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Performance of Hot Asphalt Mixes Containing Steel Slag

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نبذة مختصرة :

يبحث هذا البحث في تأثير خبث الصلب **(SS)** على خصائص خلائط الإسفلت المزيج الساخن **(HMA)** كمادة مالئة معدنية بدلا من غبار الحجر الجيري **(LD)** بنسب معينة. أربعة مخاليط **HMA** بمحتويات مختلفة من **SS** ، وهي ؛ تم تحضير 25٪ ، 50٪ ، 75٪ و 100٪ بالوزن من مادة الحشو المعدنية باستخدام طريقة تصميم خلطة مارشال لخليط السطح **.(Mix 4C)** أظهرت الاختبارات المعملية تحسنا في خصائص مارشال المختلفة لخلائط **HMA** المعدلة باستخدام **.SS** هذا مؤشر على تحسين أداء الخلائط بالإضافة إلى حقيقة أنه يمكن استخدام **SS** في رصف الأسفلت لمزايا بيئية. محتوى **SS** بنسبة 100٪ بالوزن من حشو المعادن لخليط الأسفلت هو أفضل نسبة **SS** لتحسين أداء مزيج الأسفلت. خليط الإسفلت المعدل بهذه النسبة له قيمة ثبات أعلى بحوالي 15٪ وانخفاض بنسبة 38٪ في قيمة عمق الشق مقارنة بمزيج الإسفلت المرجعي.

ABSTRACT:

This paper investigates the effect of steel slag (SS) on the properties of hot mix asphalt (HMA) mixtures as a mineral filler instead of limestone dust (LD) by specific percentages. Four HMA mixtures with various SS contents, namely; 25%, 50%, 75% and 100% by weight of mineral filler were prepared by using the method of Marshall mix design for the wearing surface mixture (Mix 4C). Laboratory testing showed an improvement in different Marshall properties of HMA mixtures modified with SS. This is an indication of mixtures performance improvement in addition to the fact that SS can be utilized in asphalt paving for environmental advantages. SS content of 100% by weight of mineral filler for asphalt mix is the best SS percentage for asphalt mix performance improvement. Asphalt mix modified with this percentage has approximately 15% higher stability value and 38% decrease in rut depth value compared with the reference asphalt mix.

Keywords

Steel slag; Mineral filler; Hot mix asphalt; Stability; Rut depth

Introduction

Asphalt mix, which is consists of filler, bitumen, and aggregate, is an excellent paving material used in road construction [1]. Filler and bitumen are primarily used to create mastic, which fills the voids between aggregates, to improve the bonding between them. [2, 3]. According to earlier studies, mastic-coated aggregates should be considered in asphalt mixtures rather than pure bitumen-coated aggregates. [4]. Due to its dual use in mastic, filler characteristics are closely related to those of the asphalt mixture.

According to experimental research, adding filler has the following main effects: (i) Improve the mixture's mechanical properties by stiffening the bitumen, especially the resistance to permanent deformation at high temperatures, fatigue life at high temperatures, and cracking resistance at low temperatures [4-6], (ii) extend the asphalt to increase the mixture's asphalt volume and decrease the optimum asphalt content [7], (iii) meet the requirements for aggregate gradation, and (iv) improve the "bond" in the aggregate-asphalt system [8]. Researchers have reported that these influences are intimately related to the volume concentration and performances of fillers and the interaction between fillers and bitumen [9-14]. However, in consideration of the actual conditions that high-quality natural mineral fillers have been used rapidly with the fast growth of road construction. Finding additional high-quality fillers to replace natural mineral fillers is therefore urgently needed. One potential method of conserving natural resources is through the use of industrial waste, such as SS.

SS, a by-product produced in steel industry, accounts for more than 10% of the world's raw steel production [15, 16]. The SS has been widely used as aggregates in asphalt mixtures due to its high alkalinity, rich angularity, tough surface features, and superior mechanical characteristics [17–19]. Studies have shown that SS can enhance the functional properties of asphalt mixtures, such as moisture stability, resistance to high temperature deformation, abrasion resistance, and skid resistance. [20-22]. SS is a perfect substitute for natural aggregates because of these performances. However, using SS as a filler in an asphalt mixture causes little concern. Additionally, SS with varying particle sizes exhibits varied characteristics, and previous research suggested that SS fine aggregate's purity will deteriorate while being stored [19, 23]. Additionally, SS fine aggregate could exhibit volume instability because it contained more free lime (f-CaO) than SS coarse aggregate [24]. Therefore, it is uncertain and requires further study if these effects may affect the fillers' qualities if they are milled from raw SS with varying particle sizes. The primary objective of this article was to investigate the feasibility of SS as mineral filler instead LD by specific percentages.

Aims

This paper aims to investigate the effect of SS as mineral filler instead of LD on HMA performance and determine the optimum SS content (O.SS.C) according to the desirable stability and flow values.

Experimental work

Firstly, ten tests were performed on the chosen materials to assure its validity, five tests on aggregate and five tests on asphalt. Secondly, the optimum asphalt content (O.A.C) was identified by Marshall mix design and remained the same for all mixtures. LD was used as a reference filler, subsequently SS was used instead of LD as a mineral filler by specific percentages. Thirdly, Marshall stability (MS) and flow tests were conducted to the mixtures. MS and flow values were used to help investigating the optimum SS content (O.SS.C). Finally, performance tests were applied to the reference mixture with 100% LD and the first comparison mixture (Comp. Mix.1) which having the O.SS.C. These tests are stability loss test and rutting susceptibility test.

Materials

Mixes of asphalt concrete tested in this study consisted of aggregate, asphalt and mineral filler. These materials were collected from common sources in Egypt then qualification tests were conducted on each type. Used materials engineering properties were identified by performing laboratory tests based on American Association of State Highway and Transportation Official (AASHTO). The following sections present the different properties of the study materials.

Aggregate

Two types of aggregate were used in the current study:

1. Coarse aggregate with 100% crushed particles, its color is brown, mineral composition is quartzite and faces are angular
2. Fine aggregate with rounded faces particles, its color is orange, mineral composition is quartzite.

Table 1 presents the gradations of the aggregate used in the mix design. The aggregate gradations confirms to the Egyptian standard specifications for the wearing surface mix (Mix 4C). Table 2 summarizes aggregate properties in the current research.

Table 1. Gradation of aggregate used

Sieve size	Design gradation	Specification limits
inch		
1	100	100
3/4	87.5	80-100
1/2	75.4	--
3/8	73.2	60-80
No.4	48.9	48-65
No.8	41.6	35-50
No.16	36.3	--
No.30	28.7	19-30
No.50	16.8	13-23
No.100	11.4	7-15
No.200	7.3	3-8

Table 2. Aggregate properties

Properties	Course	Fine	Egyptian standards
Loss angles abrasion (%)	28	3	Up to 40%
Water absorption (%)	2.4	--	Up to 5%
Apparent specific gravity (gm/cm^3)	2.66	2.7	--
Unit weight (gm/cm^3)	2.61	2.49	--
Saturated specific gravity (gm/cm^3)	2.63	2.6	--
Flakiness index (%)	8.4	--	Up to 10%
Shape index (%)	7.2	--	Up to 10%

Asphalt binder

One type of asphalt is used in this study. This is Suez asphalt cement, 60/70 penetration grade and 1.02 gm/cm^3 specific gravity is used as shown in Table 3.

Table 3. Asphalt binder properties

Test no.	Test	AASHTO designation no.	Results	Specification limits
1	Penetration (0.1 mm)	T-49	67	60-70
2	Softening point (ºc)	T-53	47	45-55
3	Flash point (ºc)	T-48	+272	+250
4	Kinematic viscosity (cst)	T-201	433	+320
5	Ductility (cm)	T-51	+100	≥ 95

Mineral filler

The mineral filler used in mixtures is LD with 2.65 gm/cm^3 bulk specific gravity. Table 4 summarizes gradation of mineral filler. Table 5 shows the total mix gradation of filler after adding the different percentages of SS instead of LD as an enhanced material. Fig. 1 displays the appearance of the two types of fillers.

Table 4. Gradation of different types of mineral filler

Sieve size	Design gradation		Specification limits
inch	LD	SS	
No.30	100	100	100%
No.50	100	100	--
No.100	92	98	85% (min)
No.200	80	96.5	65% (min)

Table 5. Gradation of total mix of filler

Sieve size	Design gradation of total mineral filler content								Specification limits
inch	LD	SS	LD	SS	LD	SS	LD	SS	
	75%	25%	50%	50%	25%	75%	0.0%	100%	
No.30	100		100		100		100		100%
No.50	99.6		99.5		99.8		100		--
No.100	93.7		94.6		95.7		96.3		85% (min)
No.200	86.3		87.4		88.5		89.8		65% (min)

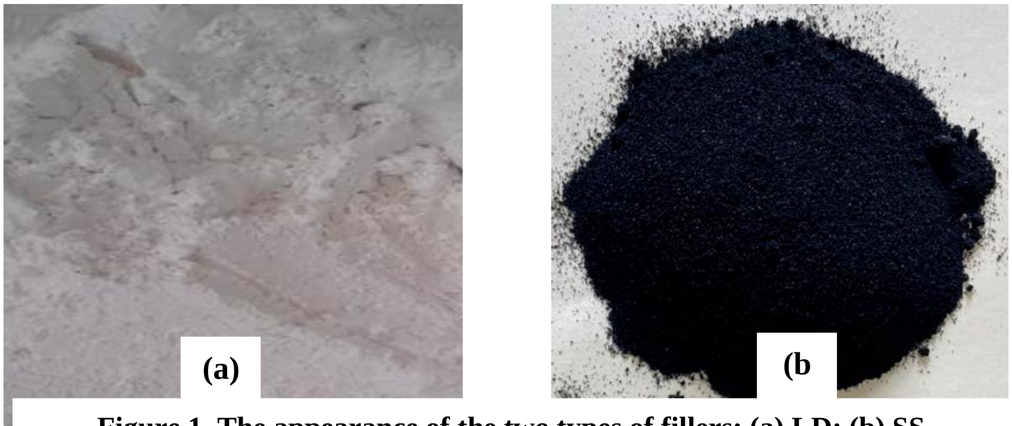

Figure 1. The appearance of the two types of fillers: (a) LD; (b) SS

Improved asphalt mixtures

Five HMA mixtures evaluated the influence of SS as a modified mineral filler instead of LD on HMA properties. The first HMA mixture included the O.A.C (5.1%) and 100% LD as a reference mineral filler and was named the (Reference Mix.). Subsequently, four HMA mixtures with the O.A.C (5.1%) and various SS ratios (25%, 50%, 75%, 100%) by mineral filler weight were prepared and conducted to method of Marshall mix design for finding the O.SS.C. So, the first comparison mixture (Comp. Mix.1) was obtained. Then, these two main mixtures (Reference Mix. and Comp. Mix.1) were conducted by special tests to compare the performance of SS additives to HMA mixtures. Table 6 presents these five HMA mixtures.

Table 6. Five HMA mixtures

Filler type	Code	Characterization	Function	Objective
LD	Mix 0	O.A.C% BC 60/70 + 100% LD	Determine Stability & Flow	Reference Mix.
SS	Mix 1	O.A.C% BC 60/70 + 25% SS + 75% LD	Determine O.MK.C of Comparison Mixes	Comp.Mix.1
	Mix 2	O.A.C% BC 60/70 + 50% SS + 50% LD		
	Mix 3	O.A.C% BC 60/70 + 75% SS + 25% LD		
	Mix 4	O.A.C% BC 60/70 + 100% SS + 0.0% LD		

Experimental works and results

Preparation of sample

Cylindrical samples of 101.6 x 63.4 mm were prepared with asphalt contents ranging from 4.5% to 6.0% with an increase of 0.5% to calculate the O.A.C. SS that is used as a part of mineral filler instead of LD was blended with the remaining amount of LD to get a homogeneous SS/natural filler mix before mixing with the O.A.C. Four HMA mixes with various SS contents, namely; 25%, 50%, 75% and 100% by mineral filler weight were prepared in accordance with the standard 75-blow Marshall mix design method for designing HMA. To keep aggregate angularities and mineralogical characteristics fixed, these designs were prepared with the same blend of coarse and fine aggregate. The filler content was fixed at 5% of the total mixture for all the mixes. The only changing in the mixtures was the percentage of SS. Three samples were prepared from each mixture for each test to provide sufficient data. So, every mixture weighing 3600 gm to give three Marshall molds. The temperatures for mixing and compaction were determined at 160 ºC and 140 ºC as shown in figures from 2 to 4. The mixes design at different asphalt contents shown in table 7. Table 8 presents the modified mixtures design by SS as a mineral filler instead of LD by specific replacement ratios.

Figure 2. Adding asphalt to aggregate

Figure 3. Mixing asphalt with aggregate at mix temperature

Figure 4. Marshall Apparatus (HUMBOLDT)

contents

Mix No.	Asphalt binder		Aggregate		Mineral filler (5%) LD (reference filler)		Total weight (gm)
	%	gm	%	gm	%	gm	
1	4.5	162	90.5	3258	5	180	3600
2	5.0	180	90	3240	5	180	3600
3	5.5	198	89.5	3222	5	180	3600
4	6.0	216	89	3204	5	180	3600
5	6.5	234	88.5	3186	5	180	3600

Table 8. Modified mixtures design

Mix code	Asphalt binder		Aggregate		Mineral filler (100%)				Total weight (gm)
					LD		SS		
	%	gm	%	gm	%	gm	%	gm	
M0	5.1	183.6	89.9	3236.4	100	180	0	0	3600
M1	5.1	183.6	89.9	3236.4	75	135	25	45	3600
M2	5.1	183.6	89.9	3236.4	50	90	50	90	3600
M3	5.1	183.6	89.9	3236.4	25	45	75	135	3600
M4	5.1	183.6	89.9	3236.4	0	0	100	180	3600

Calculation of optimum asphalt content (O.A.C)

Four HMA mixtures with the chosen materials in the past phase, various asphalt contents (4.5%, 5.0%, 5.5% and 6.0%) and 5% LD as a reference mineral filler were prepared and conducted to Marshall mix design method for the wearing surface mix (Mix 4C) to show the properties of mixtures according to (AASHTO T-166) [25]. Marshall apparatus was used to test the four HMA mixtures stability and flow. Then a result comparison was conducted to determine the O.A.C that was 5.1% which provide maximum stability and suitable flow, actual specific gravity and acceptable percentage of air voids. Table 9 presents O.A.C mixture properties with 5% LD as a reference filler.

Table 9. Marshall properties at O.A.C

Properties	Results	Specification Limits
Stability (kg)	1350	900 kg (min)
Flow (mm)	3.5	2-4 mm
Stiffness (Kg/mm)	386	300-500 Kg/mm
Unit weight (gm/cm^3)	2.394	--
% Air voids in total mix (V_a)	3.45	3-5 %
% Air voids in mineral aggregate (VMA)	14.98	--
% Air voids filled with asphalt (VFA)	76.97	--

Optimum steel slag content (O.SS.C)

Four HMA mixtures with the chosen materials, the O.A.C and various SS contents (25%, 50%, 75%, 100%) by weight of mineral filler were prepared and conducted to Marshall mix design method to find the O.SS.C that was 100%. Table 10 presents properties of SS mixtures, whereas table 11 displays O.SS.C mix properties.

Table 10. Properties of SS mixtures

Properties \ Mix. code	M1	M2	M3	M4	Specification limits
Stability (kg)	1387	1475	1542	1590	900 kg (min)
Flow (mm)	3.9	3.8	3.7	3.5	2-4 mm
Unit weight (gm/cm^3)	2.368	2.379	2.384	2.401	--
% V_a	3.97	3.86	3.74	3.53	3-5 %
% VMA	14.68	13.94	13.68	13.07	--
% VFA	72.77	70.84	71.38	72.19	--

Table 11. Properties of O.SS.C mix

Properties	Results	Specification limits
Stability (kg)	1590	> 900 kg
Flow (mm)	3.5	2-4 mm
Unit weight (gm/cm^3)	2.401	300-500 kg/mm
% V_a	3.53	--
% VMA	13.07	3-5 %
% VFA	72.19	--

Marshall stability and flow tests

Marshall stability and flow tests were conducted on compacted samples at O.A.C and various SS contents. According to the results in table 10, it can be noticed that Marshall stability increased by adding SS to HMA mixtures as mineral filler instead of LD by specific percentages. The mix (M4) achieved the highest stability value of 1590 kg at 100% SS. This value increased the stability by 15%. The mix (M1) achieved lowest stability value of 1387 kg at 25% SS, but remains higher than the reference mix stability value. The appropriate flow value is 3.5 mm which corresponding to the highest stability value at 100 SS (M4). This value kept flow the same as the reference mix (M0). The highest value of flow reached 3.9 mm at 25% SS (M1). Based on these results, it can be deduced that the replacement of LD by SS has obvious influence on the stability of mixture and flow at specified replacements percent of 100%.

Stability loss test

Stability loss test was conducted on Marshall samples as an index to mix durability under different conditions. In this test Marshall samples were placed in bath filled with water and tested at several times (0, 1 day, 2 days, 3 days) to measure the loss in stability of mixture. Figure 5 presents the stability loss percentages versus time of immersion for the reference Mix and comparison mix 1.

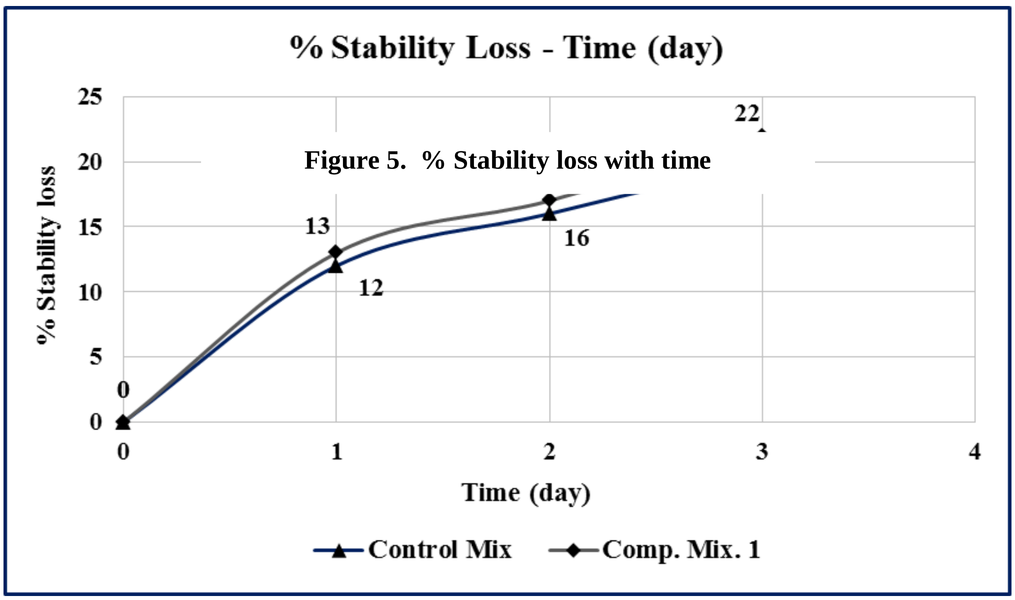

Figure 5. % Stability loss with time

Therefore, the reference mix and comparison mix.1 suffer stability loss with acceptable range (<25%) [26]. For comparison mix 1, the stability loss caused the highest loss percent 22%. This value increasing the loss ratio by 9% comparing with the reference mix. Consequently, replacing LD with SS has slight effect on stability loss at its optimum percentage 100%.

Rutting susceptibility test

The wheel tracking test was performed on specified mixtures based on the Egyptian code [27]. It was conducted on the reference mixture with 100% LD and modified mix with O.SS.C at specified replacement percent of 100% (Comp. Mix.1) to study the effect of SS on the pavement capability to withstand rutting phenomena. Figure 6 shows wheel tracking test machine. A one slab –figure 7- of 33 cm width, 44 cm length and 5 cm thickness according to (LTG 2015) [26]. Figure 8 displays compacted slab after testing. The track depth was registered at uniform periods up to 45 minutes by a gauge with spring less dial. Figure 9 shows the comparison of mixtures results.

Figure 6. Wheel track **machine**

Figure 7. Slab under wheel load

Figure 8. Compacted slab after testing

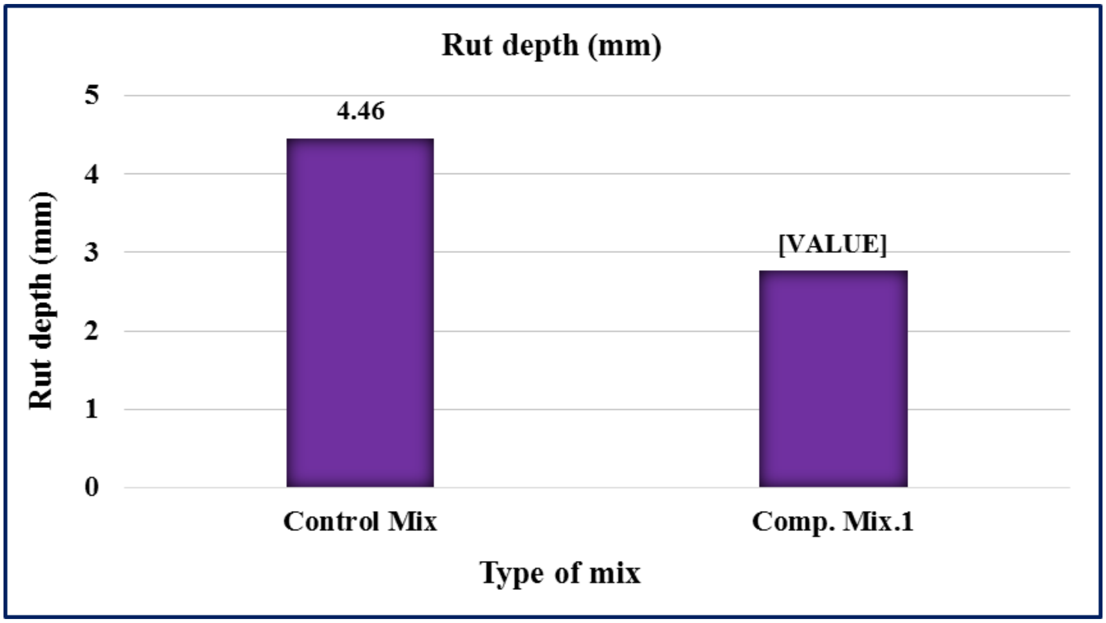

Figure 9. Rut depth of each mixture

Conclusions

Based on experimental work, results for SS modified asphalt mixtures compared with reference asphalt mix, the following points could be concluded:

1. The best percentage of SS to be added as a modifier filler instead of LD was found to be 100% by weight of mineral filler in HMA mixtures.
2. Asphalt mix modified with SS has approximately 15% a higher value of stability compared with the reference asphalt mixture.
3. Asphalt mix modified with SS had the same flow value as the reference asphalt mixture.
4. Using SS in asphalt mixes gives lower percentage of air voids as the SS percentage increased. This decrease in percentage of air voids can explained to be resultant from the smooth gradation of SS material.
5. The stability loss value increase when using SS, but, remains with accepted range (<25%).
6. Using SS in asphalt mixes reduce the rutting depth by about 38% compared with the reference mix.
7. Based on the study results, a proposed mix was prepared with 100% SS by weight of filler. It gave a proper mix property for all properties.

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