Investigation and Performance Improvement of Hot Mix Asphalt Concrete Containing EAF Slag

N. Hosseinzadeh, M. J. Rezaei, and S. M. Hosseini

***Abstract*—Over one million tons of electric arc furnace slag (EAF) wastes per year is produced just in Mobarakeh Steel Company of Isfahan (MSC). According to large number of steel making factories all around the world, in recent years many researches have been done to minimize environmental impacts of these wastes by using them again in production of different materials like recycled structural concrete or hot mix asphalt concrete (HMAC). In this research EAF slag wastes which were produced by Mobarakeh Steel Company (MSC) in Iran, were applied to produce an environmental friendly HMAC. Marshall stability and flow tests, indirect tensile strength test and resistance to moisture damage test were performed on specimens. Results showed that by optimizing combined gradation of HMAC mixtures containing EAF slags as fine aggregate and crushed stone as medium and coarse aggregate a relatively moisture resistant mixture with significant increase in Marshall stability and indirect tensile strength can be gained preserving asphalt cement content in same ratio and flow test result almost the same.**

***Index Terms*—Electric arc furnace slag, asphalt concrete, hot mix, marshall test, indirect tensile strength, moisture damage.**

I. Introduction

The mineral aggregate in hot mix asphalt concrete (HMAC), including fine and coarse aggregate contain almost 90 percent in total volume of the HMAC. These aggregate work like the structural skeleton of the pavement and therefore have a significant influence on properties of pavements [1].

In recent years many researches have been performed to investigate influences of applying different waste materials as aggregate on performance of HMAC. Blast furnace slag and electric arc furnace slag are two of these waste materials which are produced in large amounts by steel making factories all over the world.

Marco Pasetto and Nicola Baldo's in their research in 2009 on application of EAF slags in HMAC tested four HMAC mixtures which two of them contained EAF slag aggregate with maximum size of 15mm and in 2010 tested four HMAC mixtures which three of them contained EAF slags with maximum aggregate size of 10mm. Both experiments have verified that the use of waste material from steel production in the lithic skeleton of asphalts is a technically satisfactory option that fulfils the spirit of the‘‘ Zero Waste ’’target, that the iron and steel industry has been aiming for in the last decade [2], [3].

Perviz Ahmedzadea and Burak Sengoz in 2008 investigated performance of HMAC containing blast furnace slags as coarse aggregate. Results showed that applying blast furnace slag as coarse aggregate, increases Marshall stability and indirect tensile strength of HMAC and decreases flow test results [4].

From the technical viewport as mentioned before these slags possess physical, chemical and mechanical properties of HMAC and also from the ecological viewport, fewer areas are required for storing EAF slags and thus fewer environmental impacts there will be. Less amount of natural aggregate will be used in the road construction because of their replacement with slags and there is also potential risk of groundwater pollution by elution. On the other hand there is economical viewport which considers preparation costs of steel slags, necessity for accurate quality control and stricter environmental protection and decreasing maintenance of the road pavement including steel slags. These considerations are enough to make these slags highly suitable as an alternative replacement for natural aggregate in HMAC [3].

Because of their high resistance to polishing, steel slags including EAF slags are mostly used in surface layers of road pavements [5] however, another application of these slags is in road base and base course layers of flexible pavements which are not in direct contact with the vehicle tires and so the surface roughness of the slag grains contributes mainly to creating high internal friction, which is useful for increasing the mechanical stability of the bituminous mix.

The study described here was aimed at investigating and improving the performance of a wider range of HMAC mixtures containing EAF slag and crushed stone which can be briefed in more varied mixed aggregate gradation checking all possible mix designs. Marshall stability and flow test, indirect tensile strength (ITS) and resistance to moisture damage tests were performed on each specimen and results were compared with the corresponding traditional, natural solutions.

II. Experimental Procedures

A. Materials

60/70 type asphalt cement was used in this study. The asphalt cement was procured from Jey Asphalt Cement Factory in Isfahan. Table I gives a summary of the results for some tests performed on the asphalt cement ordered by our research unit in MSC.

Crushed stone (CS) aggregate was procured from a stone mine near Isfahan and electric arc furnace slag produced in

Manuscript received November 29, 2014; revised February 27, 2015.

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DOI: 10.7763/IJET.2016.V8.895

MSC was used in this research. All aggregate were distributed into three fractions of 0-5mm, 5-12mm and 12-25mm (see Fig. 1). Physical properties of the crushed stone aggregate and the EAF slag aggregate are shown in Table II and Table III. Based on MSC laboratory analysis report, chemical composition of EAF slag is as shown in Table IV. Sieve analysis results for the crushed stone and the EAF slag aggregate are shown in Fig. 2 and Fig. 3.

TABLE I: PHYSICAL PROPERTIES OF THE UTILIZED ASPHALT CEMENT

Properties	Standard	Asphalt cement
Specific gravity (g/cm3) at 25◦C	ASTM D70	1.014
Ductility (cm) at 25◦C	ASTM D113	49.6
Penetration, (0.1mm), 100g, 5s	ASTM D5	60
Softening point (◦C)	ASTM D36	>100
Fire point (◦C)	ASTM D92	298
Kinematic viscosity, 135◦C (μm2/s)	ASTM D2170	280
Penetration index (PI)	-	-0.87
Penetration viscosity number	-	-1.27

TABLE II: PHYSICAL PROPERTIES OF THE CRUSHED STONE AGGREGATE

Properties	Standard	Coarse	Fine
Abrasion loss (%) (Los Angeles)	AASHTO T96	25	-
Specific gravity (g/cm3)	ASTM C-127	2.41	-
Specific gravity (g/cm3)	ASTM C-128	-	2.44

TABLE III: PHYSICAL PROPERTIES OF THE EAF SLAG AGGREGATE

Properties	Standard	Coarse	Fine
Abrasion loss (%) (Los Angeles)	AASHTO T96	19	-
Specific gravity (g/cm3)	ASTM C-127	3.05	-
Specific gravity (g/cm3)	ASTM C-128	-	3.10

B. *Preparation of Samples (Step 1)*

At first step a total of seven combined mixed gradation (Table V) were prepared which each of them had three sub-mixtures involving 3%, 3.5% and 4% asphalt cement content by mass of aggregate resulting in twenty-one different mix designs briefed in Table VI. Combined gradation curves are shown in Fig. 4 and Fig. 5 and are compared with ASTM D2940 master range for base layer [6]. After tests are performed, according to the results, the mix design with the best performance will be investigated more at second step to check if its performance can be improved.

TABLE IV: CHEMICAL PROPERTIES OF EAF SLAG

Compounds	EAF slag utilized (%)
CaO	31.315
SiO2	12.256
Al2O3	2.542
MgO	12.263
FeO	36.948
MnO	0.337
P2O5	0.784
TiO2	1.292
CaO/SiO2	2.555

C. *Marshall Stability and Flow Test*

Marshall stability and flow test was performed using Marshall apparatus (see Fig. 6) on three specimens of each mixture with various bitumen contents and the optimum bitumen content was determined in accordance with ASTM D1559 [7]. Bulk specific gravity was measured in accordance with ASTM D2726 [8].

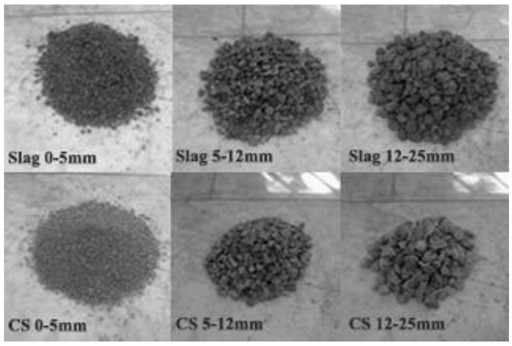

Fig. 1. Physical appearance of aggregate.

TABLE V: MIXED GRADATION AGGREGATE DISTRIBUTION

Aggregate	M1	M2	M3	M4	M5	M6	M7
Crushed Stone 0-5			●		●	●	●
Crushed Stone 5-12		●		●	●	●	
Crushed Stone 12-25		●				●	●
SLAG 0-5	●	●		●			
SLAG 5-12	●		●	●			●
SLAG 12-25	●		●		●		
All mix designs involve 3%, 3.5% and 4% asphalt cement content by mass of aggregate							

TABLE VI: COMBINED GRADATION SIEVE ANALYSIS

Sieve No.	M1	M2	M3	M4	M5	M6	M7
1	100.0	100.0	100.0	100.0	100.0	100.0	100.0
3/4-in.	97.2	98.1	95.1	92.5	91.7	91.0	94.9
1/2-in.	87.8	85.9	85.7	80.7	77.7	80.0	79.9
3/8-in.	73.3	67.8	75.7	74.6	64.3	66.3	72.1
No.4	48.0	56.3	61.0	52.5	48.9	56.8	57.3
No.8	18.9	35.1	40.2	32.3	24.2	37.5	34.6
No.16	0.0	0.0	0.0	0.0	0.0	0.0	0.0
No.30	0.0	0.0	0.0	0.0	0.0	0.0	0.0
No.50	5.4	8.8	11.5	12.0	7.5	9.7	8.6
No.100	0.0	0.0	0.0	0.0	0.0	0.0	0.0
No.200	1.1	2.2	2.7	1.0	1.7	1.9	0.8
Pan	0.0	0.0	0.0	0.0	0.0	0.0	0.0

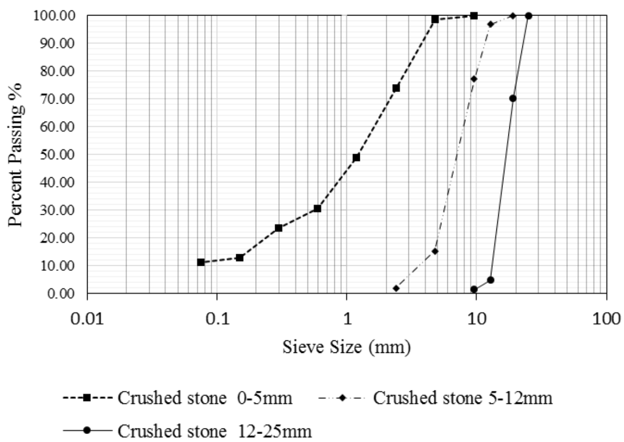

Fig. 2. Gradation curves for the crushed stone aggregate.

D. *Calculation of Marshall Quotient*

The Marshall quotient (MQ) (kN/mm) can be calculated as the ratio of stability (kN) to flow (mm) and is used as a measure of the material's resistance to permanent deformation in service. A higher value of MQ indicates a stiffer mixture and indicates that the mixture is likely more resistant [9].

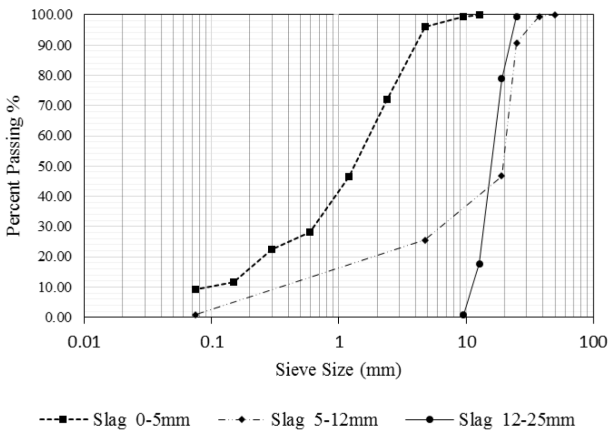

Fig. 3. Gradation curves for the EAF slag aggregate.

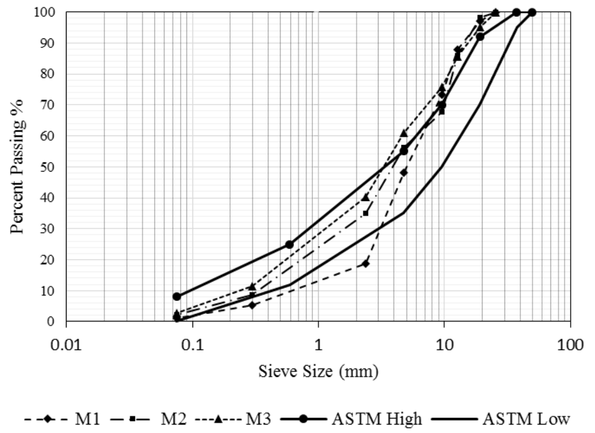

Fig. 4. Mixed gradation curves for M1, M2 and M3.

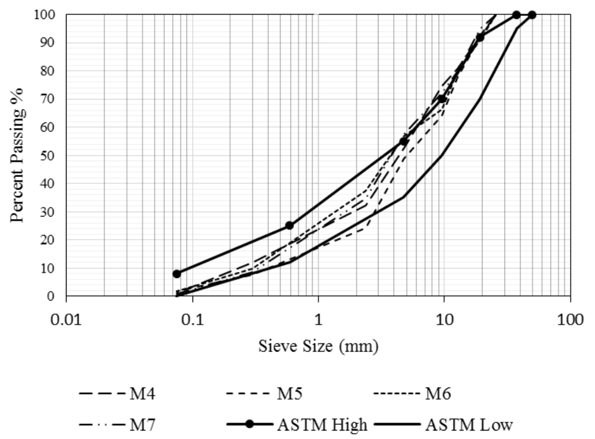

Fig. 5. Mixed gradation curves for M4, M5, M6 and M7.

E. Indirect Tensile Strength Test

Indirect tensile strength (ITS) test was performed according to ASTM D6931 on prepared specimens. ITS can be calculated using (1). Where P_{max} is the maximum applied load (kN), t is thickness of the specimen (mm), d is diameter of the specimen (mm) [10].

$$ITS = \frac{2P_{\max}}{\pi td} \qquad (1)$$

Fig. 6. The Marshall Test apparatus used in this research.

F. Resistance to Moisture Damage

The moisture susceptibility of asphalt mixtures was evaluated according to AASHTO T283 test [11]. Three more specimens from each mixture were prepared be conditioned by saturating with water (55–80% saturation level) followed by a freeze cycle (−18 ◦C for 16 h) and subsequently having a warm-water soaking cycle (60 ◦C water bath for 24 h). The specimens are then tested for ITS. Tensile strength ratio (TSR) is calculated according to (2). Where ITS_{wet} and ITS_{dry} are indirect tensile strength of specimens treated in water and untreated.

$$TSR = \frac{ITS_{wet}}{ITS_{dry}} \qquad (2)$$

III. Results and Discussion

A. Marshall Stability and Flow Test Results

Table. VII illustrates average results of three specimens for twenty-one HMAC mixtures. According to the results M2 mixture containing 0-5mm slag aggregate mixed with 5-12mm and 12-25mm crushed stone, M3 mixture containing 0-5mm crushed stone aggregate mixed with 5-12mm and 12-25mm slag aggregate and also M6 mixture containing 0-5mm, 5-12mm and 12-25 crushed stone aggregate had a qualified performance in Marshall test but affected by flow test results M2 mixture had a better total performance according to calculated MQ.

B. Indirect Tensile Strength Test Results

Results of Indirect tensile strength test for all mixtures are shown in Table VIII. According to test results M2 and M6 mixtures having 3% asphalt cement content by mass of aggregate had ITS of 1274 kN and 1210 kN resulting in best performance among all mixtures.

C. Resistance to Moisture Damage Test Results

Indirect tensile strength test was performed on water treated specimens of all mixtures. Then TSR was calculated according to (2). Results are shown in Table VIII.

Mixtures with tensile strength ratios less than 0.7 are moisture susceptible and mixtures with ratios greater than 0.7 are relatively resistant to moisture damage [12]. Based on results achieved by performed ITS tests, calculated TSR for all mixtures is in a range between 0.62 and 0.71. Like Marshall and ITS test results M2 mixture had a greater resistance to moisture damage resulting in a tensile strength ratio equal to 0.71.

TABLE VII: MARSHAL STABILITY AND FLOW TEST AND MQ RESULTS

Mix	Asphalt cement (%)	Mix bulk specific gravity (g/cm^3)	Marshal stability (kN)	Flow (mm)	MQ (kN/mm)
M1	3	2.7	14.18	2.9	4.9
	3.5	2.7	16.02	2.9	5.5
	4	2.71	13.78	3.8	3.6
M2	3	2.55	26.44	3.1	8.5
	3.5	2.57	22.27	4.0	5.6
	4	2.58	20.90	4.5	4.6
M3	3	2.65	19.62	3.2	6.1
	3.5	2.66	21.88	4.5	4.9
	4	2.68	17.76	3.3	5.4
M4	3	2.64	12.26	2.9	4.2
	3.5	2.65	15.21	3.0	5.1
	4	2.65	11.67	3.2	3.6
M5	3	2.57	12.36	2.8	4.4
	3.5	2.59	15.25	3.0	5.1
	4	2.58	11.72	3.2	3.7
M6	3	2.53	22.76	4.0	5.7
	3.5	2.55	19.82	4.2	4.7
	4	2.55	18.74	3.9	4.8
M7	3	2.56	18.44	4.1	4.5
	3.5	2.53	21.78	2.8	7.8
	4	2.54	17.17	4.0	4.3

TABLE VIII: INDIRECT TENSILE STRENGTH TEST RESULTS

Mix	Asphalt cement (%)	ITS_{dry} (kPa)	ITSwet (kPa)	TSR (-)
M1	3	1108	687	0.62
	3.5	1129	745	0.66
	4	1084	683	0.63
M2	3	1274	905	0.71
	3.5	1203	830	0.69
	4	1186	806	0.68
M3	3	1174	763	0.65
	3.5	1198	791	0.66
	4	1145	744	0.65
M4	3	1067	704	0.66
	3.5	1120	773	0.69
	4	1052	684	0.65
M5	3	1065	714	0.67
	3.5	1124	776	0.69
	4	1058	698	0.66
M6	3	1210	835	0.69
	3.5	1171	796	0.68
	4	1160	754	0.65
M7	3	1166	781	0.67
	3.5	1192	811	0.68
	4	1141	764	0.67

D. Optimization (Step 2)

According to Marshal stability and flow test results, M2 mixture containing 3% asphalt cement content, crushed stone as medium and coarse aggregate and EAF slag as fine aggregate had maximum Marshall stability of 26.44 kN and flow of 3.1 mm which results in MQ of 8.5 kN/mm. Based on ITS test results it had the maximum tensile strength equal to 1274 kPa and was relatively resistant to moisture damage which offers a high performance asphalt concrete. Therefore, it was chosen for optimization.

Improvements in combined gradation was done and new mix design was titled MO2 satisfying ASTM D2940 master range (see Fig. 7). Samples involving 2.5%, 3%, 3.5%, 4%, 4.5% and 5% asphalt cement content by mass of aggregate were prepared and same tests were performed on each of them. Results are shown in Table IX and Table X.

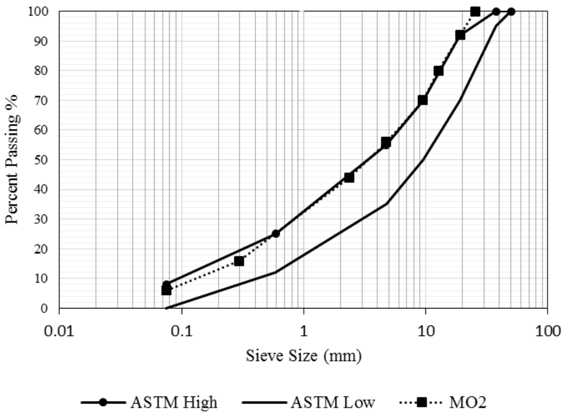

Fig. 7. Optimized combined gradation curve for M2.

E. Discussion on Final Results

As expected before performing tests on MO2 optimized mixture, the prepared HMAC performance was increased significantly. In order to have a better judgment about Marshall test results refer to Fig. 8 and Fig. 9.

TABLE IX: OPTIMIZED MARSHAL STABILITY AND FLOW TEST RESULTS

Mix	Asphalt cement (%)	Mix bulk specific gravity (g/cm^3)	Marshal stability (kN)	Flow (mm)	MQ (kN/mm)
MO2	2.5	2.55	28.55	2.8	10.4
	3	2.56	31.39	3.1	10.1
	3.5	2.55	30.41	3.4	8.9
	4	2.57	27.47	3.7	7.5
	4.5	2.57	24.62	3.9	6.4
	5	2.59	21.58	4.1	5.3

TABLE X: OPTIMIZED INDIRECT TENSILE STRENGTH TEST RESULTS

Mix	Asphalt cement (%)	ITS_{dry} (kPa)	ITSwet (kPa)	TSR (-)
MO2	2.5	1311	918	0.70
	3	1352	1041	0.77
	3.5	1333	960	0.72
	4	1292	918	0.71
	4.5	1234	851	0.69
	5	1196	837	0.70

Optimized results proved that by improving mixed gradation it's possible to increase Marshall stability of HMAC by 19 percent preserving flow results in same value which provides a significant MQ increase. Indirect tensile strength was increased by 6 percent and TSR for all asphalt contents was in a range between 0.69 and 0.77.

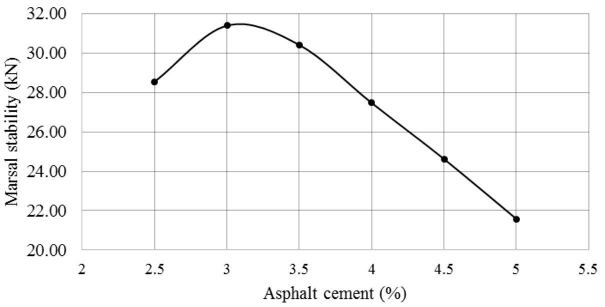

Fig. 8. Marshal stability test results for optimized gradation.

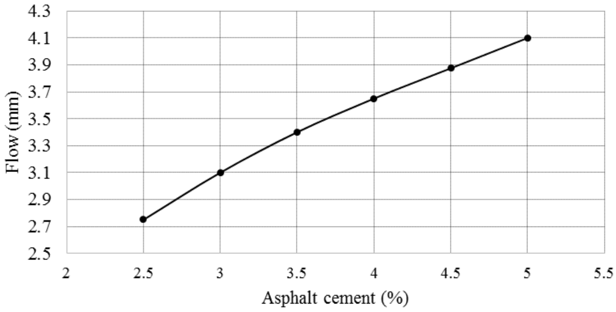

Fig. 9. Flow test results for optimized gradation.

IV. Conclusion

Based on the results and laboratory experiences of this progress, following conclusions can be drawn:

1) HMAC with qualified performance can be prepared using electric arc furnace slags manufactured in MSC decreasing their influences on environment.
2) Using 0-5mm EAF slags in mixed gradation of HAMC improves their Marshall Stability.
3) A significant decrease of Marshall Stability was observed in HMAC mixtures containing EAF slag as 100% of their aggregate.
4) HMAC mixtures containing 0-5mm EAF slag aggregate in their mixed gradation are relatively resistant to moisture damage.
5) HMAC mixtures containing 0-5mm EAF slag aggregate have greater Marshall quotient than other tested mixtures.
6) Indirect tensile strength of dry specimens for tested mixtures wasn't majorly affected by EAF slag presence according to comparison of mixtures containing EAF slag as all of their aggregate and mixtures containing crushed stone.
7) According to results, by optimizing mixed gradation of mixtures containing 0-5mm EAF slag as their fine aggregate significant improvements in properties of HMAC like Marshall stability, Indirect tensile strength and resistance to moisture damage was observed.

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