1408	3.28	3.5	2.325	13.9
8	4.77	1440	2.8	3.95	2.318	14.15
9	4.76	1280	2.3	4.3	2.309	14.4
10	4.82	1400	2.8	3.45	2.324	14
11	4.74	1200	2.48	3.8	2.316	14.2
12	4.75	1190	2.2	4.2	2.308	14.5
13	4.83	1220	3.4	4	2.313	14.3
14	4.78	1190	3.12	4.4	2.31	14.5
15	4.75	920	3	4.4	2.308	14.55
16	4.80	1240	3.24	4.1	2.312	14.5
17	4.77	1360	3	4.2	2.308	14.6
18	4.80	1200	2.84	4.3	2.305	14.65
Average	4.86	1179.58	2.98	3.99	2.31	14.45
STDEV.S	0.13	166.29	0.39	0.34	0.01	0.24
STDEV.S/Average	0.027163	0.140976	0.12933	0.084983	0.002687582	0.016941

2. The mixing arrangement, according to the Marshall Test results, indicated that the best mix was Comparison Mix 2 (M8), Followed by Comparison Mix 3 (M17), and Finally Comparison Mix 1 (M6).
3. The addition of polymer (HDPE) and crumb rubber powder (CRP) improves the long-term performance of the asphalt mixture. It has been proven that the mixture exhibits greater crack resistance at lower temperatures by increasing the indirect tensile strength and tensile strength ratio. Comparison Mix 2 demonstrated the best performance, followed by Comparison Mix 3, and finally Comparison Mix 1.
4. The addition of polymer (HDPE) and (CRP) improves the permanent deformation of asphalt mixture. According to the rutting test results, there is approximately no difference between Comparison Mix 2 and Comparison Mix 3, as they yielded almost the same results (1.02 mm and 0.95 mm), with reduction rate of 40.35% and 44.44%, respectively, compared with the control mix (M0), which had a rutting depth of 1.71 mm. This is followed by Comparison Mix 1, which yielded a rutting depth value of 1.28 mm, representing a decrease rate of 25.14%.
5. The SEM microstructural investigation illustrated good dispersion of HDPE (PE100) and CRP within the bitumen (modified binder).
6. The economic analysis for all mixes shows that the prices of mixes comparison mix 1 (M6), comparison mix2 (M8), and comparison mix3 (M17) increased by 2.84%, 4.15%, and 108.24%, respectively, with respect to mix M0. According to the performance characteristics and economic analysis, comparison mix2 (M8) is considered the best alternative in this research.
7. It is recommended to conduct an experimental section on an asphalt pavement to measure the segregation between the asphalt binder and the additives.
8. Statistical analysis reveals the degree of homogeneity of the samples, as the unit weight demonstrates the greatest consistency, exhibiting only a 0.26% variation. The optimum bitumen content is also a reliable measure, showing a minimal coefficient of variation of 2.7%. In contrast, stability and flow are the most variable factors, with variations of 14.1% and 12.9%, respectively. This suggests that while the unit weight of the mixtures remains relatively uniform, their structural performance is significantly affected by variations in the mix composition.

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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

Data availability

No data was used for the research described in the article.

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