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PERFORMANCE INVESTIGATION OF HOT- AND WARM- ASPHALT MIXTURES MODIFIED WITH SUPERPLAST

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Abstract

Moisture and stripping damages are the most prevalent cause of defects of both Hot-Mix Asphalt (HMA) and Warm-Mix Asphalt (WMA). Adhesion between aggregates and bitumen is a crucial factor that affects such defects. Various methods, such as incorporating additives, have strengthened the asphalt mixture's resistance to moisture and stripping. This paper aimed to experimentally investigate the effect of including a low-cost polymer additive (Superplast) into HMA and WMA mixtures. For this goal, a 60/70 penetration grade bitumen was used. For preparing the WMA mixtures, Showax was employed with percentages of 2, 3, 4, 5, and 6% by weight of bitumen. Polymer modified mixtures (HMA and WMA) were prepared by adding 3%, 4, and 5%

of Superplast by weight of the binder. Performance characterizations of the unmodified and Superplast-modified mixtures include stiffness, moisture damage resistance, and bonding. These characteristics were evaluated via Marshall, Lottman, and Double Punching tests, respectively. Results revealed that incorporating Superplast improved the adhesion between bitumen and aggregates, which ultimately led to an increase in the stiffness and moisture resistance of both HMA and WMA. Moreover, Superplast-modified WMA mixtures exhibited the best moisture and stripping resistance performance compared to Superplast-modified HMA and other unmodified mixtures.

Keywords: Hot-mix Asphalt, Warm-mix Asphalt, Pavement, Polymer, Moisture Susceptibility, Stripping, Lottman Test, Double Punch Test

1 Introduction

Based on mixing and compaction temperatures, asphalt mixtures can be classified into three alternatives: hot-mix asphalt (HMA), warm-mix asphalt (WMA), and cold-mix asphalt (CMA). Warm-mix asphalt (WMA) is an energy-saving and environmentally friendly alternative compared to conventional HMA since it can be mixed and compacted at lower temperatures, therefore, reducing energy consumption and exhaust emissions while maintaining good road performance [1, 2]. WMA can be produced in three ways: by using organic additives such as Aspha-min, Showax, and Sasobit, by using emulsified asphalt, and by using foamed asphalt technologies. Many studies were performed for WMA investigation, with the majority of them focusing on road efficiency validation, additive dose determination, and construction technology [3, 4]. The lower temperature rate associated with WMA mixing and compaction may have adverse effects. It may reduce the oxidation level of the utilized asphalt binder and consequently increase the fatigue and oxidation resistance [5-8]. On the other hand, it may cause a reduction in the aggregate/binder adhesion, i.e., stripping [9-12]. Some previous studies showed that WMA could have similar or better performance properties compared to the conventional HMA [13-18]. However, other studies showed that the performance of HMA outperforms that of WMA, particularly in the resistance against rutting and moisture damage [19-28].

Showax additives have two completely different functions that depend on the physical phase of the asphalt binder. The first function of wax can be observed when the asphalt binder is in the liquid phase at temperatures above 100 ° C. Above this temperature; the wax reduces the viscosity of the binder. The second function of wax can be observed in the middle and low-temperature ranges, where the asphalt binder is in the colloidal phase or solid phase, increasing the asphalt binder's viscosity. However, low, and high viscosity values at high and medium temperatures are more desirable in terms of lowering construction temperatures and improving resistance to rutting. The effect of the wax depends on the chemical composition and rheological properties of the asphalt binder, the crystallinity of the wax, the range of applied temperature, and the amount of wax [29].

Utilizing polymers modified asphalt (PMA) for roadway construction has earned remarkable attention due to their superior performance, including thermal-crack resistance, moisture susceptibility, and rutting resistance [30-36]. However, polymer-modified asphalt mixtures require high mixing and compacting temperatures, increasing energy consumption and exhaust emissions [37]. Wu and Montalvo presented a literature review about incorporating ten different polymers into HMA mixtures [38]. They concluded that polymers incorporation improved stiffness, rutting, and fatigue resistance. However, the performance of PMA mixtures tended to be temperature-dependent, i.e., they performed better at high temperature (rutting resistance) and worse at low temperature (fatigue cracking resistance). Kim et al. evaluated the performance of PMA binder containing warm mix asphalt additives (Alpha-min and Sasobit). They reported that incorporating WMA additive improved binder rutting resistance but reduced fatigue cracking resistance [39].

Most WMA modification studies focused on incorporating high-cost materials such as; thermoplastic-elastomer polymers (styrene butadiene styrene (SBS) and styrene-butadiene rubber (SBR)), anti-striping agent, and hydrated lime [40-44]. While their reported results revealed performance enhancements, their application for a wide field of pavement construction was not practical due to their high cost.

To this end, if a low-cost polymer can be incorporated into WMA technology, the benefit of polymers while reduced mixing- and compaction- temperatures can be attained. However, such integration needs more investigation. Therefore, this study aimed to investigate the effect of incorporating a low-cost polymer additive (Superplast) into both HMA and WMA mixtures then compare their performance.

2 Materials and testing methods

2.1 Materials

Asphalt with a penetration grade of 60/70 and a specific gravity of 1.02 from Suez refinery was used as the control asphalt; its physical properties are shown in Table 1. The coarse and fine aggregates used in this study were crushed dolomite stone and siliceous sand obtained from a quarry in El Kawamel City. The mineral filler employed in this study is a cement fume dust with 3.8 specific gravity. The course, fine aggregate, and mineral filler gradation are shown in Tables 2, 3, and 4, respectively.

Table 1: Physical properties of the control Asphalt Binder

Test	Standard test method	Results	Specification
Penetration,	ASTM D5/D5M-20 [45]	69.6	60-70
Softening	ASTM D36/D36M-20 [46]	47	45-55

Table 2: Gradation of Coarse Aggregate

Sieve Size (mm)	Passing (%)	
	Pin 2	Pin 1
25.4	100	100
19.0	78	100
9.52	0	80
4.75	--	9
2.36	--	0

Table 3: Gradation of Sand

Sieve Size (mm)	Passing
4.75	100
2.36	100
0.6	52
0.3	16
0.15	4
0.075	2

Table 4: Gradation of Mineral Filler

Sieve Size (mm)	Passing
0.3	100
0.15	96
0.075	86

For achieving a low-level temperature for producing WMA, a wax additive, namely Showax is used. Showax is the commercial name of organic additive (fatty acid amid wax). It is one of the essential additives used in warm asphalt mixtures to improve workability and low asphalt mixing temperatures. A low-cost plastomeric polymer additive; Superplast, is a compound of formed Ethylene-vinyl acetate (EVA), Low-density polyethylene (LDPE), and other polymers with low molecular weight and a medium fusion point. The data-sheet for the physical and mechanical properties of the used Showax and Superplast are presented in Tables 5 and 6, respectively, as listed in the manufacturer's brochure (Shorouk Chemical Company - Egypt) [47]. Fig. 1. Illustrates the utilized Showax and Superplast particles.

Table 5: Physical properties of the Showax[47]

Additives	Melting Point (ºC)	Brookfield viscosity at 160ºC (cP)	Penetration at 25ºC (0.1 mm)	Size (mm)
Showax	100-120	15	2-7	1-2

Table 6: Physical properties of Superplast[47]

Additives	Aspect	Softening point	Fusion point	Melt Index	Size (mm)
Superplast	black/grey granules	150°C	160°C	1÷5	4

2.2 Methods

To attain the goal of the study, the following stages were considered; first, binder samples (unmodified and modified) were prepared. The second stage considered designing HMA and WMA mixers (unmodified and modified) and determining optimum binder contents using the Marshall Mixture design method according to ASTM D6927 [48]. Finally, all prepared mixtures were experimentally evaluated. Mixtures' stiffness (hardening), moisture damage resistance, and stripping susceptibility were assessed via the Marshall test, modified Lottman test, and double punching test, respectively [49, 50]. All experimental tests in the third and fourth phases were performed on three replicates for each group of mixtures. Fig. 2 displays the outline of the laboratory work undertaken.


(a) (b)

Fig. 1. Utilized additives; (a) Showax; (b) Superplast

2.2.1 *Sample preparation*

In this study, a wet method was used to prepare the asphalt binders containing Showax additives. For this purpose, the Showax was added to a pre-heated control binder at 140 ^{o}C and stirred until complete dissolution is attained. The dosage of the employed Showax was 2%, 3%, 4%, 5%, and 6% by weight of asphalt binder. Then, WMA mixtures were prepared using these binders. The blending temperature of the employed Showax was 140°C according to the manufacturer's recommendations[47].

For incorporating Superplast, a dry process was used. Superplast was incorporated into a pre-heated aggregate at 180^{o}c until Superplast coated aggregate, then it was mixed with hot bitumen (160°C). The incorporated dosage of Superplast was 3%, 4%, and 5% by weight of the binder, based on the manufacturer's recommendations[47]. Then blending calculations of the conventional wearing surface layer of (4C) gradation according to Egyptian specifications were performed [51].

2.2.2 *Mixtures Design*

Conventional Asphalt mixture: In this study, the 4C dense gradation for wearing course (surface mixes) according to the Egyptian specifications was selected (ECP)[52]. To achieve this gradation, the following blend was used: 25% pin 2, 29% pin 1, 39% sand, and 7% mineral filler. The specification limits of the 4C gradation and the design gradation (Asphalt

Mix Design) of the investigated mixture are shown in Fig. 3.

Marshall mix design following AASHTO T 245 was used to define the optimum asphalt content (OAC) of a control asphalt mix using conventional asphalt.

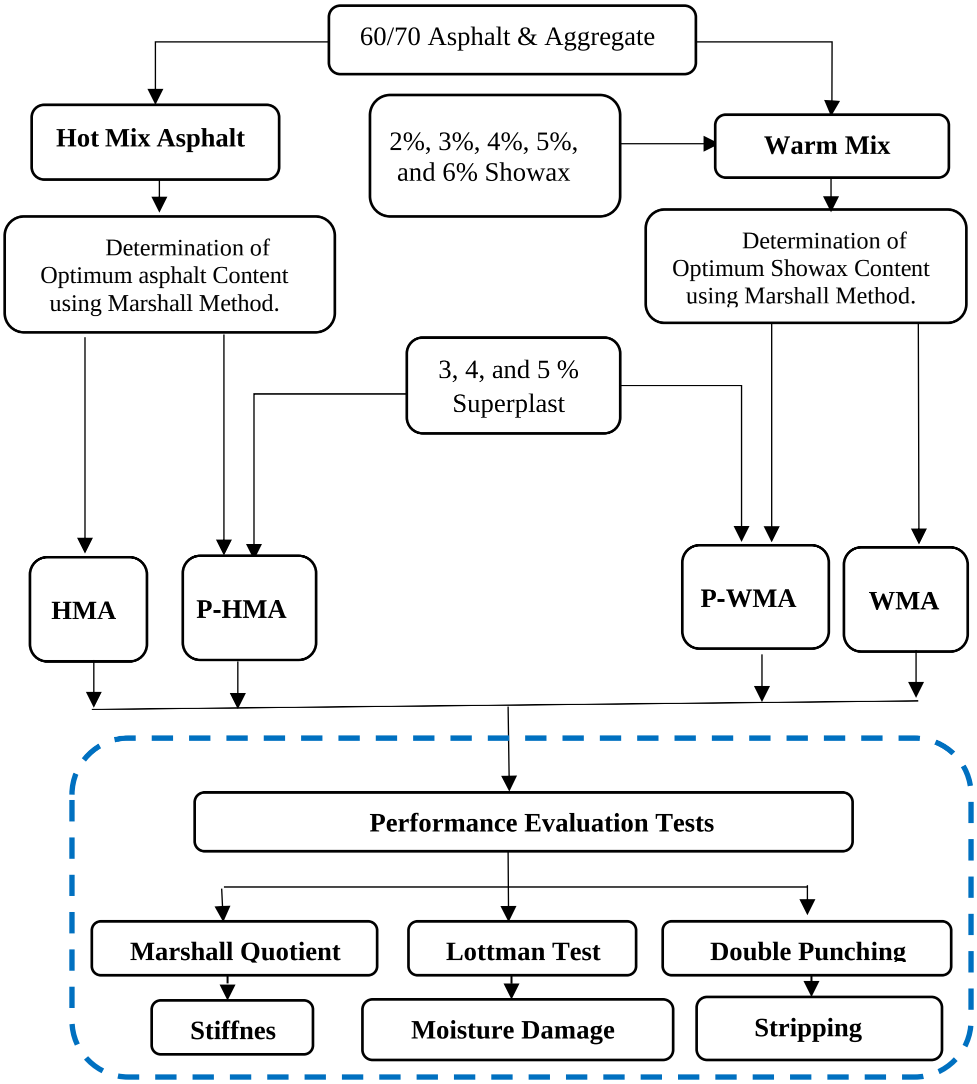


Fig. 2. Research Methodology

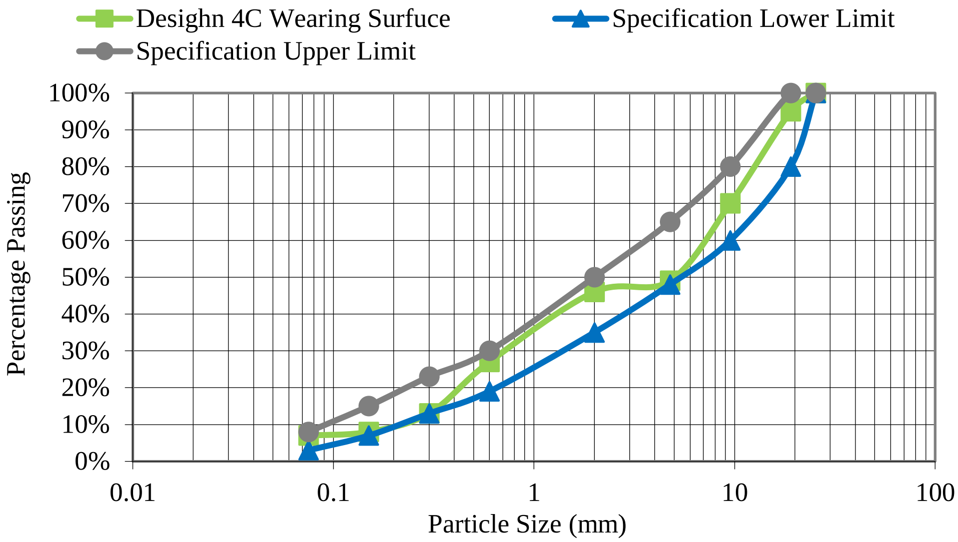


Fig. 3. Job Mix Formula and the Specification Limits

Warm Mix Asphalt (WMA): For preparing WMA, the 60/70 asphalt was heated to140 °C then Showax was added as described early. After that, the binder at 140 °C was added to the designed aggregate blend[47]. It should be noted that the mixing time was longer than the mixing time for HMA mixtures.

2.2.3 *Performance Characterization Tests*

Stiffness Test: For evaluating the prepared mixtures' stiffness (rigidity), Marshall Quotient (MQ) value was estimated using the Marshall Test results (ASTM D 6927). MQ is a well-known indicator representing the asphalt mixture's stiffness and its rutting tendency [53-56]. According to ASTM D-6927, for each mixture, three Marshall specimens were immersed in water for 30-min at 60 °C just before testing. Then, samples were loaded at a 50.8 mm/min loading rate in the Marshall testing machine until the failure (maximum load). For each mixture, three replicants were tested. By dividing the average failure load value by the associated deformation value, the Marshall Quotient (MQ) is estimated for that mixture.

Moisture Susceptibility: The modified Lottman test is considered a standard test for assessing the moisture resistance of asphalt mixes. In this study, a modified Lottman test was conducted on both conventional and modified mixtures samples to determine the effect of moisture on the asphalt mixture's tensile strength following AASHTO T283-14 [57]. Six Marshall Samples were prepared for each mix with 7 ± 1 % air void ratios. Three samples were stored in an air bath at 25°C for at least four hours before testing (dry set). The other three samples were immersed in a water bath at 60 ± 1.0°C for 24 hours then stored in another water bath at 25°C for 2 hours before testing (wet set). Then the indirect tensile strength (ITS) and the tensile strength ratio (TSR) were calculated as follows[57],

$$\text{ITS} = \frac{2P}{\pi HD} \tag{1}$$

$$\text{TSR} = \frac{ITS_{wet}}{ITS_{dry}} \times 100 \tag{2}$$

Where, P (kN) is the failure load, H (mm) is sample thickness, D (mm) is sample diameter, ITS_{dry} (kPa) is the average indirect tensile strength for the first group samples, and ITS_{wet} (kPa) is the average indirect tensile strength for the second group samples.

Stripping susceptibility: Stripping susceptibility (deboning) of conventional and -modified mixtures is assessed using the double punching (DP) test. This test procedure was advanced at the University of Arizona by Jimenoz (1974), which was used for measuring the stripping of the binder from the aggregate [49]. Then several studies have reported this test [34, 58-61]. Marshall samples were used for the test, and three specimens were conditioned by placing them in water at 60 ± 1°C for 30 minutes. The specimen was centered between two cylindrical steel punches (2.54 cm in diameter) perfectly aligned one over the other and then loaded at a rate of (2.54 cm/minute) until failure, as shown in Fig.4. Then the maximum resistance was recorded. The punching strength can be calculated as follows.

$$\sigma = \frac{\text{p}}{\pi(1.2\text{bH} - a^2)} \tag{3}$$

where, σ (Pa) is punching shear stress, p (N) is the maximum load, a (mm) is the radius of punch, b (mm) is the specimen radius, and H=2h (mm) is the specimen height.

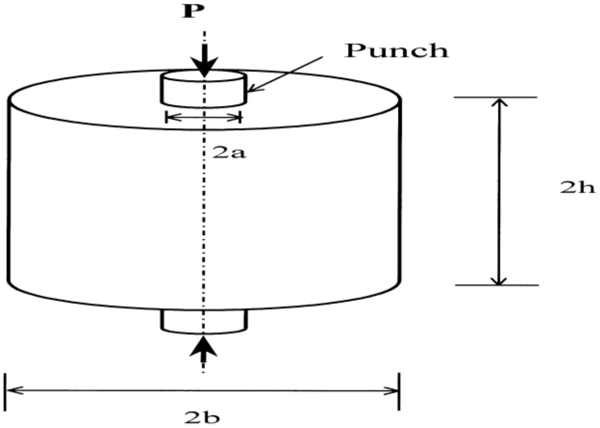


Fig. 4. Double punch test Setup [62]

3 Results and analysis

3.1 Hot Mix Asphalt Mixtures

3.1.1 *Conventional HMA*

Five different percentages of AC (4.0, 4.5, 5.0, 5.5, and 6.0) were mixed with the blended aggregate. A total of 15 Marshall Plugs were prepared (three plugs at each AC percentage). The volumetric properties of each sample were determined, and the samples were loaded in the Marshall Equipment to determine the stability and flow at 60 °C.

The optimum Asphalt content (OAC) was determined based on the asphalt institute method as the average of three values (asphalt content at maximum stability, maximum density, and 4% air voids in hot mix asphalt). Then this asphalt content was used to make sure it meets the mixed design criteria. The conventional asphalt mixture was designed by the Marshall method, and the properties of the asphalt mixture are presented in **Error! Not a valid bookmark self-reference.**.

Table 8: Marshall Mix Design Properties

Parameter	**Value**	**Asphalt Institute[63]**	
		Minimum	Maximum
Marshall bulk density (t/m^3)	2.34	----	----
Theoretical Maximum Specific Gravity, Gmm	2.44		
Stability (kg)	1588	900	
Flow (mm)	3.05	2	4
Air voids (AV) (%)	4.14	3	5
Voids in mineral aggregates (VMA) (%)	15.62	15	----
Voids filled with binder (VFB) (%)	73.46	65	----
Asphalt cement (%)	5.0	----	----

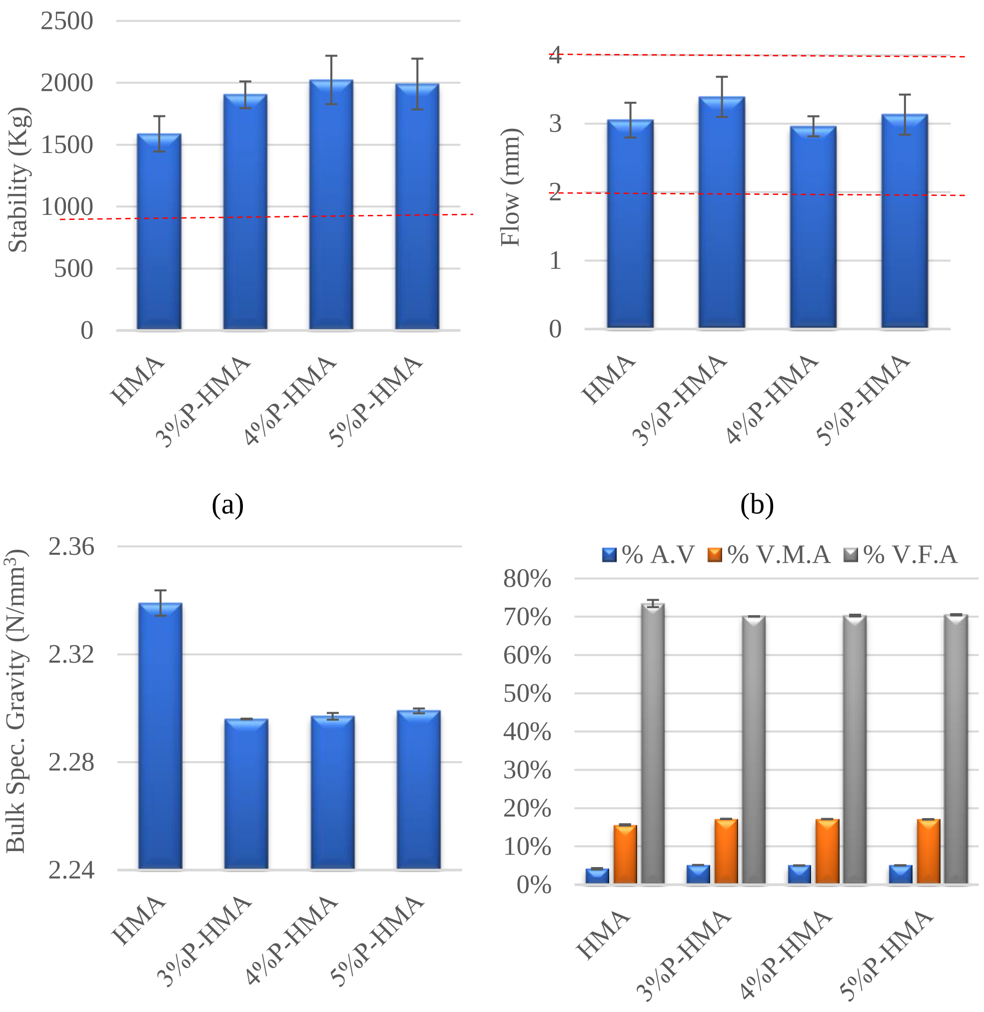
3.1.2 *Polymer modified HMA*

Fig. 5 presents the average Marshall test results and the corresponding volumetric properties for the convention HMA and Superplast modified HMA (P-HMA) in comparison. Based on the results, adding Superplast to the HMA increased the stability, and the maximum value attained at 4% Superplast (4%P-HMA).

From Fig. 5-b, it can be observed that with the increase in modifier content, there is a change in the flow values with the observation that there is no specific trend of increase or decrease. The stability and flow values for all modified mixtures satisfied the design standards for the Egyptian code's surface layer with heavy traffic, i.e., more than 900 kg and within 4.06 to 2.03 mm for the stability and flow, respectively [52].

Based on Fig. 5-c, adding Superplast to the asphalt mixture reduced the bulk density compared to the convention HMA. The highest bulk density was attained when incorporating 5% of Superplast (5%P-HMA).

Fig. depicts the variation of the percentage of air voids (AV %), the percentage of voids in mineral aggregate (VMA %), and the percentage of voids filled with aggregate (VFA %) values of the convention HMA and Superplast-modified HMA with different Superplast contents. Adding Superplast to the HMA did not significantly affect the AV%, VMA%, and VFA%. The air voids values for all mixtures satisfied the specifications, i.e., 3 to 5% [52]. Based on Marshall's results the optimum content of Superplast was remarked to be 4%.



(a) (b)

(c) (d)

Fig. 5. Marshall results of HMA and Superplast-modified HMA mixtures; (a) stability, (b) flow, (c) bulk specific gravity, and (d)volumetric properties

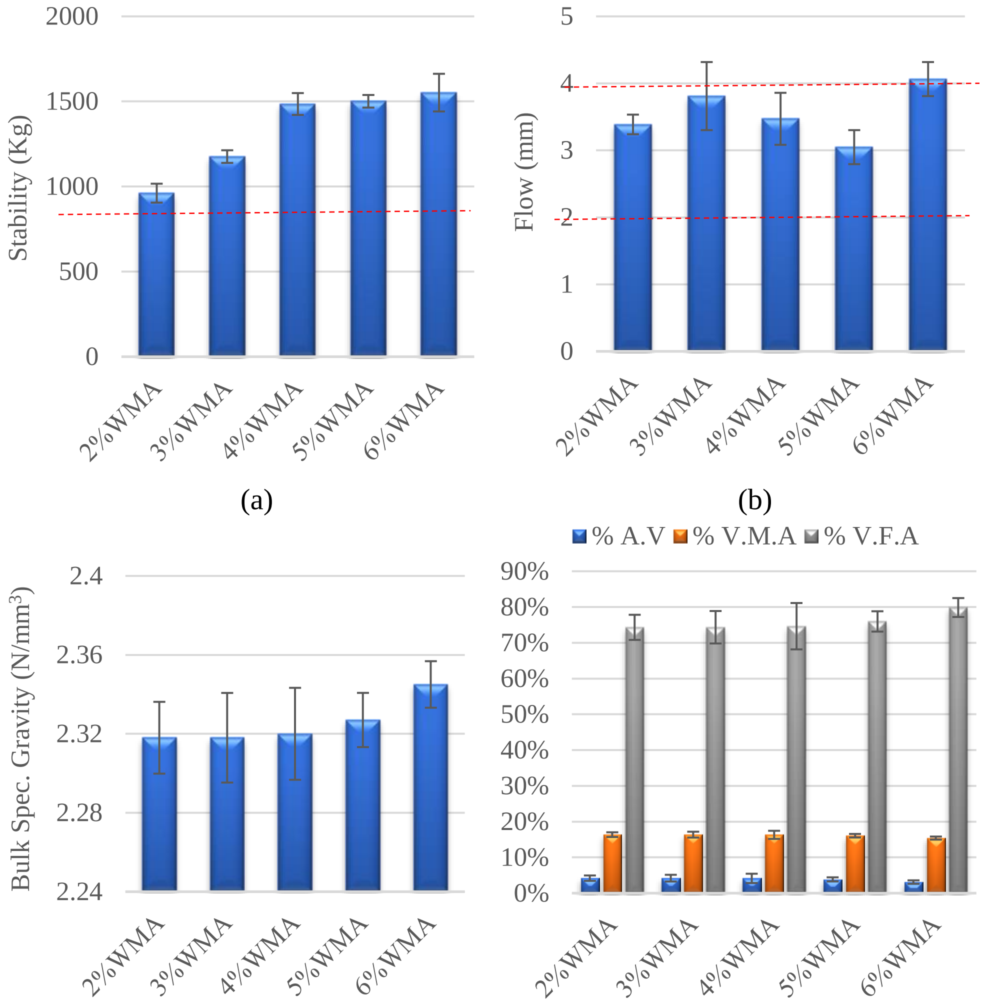
3.2 Warm Mix Asphalt (WMA)

3.2.1 *Convention WMA*

The average Marshall test results as well as their corresponding volumetric properties for WMA with incorporating 2%, 3%, 4%, 5%, and 6% Showax are depicted in Fig.6. At all Showax contents, the stability and the flow values were within the permissible limits according to Egyptian specifications [52]. **Error! Reference source not found.** shows the effect of employing different percentages of Showax on the specific gravity of WMA. In the beginning, there was a gradual decrease in the specific gravity values with increasing Showax content till 4% of Showax, and then the values increased to their most enormous value at 6%. The effect of using different percentages of Showax on VFA%, AV%, and VMA% values of WMA is shown in **Error! Reference source not found.**. The values of the AV% and the (VMA%) decreased with the increase in the percentage of Showax in the mixture. On the contrary, the values of (VFA%) increased with the increase in the percentage of Showax. Generally, the air voids content was within the range of 3% to 5% for all samples. Based on the results presented in **Error! Reference source not found.**, the optimum content of Showax was 5% of the weight of the asphalt.

3.2.2 Polymer modified WMA

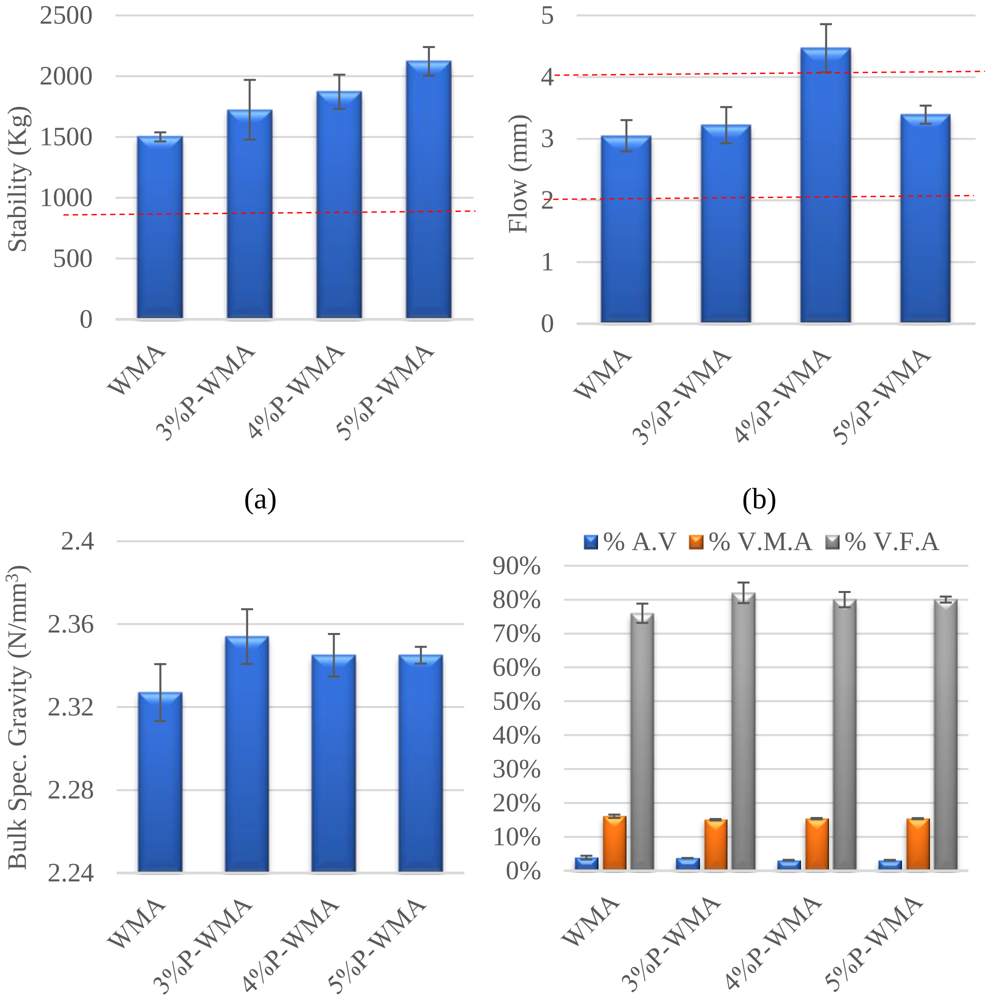
Error! Reference source not found. presents the average Marshall test results and the corresponding volumetric properties for the convention WMA and Superplast modified WMA (P-WMA) while employing 5% Showax and 3%, 4%, and 5% Superplast. From **Error! Reference source not found.**, it was observed that the stability values increased with the increasing percentage of Superplast, as the Superplast significantly improved stability in all ratios compared to the control mix. The maximum stability was attained at 5% Superplast. In general, the flow values of all mixtures with different Superplast ratios are within the Egyptian specifications except 4% Superplast as shown in **Error! Reference source not found.**. **Error! Reference source not found.** shows specific gravity values for WMA and P-WMA. Adding Superplast into WMA increased mixtures specific gravity value and the maximum value was attained at 3% Superplast. Moreover, the effect of using different percentages of Superplast on VFA%, AV%, and VMA% values of WMA is shown in **Error! Reference source not found.**. The values of the AV% and the (VMA %) slightly decreased with increasing the percentage of Superplast. On the contrary, the values of (VFA %) increased with the increase in the percentage of Showax. Generally, the air voids content was within the range of 3% to 5% for all samples. Based on the presented results, the best P-WMA performance was attained when incorporating 5% of Superplast, i.e., 5%P-WMA.



(a) (b)

(c) (d)

Fig. 6. Marshall results of WMA mixtures; (a) stability, (b) flow, (c) bulk specific gravity, and (d)volumetric properties



(a) (b)

(c) (d)

Fig. 7. Marshall results of WMA and Superplast-modified WMA mixtures; (a) stability, (b) flow, (c) bulk specific gravity, and (d)volumetric properties

3.3 Performance Evaluation

This section presents the results of the performance evaluation tests conducted on the four mixtures: HMA, Superplast-modified HMA (P-HMA), WMA, and Superplast-modified WMA (P-WMA).

3.3.1 Stiffness Test

For evaluating the mixtures' stiffness (rigidity), Marshall Quotient (MQ) value was obtained using the Marshall Test results

(ASTM D 6927). MQ calculated from dividing the stability over the flow, which can be used as an indication for the mixture's rutting resistance. The higher MQ values indicate higher mixtures' stiffness and consequently higher resistance to permanent deformation i.e., rutting [64]. The outcomes of the test results (

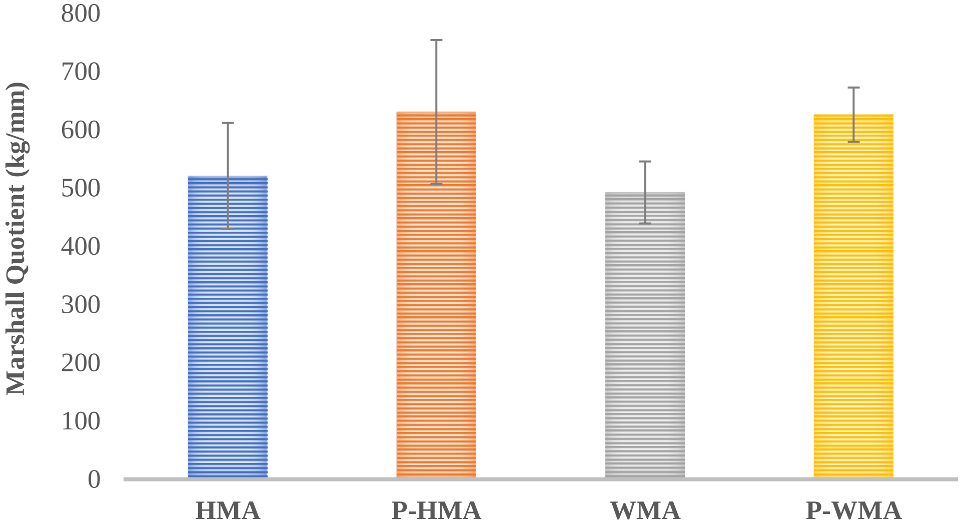


Fig.) indicate that MQ values increased with the application of Superplast, which reveals higher resistance to rutting, especially in hot climatic areas. Where incorporating Superplast significantly improved the stiffness of both HMA, and WMA compared with the unmodified ones. The convention HMA presented a slightly higher stiffness than WMA (about 5% more). However, the stiffness of both Superplast-modified mixtures (P-HMA and P-WMA) was almost the same.

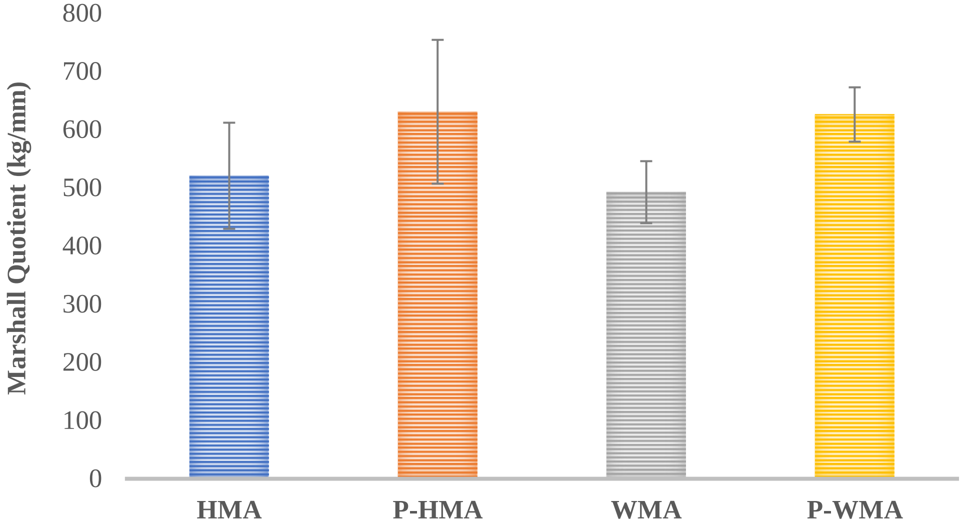


Fig. 8. Marshall quotient values for the unmodified and modified mixtures

3.3.2 Moisture Damage Resistance Test

The results of the modified Lottman test for both unmodified and Superplast-modified hot and warm mixtures are depicted in Fig. 9. In which the indirect tensile strength (ITS) values, for both dry and wet subgroups, as well as the calculated tensile strength ratio (TSR) are presented.

Based on Fig.9, incorporating Superplast improved the mean tensile strength (ITS) values for both HMA and WMA, with this increase being most pronounced for wet subgroups. Moreover, the attained improvement in WMA was significantly higher than that for HMA when incorporating Superplast. Compared with the unmodified WMA, Superplast-modified WMA (P-WMA) had an increase in the ITS values for dry and wet subgroups by 34.3% and 77.4%, respectively. On the other hand, the ITS values associated with Superplast-modified HMA (P-HMA) were higher by 18% and 21.7% for dry and wet subgroups, respectively, in comparison with the conventional HMA.

Moreover, the tensile strength ratios (TSR) values also improved when incorporating Superplast for both HMA and WMA, as shown in Fig.9. Generally, warm mix asphalt mixtures exhibited higher TSR values than hot-mix asphalt, revealing higher resistance against moisture damage. However, Superplast-modified WMA (P-WMA) was the only mixture that satisfied the specification of Egyptian Code and (AASHTO T 283), i.e., more than 80% [52]. For the P-WMA mixture, TSR was above 100%, which indicated that the mixture was insensitive to moisture. Similar results were reported by Peerapong Jitsangiam, Korakod Nusit, and Hamid Nikraz [65].

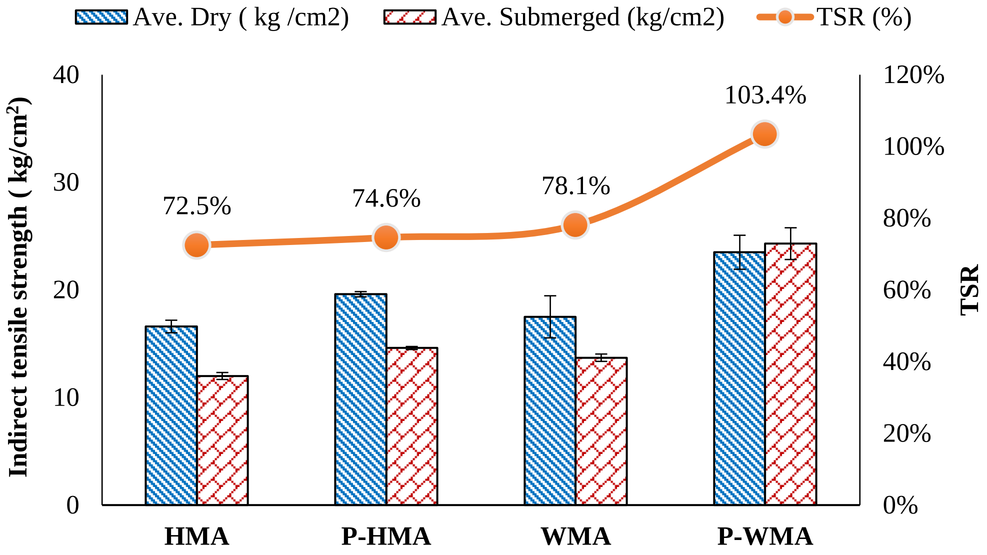


Fig. 9 Moisture damage results of the unmodified and modified mixtures

3.3.3 Stripping susceptibility

Fig. shows the Double Punch shear test results for the unmodified and Superplast-modified HMA and WMA mixtures. The double Punch test signifies the bonding strength between the aggregate and the binder. Results show that WMA had a little higher bonding strength than both convention HMA and Superplast-modified HMA. While incorporating Superplast significantly improved the shear stress value of WMA, it slightly enhanced the HMA's shear stress. Moreover, Superplast-modified WMA (P-WMA) had the superior shear stress value which is 49.4%, 43.8%, and 37.5% higher than those of HMA, P-HMA, and WMA, respectively.

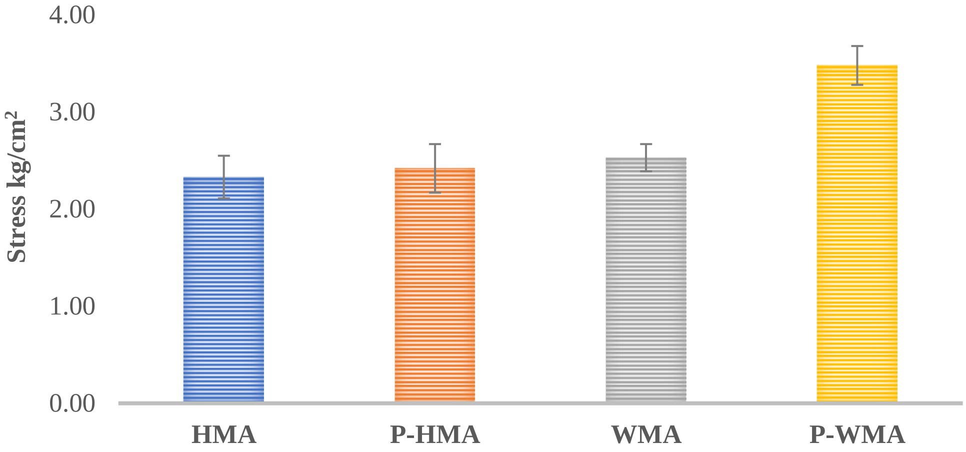


Fig. 10. Punching strength results for unmodified and modified mixtures

4 Conclusions

This study experimentally evaluated the performance of HMA and WMA mixtures when incorporating different percentages of low-cost polymer (Superplast). In the following, the main conclusions from the performance evaluation tests are presented:

- Generally, WMA mixtures exhibited higher resistance to moisture damage and stripping than HMA mixtures.
- While incorporating Superplast into HMA significantly improved the stiffness, it slightly enhanced the moisture damage resistance and stripping susceptibility.
- Incorporating Superplast into WMA significantly improved the stiffness, moisture damage resistance, and stripping susceptibility.
- Incorporating Superplast improved the adhesion between bitumen and aggregates, which ultimately led to an increase in the stiffness and moisture resistance of both HMA and WMA.
- While the stiffness of both Superplast-modified hot- and warm-asphalt mixtures was almost the same, Superplast-modified WMA exhibited significantly higher moisture susceptibility and stripping resistance than that for Superplast-modified HMA.

- Overall performance of Superplast-modified WMA mixtures is observed to be better compared to polymer modified HMA mixtures.

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التحقيق في أداء خلطات الأسفلت الساخنة والدافئة المعدلة باستخدام السوبربلاست

الملخص:

تعد أضرار الرطوبة والتعرية من أكثر العيوب انتشارًا في كل من الخلطات الاسفلتية الساخنة (HMA) والخلطات الاسفلتية الدافئة (WMA). يعتبر الالتصاق بين الركام والبيتومين عاملاً مهمًا يؤثر على مثل هذه العيوب. تم استخدام طرق مختلفة، مثل دمج الإضافات، لتقوية مقاومة خليط الإسفلت للرطوبة والتعرية. هدفت هذه الورقة إلى التحقيق التجريبي في تأثير اضافة مادة بوليمر منخفضة التكلفة السوبربلاست (Superplast) الي الخلطات الاسفلتية الساخنة والدافئة (HMA وWMA). لهذا الهدف، تم استخدام بيتومين ٦٠/٧٠. ولتحضير مخاليط WMA، تم استخدام Showax بنسب ٢ و٣ و٤ و٥ و٦٪ من وزن البيتومين. تم تحضير الخلطات البوليمرية المعدلة (HMA وWMA) بإضافة ٣٪، ٤، و٥٪ من Superplast من وزن البيتومين. تم تقييم الأداء للخلائط غير المعدلة والمعدلة بالبوليمر من خلال تقييم الصلابة ومقاومة تلف الرطوبة وقابلية التجريد عبر اختبارات Marshall وLottman و Double Punching. أظهرت النتائج أن دمج Superplast أدى إلى تحسين الالتصاق بين البيتومين والركام، مما أدى في النهاية إلى زيادة الصلابة ومقاومة الرطوبة لكل من الخلطات الاسفلتية الساخنة والدافئة. علاوة على ذلك، لوحظ أن الأداء العام للخلطات الاسفلتية الدافئة المعدلة بال Superplast كان الأفضل مقارنة بباقي الخلطات الاسفلتية الساخنة الأخرى.