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Effect of Blast Furnace Iron Slag on the Mechanical Performance of Hot Mix Asphalt (HMA)

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***Abstract*—**This paper discusses the effect of using blast furnace iron slag as a part of fine aggregate on the mechanical performance of hot mix asphalt (HMA). The mechanical performance was evaluated based on various mechanical properties that include; Marshall/stiffness, indirect tensile strength and unconfined compressive strength. The effect of iron slag content on the mechanical properties of the mixtures was also investigated. Four HMA with various iron slag contents, namely; 0%, 5%, 10% and 15% by weight of total mixture were studied. Laboratory testing has revealed an enhancement in the compressive strength of HMA when iron slag was used. Within the tested range of iron slag content, a considerable increase in the compressive strength of the mixtures was observed with the increase of slag content. No significant improvement on Marshall/stiffness and indirect tensile strength of the mixtures was observed when slag was used. Even so, blast furnace iron slag can still be used in asphalt paving for environmental advantages.

***Keywords*—**Blast furnace iron slag, HMA, Marshall/stiffness, indirect tensile strength, compressive strength.

I. Introduction

WASTE material recycling into useful products has become a main solution to waste disposal problems. Many highway agencies are conducting wide variety of studies and research projects concerning the feasibility, environmental suitability, and performance of using recycled products in highway construction [1]. These studies try to match society's need for safe and economic disposal of waste materials with the highway industry's need for better and more cost-effective construction materials. Blast furnace iron slag is an industrial byproduct of iron produced in a blast furnace. This slag consists primarily of constituent of the iron ore mixed with the silicates and aluminosilicates of lime and other bases [2]. Improper disposal of slag has become a serious environmental problem. Therefore, iron slag has been used extensively around the world as; railway ballast, tricking filter bed media, pipe bedding, water course protection, land reclamation, bulk fill embankments and gabion stone [3].

Recently, many environmental and highway agencies has considered using iron slag in highway construction [4]-[5]. It is mainly used as a good sub-base material because it is free draining granular material which has an excellent internal friction as well as good compact ability [6]. Also because of its very low water absorption it will not “pump” either from high water tables or from inclement weather [7]. Iron slag was proven to have many advantages over natural aggregates such as having a higher value of soundness, strength, and abrasion resistance. It also has a high resistance to crushing and polishing under traffic [8].

Very little research work has been done to test the possibility of using iron slag in HMA as a replacement of coarse and fine aggregates. Since slag has a good friction resistance property it can provide an excellent skid resistance asphalt concrete layer surface. The current study is performed to study the effect of using blast furnace iron slag in HMA as a part of the fine aggregate. The effect of iron slag content on the mechanical properties of HMA was also evaluated. A laboratory study was conducted on four asphalt mixtures with various iron slag contents, namely; 0%, 5%, 10% and 15% by weight of total mix. Mechanical testing used includes; Marshall stiffness, indirect tensile strength and unconfined compressive strength.

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II. Material Characterization

A. Asphalt Binder

Asphalt binder 60/70 supplied by Suez Bitumen Supply Company was used within this research. The used asphalt binder was subjected to a series of standard laboratory tests to determine its physical properties. Results of those tests are shown in Table I.

TABLE I
PROPERTIES OF USED ASPHALT BINDER

Test	Results
Penetration at 25 Co	68
Kinematics Viscosity (centistokes at135 C o)	430
Ring and Ball softening Point	51.5 Co
Specific gravity	1.03
Flash Point	275 Co

B. Aggregate

Coarse aggregate and fine aggregate (Bulk specific gravity of 2.77 and 2.68 respectively) were used in the preparation of the HMA. Limestone was used as mineral filler. The selected gradation of aggregate incorporated in all asphalt concrete specimens confirms to the mid point of the standard 4-c aggregate gradation specified in the Egyptian highway standard specifications. Table II presents the selected mix gradation (including iron Slag).

C. Iron slag

Blast furnace iron slag was crushed and screened to produce aggregate that satisfies the gradation requirements for hot mix asphalt.

D. Physical Properties of Used Iron Slag

Physical properties (Specific Gravity, Unit Weight and Absorption) of the used iron slag are given in Table III.

TABLE II
SELECTED MIX GRADATION

Sieve	% Passing	
	Used Gradation	Gradation Limits [Egyptian Specs. (4 C)]
1	100	100
¾	100	80-100
3/8	79	60-80
3/16	50	48-65
N0.10	45	35-50
N0.30	24	19-30
50	22	13-23
100	9	7-15
200	6	3-8

TABLE III
PHYSICAL PROPERTIES OF USED IRON SLAG

Property	Value
Specific Gravity	3.4
Unit Weight, kg/m3	1800
Absorption	2%

TABLE IV
CHEMICAL PROPERTIES OF USED IRON SLAG

Constituent	Composition (%)
CaO	45
SiO2	15
FeO	25
MnO	7
MgO	5
Al2O3	2
P2O5	1

TABLE V
MECHANICAL PROPERTIES OF USED IRON SLAG

Property	Value
Los Angeles Abrasion (%)	20
Sodium Sulfate Soundness Loss (%)	8
Angle of Internal Friction	45°
California Bearing Ratio (CBR)(%)	200

E. Chemical Properties of Used Iron Slag

Table IV lists the range of compounds present in iron slag from a typical base oxygen furnace.

F. Mechanical Properties of Used Iron Slag

Table V presents the mechanical properties of the used iron slag. As seen, iron slag has favorable mechanical properties for aggregate use, including good abrasion resistance, good soundness characteristics, and high bearing strength.

III. EXPERIMENTAL PROCEDURE

A. Sample Preparation

Constant asphalt ratio of 5% was used for all mixtures. Iron slag that is used as apart of fine aggregate is blended with the natural aggregate to obtain a uniform iron slag/natural aggregate mix before mixing with the asphalt binder. Four HMA with various iron slag contents, namely; 0%, 5%, 10% and 15% by weight of total mixture were prepared in accordance with the Standard 75-blow Marshall design method for designing hot HMA, designated as (ASTM Designation: D 1559-89) [9] using automatic compaction. To provide adequate data three samples were prepared from each mixture for each test.

B. Marshall Stiffness Test

The Marshall stability test (*ASTM Designation: D 1559-82*), which is one of the most common tests, is used in highway engineering for both mix design and evaluation. Although Marshall method is essentially empirical, it is useful in comparing mixtures under specific conditions. Therefore, it was selected within this research to study the affect of iron slag when added to HMA. Maximum value of Marshall stability was divided by the corresponding flow for each mix to determine Marshall Stiffness value.

C. Indirect Tensile Strength Test

A mechanical displacement control testing frame was used to conduct the indirect tensile tests in accordance with (ASTM D4123) to evaluate the tensile strength of HMA. Test specimens 2.5 inches thick and 4 inches diameter were compacted and then tested using curved steel loading strips 0.5 inch wide. The load was applied at a vertical deformation rate of 4 mm/min. The indirect tensile strength is the maximum stress developed at the center of the specimen in the radial direction during loading. Two diametrically opposite dial gauges were attached to each specimen at its longitudinal mid-point to measure the diametral (tensile) deformation resulting from the applied loading in an orthogonal direction.

D. Unconfined Compressive Strength Test

The unconfined compression tests were performed using a 15-ton capacity universal testing machine. Test specimens 2.5 inches thick and 4 inches diameter were placed on the lower fixed platen of the testing machine. Load was applied with a uniform rate of 2 mm/min on the circular face of the testing samples until failure occurred. The maximum load to failure was recorded and hence the compressive strength was calculated.

IV. RESULTS AND DISCUSSION

A. Marshall/Stiffness Factor

The results of all Marshall Stability tests using a constant asphalt ratio of 5% are summarized in Table VI for mixtures with different iron slag content. All results shown for each specimen are the average value for three tests.

It is indicated from Table VII that Marshall stiffness value slightly increases as the iron slag content increases up to iron slag content of 10% and then it slightly decreases. It is noticed from Fig. 1, that the values of stiffness factor for the four mixtures are very close to each other and the maximum difference between them is in the range of 5%. Thus, it can be concluded that there is no obvious change in Marshall stiffness factor of the mixtures when iron slag were added. It can be also concluded that Marshall/stiffness is not significantly sensitive to iron slag content.

TABLE VI
MARSHALL STABILITY TEST RESULTS FOR MIXTURES WITH DIFFERENT IRON SLAG CONTENT

Iron Slag Content % of Total Mix	Iron Slag Content % of Fine Agg.	Stability (lbs)	Flow (0.01 inch)	Marshall Stiffness (psi)
0 %	0 %	1612	8	2010
5 %	12.5 %	1643	8	2050
10 %	25 %	1788	8.5	2100
15 %	37.5 %	1872	9	2080

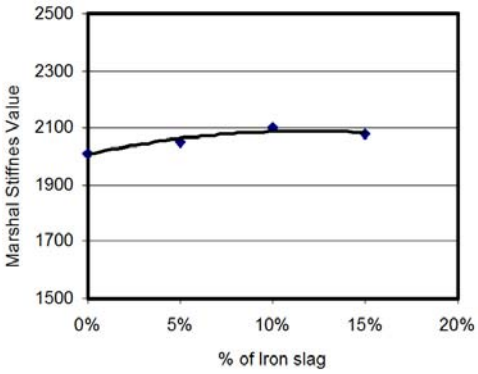

Fig. 1 Marshall/Stiffness of Mixtures with Different Iron slag Content

B. Indirect Tensile Strength

The indirect tensile test was developed to determine the tensile properties of cylindrical concrete and asphalt concrete specimens through the application of a compression load along a diametrical plane through two opposite loading heads. It was shown [10] that this type of loading produces a relatively uniform stress acting perpendicular to the applied load plane, causing the specimen to fail by splitting along the loaded plane. The expression for the maximum tensile strength can be stated as;

$$\sigma_t = \frac{2\,P_{max}}{\pi DH} \quad (1)$$

where σ_t is the indirect tensile strength, P_{max} is the maximum applied load and H, D are the thickness and the diameter of the specimen respectively.

The indirect tensile strength test was performed on three samples from each mixture. Values of indirect tensile strength are calculated based on (1). It is evident from Table VII that the indirect tensile strength of the iron slag mixtures is almost close to that for mixture without iron slag.

Fig. 2 also presents the relation between indirect tensile strength and iron slag content. It is indicated that the indirect tensile strength of the mixtures slightly increases as the slag cont increases. The maximum difference in indirect tensile strength of the mixtures is in the range of 7% which is considered a very low percent. Thus, it can be stated that the increase in the indirect tensile strength is not significant with the increase in slag content and hence it can be concluded the indirect tensile strength is not sensitive to slag content.

TABLE VII
FAILURE TENSILE LOAD AND INDIRECT TENSILE STRENGTH MIXTURES WITH DIFFERENT IRON SLAG CONTENT

Iron Slag Content % of Total Mix	Iron Slag Content % of Fine Agg.	Indirect Tensile Strength (psi)
0 %	0 %	24.06
5 %	12.5 %	25.40
10 %	25 %	25.91
15 %	37.5 %	26.74

C. Unconfined Compressive Strength

The unconfined compressive strength test was performed to determine the compressive properties of the four studied mixtures. A compression load is applied on the circular face of the circular specimens. The load is increased until failure occurs. The compressive strength can be calculated using the following expression;

$$\sigma_c = \frac{4P_{max}}{\pi D^2} \quad (2)$$

where σ_c is the Unconfined Compressive Strength, P_{max} is the maximum applied compressive load and, D is the diameter of the specimen.

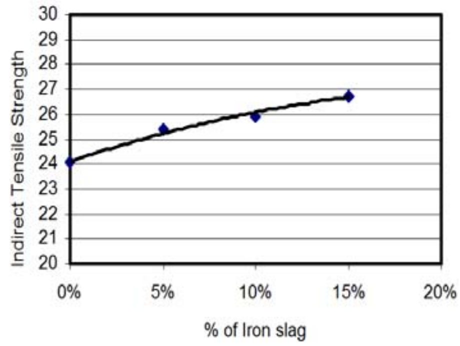

Fig. 2 Indirect Tensile Strength of Mixtures for Different Iron slag Content

TABLE VIII
FAILURE COMPRESSIVE LOAD AND UNCONFINED COMPRESSIVE STRENGTH FOR MIXTURES WITH DIFFERENT IRON SLAG CONTENT

Iron Slag Content %of Total Mix	Iron Slag Content % of Fine Agg	Unconfined Compressive Strength (psi)
0 %	0 %	155
5 %	12.5 %	191
10 %	25 %	201
15 %	37.5 %	249

The average unconfined compressive strength for various mixtures is calculated based on (3) and listed in Table VIII.

As seen in Table VIII, the compressive strength of HMA increases as the iron slag content increases. The mean compressive strength of the 15% iron slag mixture was determined to be almost 1.6 times that of the control mixture (0% iron slag). Fig. 3 presents the relation between compressive strength and iron slag content. The figure indicates that the as the iron slag content increases the compressive strength increases with a higher than that of the indirect tensile strength. Thus, it can be concluded that, using iron slag enhances the compressive strength characteristics of HMA. *This* can be attributed to the high frictional resistance of the mixture due to the angular shape and high friction angle (40° to 45°) of crushed iron slag.

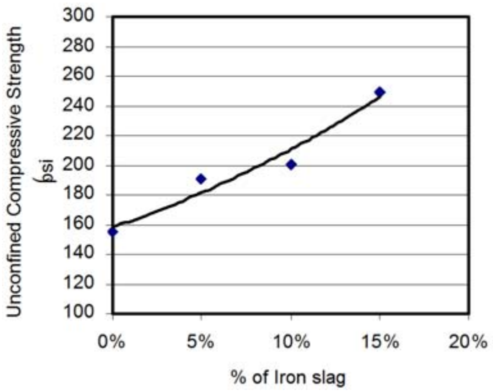

Fig. 3 Unconfined Compressive Strength of Mixtures with Different Iron Slag Content

V. Conclusion and Recommendations

Results of mechanical properties evaluation of HMA have revealed an enhancement in their compressive strength when blast furnace iron slag was used in the mixtures as a part of fine aggregate. Within the tested iron slag content range (0% - 15% of total mixture), the compressive strength increases with the increase of iron slag content. Further investigation is needed to test HMA with iron slag content higher than 15%. No significant improvement on Marshall/stiffness and indirect tensile strength of the mixtures was observed when iron slag was used. Nevertheless, blast furnace iron slag can still be used in HMA for environmental aspects. Before widely adapting iron slag in asphalt paving, trial sections and adequate provisions should be provided.

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