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Laboratory Investigation to Evaluate the Effect of Electric Arc Furnace Dust (EAFD) on Properties of Asphalt Concrete

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Abstract

One of the hazardous by-products of steelmaking industry is the electric arc furnace dust EAFD. It has been estimated that per each ton of produced steel there are about 15-20 kg of EAFD. Due to containing heavy metals such as Zinc, Cobalt, Copper, Lead or Cadmium, this dust has been classified as hazardous, and therefore it should be treated appropriately to protect the environment. Solidification/stabilization was used in this study to treat this hazardous dust. One type of asphalt cement and one type of aggregate were used in this study. EAFD was used as an additive to the asphalt cement with five contents (5%, 10%, 15% and 20%) by volume of binder. Marshall specimens were prepared using the five concentrations of this material. Marshall stability, flow, unit weight, voids in mineral aggregate (VMA), air voids, voids filled with binder (VFB), and stiffness of asphalt concrete mixtures were analyzed. Test results show that stability, unit weight, voids filled with bitumen (VFB) and stiffness increase then decrease with the increasing % EAFD in the asphalt concrete mixtures. Flow increases with the increasing of % EAFD in the asphalt concrete mixtures while VMA and air voids decrease then increase with the increasing % EAFD in the asphalt concrete mixtures. A 5% EAFD content by volume of binder is found to meet the criteria of Marshall properties of asphalt mixtures. Finally it has been concluded that the results are promising for dual achievement (1) to solve an environmental problem and (2) to use the dust for road construction.

Keywords: electric arc furnace, asphalt cement, road construction, Marshall test, binder properties, asphalt concrete, stiffness

1. Introduction

The process of steelmaking by the electric furnace consists of 5 main steps, these are: (1) loading the scrap iron and additives to the furnace, (2) melting the scrap using an electric arc forming a steel path covered by slag layer, (3) refining to remove phosphorous and other dissolved gases, (4) Slag foaming caused by CO-bubbles crossing the slag layer and (5) casting of steel. During the process the fumes are extracted, post-combusted and cooled forming the electric arc furnace dust EAFD (Guezennec et al., 2005). It is estimated that 15-20 kg of EAFD are formed for each ton of steel produced (Nestor & Borja, 2003).

This EAFD is classified according to the European Waste Catalogue (EWC, 2002) and the Environmental Protection Agency as a hazardous waste, not disposable in the environment, because they can release pollutants to the environment such as zinc, lead or cadmium (Guezennec et al., 2005; Cubukcouglu & Ouki, 2009; Pavao,Vargas, Masuero, Mlin, & Vilela, 2009; Hollagh, Alamdry, Moradkhani, & Salardini, 2013; Ruiz, Clemenete, Alonso, & Alguacil, 2007; Alsheyab & Khedaywi, 2013)

For a sustainable use of natural resources and environmental protection, steelmaking industrial by products such as slag and EAFD must be utilized as secondary resources when possible. An example on that is the use of steel slag in road construction or asphalt binder (Jones, 2001; Miklos, 2001; Ye, Burström, & Fällman, 1995).

On one hand, the increasing demand on steelmaking industry and consequently the increasing amounts of EAFD byproduct, and on the other hand, the strict environmental regulations, makes the treatment of EAFD a challenging issue. One of the most economic and practical technologies to treat different types of hazardous waste is the solidification/stabilization (S/S) (Barth, 1990; Cubukcouglu & Ouki, 2012).

According to EPA definition (EPA, 1997; Portland Cement Association, 1991), Solidification refers to processes that encapsulate a waste to form a solid material and to restrict contaminant migration by decreasing the surface area exposed to leaching and/or by coating the waste with low-permeability materials. Solidification can be accomplished by a chemical reaction between a waste and binding (solidifying) reagents or by mechanical processes. Solidification of fine waste particles is referred to as microencapsulation, while solidification of a large block or container of waste is referred to as macroencapsulation, and stabilization refers to processes that involve chemical reactions that reduce the leachability of a waste. Stabilization chemically immobilizes hazardous materials or reduces their solubility through a chemical reaction. The physical nature of the waste may or may not be changed by this process. Many materials can be used as a binder in S/S; organic binders include asphalt, organophilic clay, or activated carbon; and inorganic binders that may include cement, fly ash, lime, phosphate, soluble silicates, or sulfur. This study will focus on using asphalt as the binding agent (Alsheyab & Khedaywi, 2013).

There are about 13 steelmaking factories in Jordan and United Iron and Steel Manufacturing Company was chosen as a case study for this research. In this factory, for each ton of steel produced, the amount of EAFD is about 25-30 kg. The produced amounts of EAFD byproduct is collected and stored underground without any treatment. This could be a potential risk for the aquifers of the surrounding area, especially that Jordan is one of poorest countries in water resources. This situation was the driving force for us to investigate an appropriate solution.

In previous study, the authors of this research studied the effect of electric arc furnace dust (EAFD) on properties of asphalt cement mixture (Alsheyab & Khedaywi, 2013). A continuation to their previous study, the authors conducted a laboratory investigation to evaluate the effect of EAFD on properties of asphalt concrete. The objectives of this research are as follows: (i) To investigate the feasibility of using the EAFD as an additive to asphalt concrete mixtures. (ii) To analyze the effect of this EAFD on the properties of asphalt concrete mixtures. (iii) To determine the optimum EAFD that should be added to asphalt cement to give the best properties of asphalt concrete mixtures. (iv) To check the applicability of the EAFD – asphalt mixture for road construction; surface treatments for roads, airfields and other trafficked areas.

2. Material Used

The materials used in the research are:

2.1 Aggregate

One type of limestone aggregate was used, which was brought from Al-Halabat queries in the northeast part of Jordan. Gradation type was used according to the Ministry of Public Works and Housing (MPWH) specifications in Jordan. Table 1 shows the aggregate gradation. Table 2 presents aggregate properties used in this research.

Table 1. Aggregate gradation used in the mixtures

Sieve size	Specification limits* (% Passing)	% Passing (midpoint)
1" (25mm)	100	100
¾" (19mm)	90-100	95.0
½" (12.5mm)	71-90	80.5
3/8" (9.5mm)	56-80	68.0
No.4 (4.75mm)	35-65	50.0
No.8 (2.35mm)	23-49	36.0
No.20 (850μm)	14-43	28.5
No.50 (300μm)	5-19	12.0
No.80 (180μm)	4-15	9.5
No. 200 (75μm)	2-8	5.0

* Ministry of Public Works and Housing (MPWH) specification wearing mix.

Table 2. Aggregate properties used in the research

Aggregate type (Limestone)	ASTM test Designation	Bulk specific Gravity	Apparent specific Gravity	Absorption (%)
Coarse	C127	2.523	2.660	2.03
Fine	C128	2.488	2.702	3.89
Mineral filler	C128	2.65	2.788	4.20

2.2 Asphalt Cement

One penetration grade of asphalt cement (60-70) decimillimeter was used in this study. Asphalt was obtained from the Jordan Petroleum Refinery Company in Zerqa/Jordan, and it is widely used in flexible pavement construction. Table 3 presents the physical properties of this asphalt.

Table 3. Physical properties of asphalt

Properties	Methods	Test Result
Penetration (0.1 mm), 25^{o}C,100 g, 5 sec	ASTM D 5	65
Ductility (cm) at 25^{o}C	ASTM D 113	108
Specific gravity at 25^{o}C	ASTM D 70	1.010
Softening point (^{o}C)	ASTM D 36	50.3
Flash Point (^{o}C)	ASTM D 92	312.5
Fire Point (^{o}C)	ASTM D 92	318

2.3 Electric Arc Furnace Dust

EAFD was provided by United Iron and Steel Manufacturing Company in Jordan and it was characterized at the laboratories of the Royal Scientific Society in Jordan. The results of analysis are summarized in Table 4, where it shows that the major components are ferric oxide (Fe_2O_3 = 32%) and zinc oxide (ZnO = 29%). All samples of EAFD used in this research were passing No. 200 sieve.

Table 4. EAFD characterization (weight %)

Compound	Percentage
Fe_2O_3	32
ZnO	29
Al_2O_3	1.28
Cu_2O	0.7
SiO_2	4
Loss on ignition at 1000 °C	11.63
$CaSO_4$	3.43
$CaCl_2$	1.91
CaO	1.4
NaCl	5.79
K_2O	2.7
MgO	4.66
Others	1.5

3. Laboratory Work

3.1 Preparation of EAFD - Asphalt Binder

It has been decided to study different volume percentages of EAFD – asphalt binder. The studied percentages are: 5, 10, 15 and 20% of EAFD by volume of binder. It has been realized that percentages of EAFD more than 20% were difficult to mix with asphalt. For each experiment, the corresponding weight to each volume percentage for both the asphalt and EAFD was prepared. The asphalt was heated while adding the corresponding volume of EAFD with mixing to guarantee a homogeneous mixture for each experiment. Mixtures were left to cool down to ambient temperature to be ready for mixing with aggregate. At the end of the mixing operation, the EAFD asphalt binder was mixed with the heated aggregate to prepare EAFD asphalt concrete specimens.

3.2 Determination the Optimum Asphalt Content for Conventional Mixes

To determine the optimum asphalt content by weight of total mix, Marshall mix design procedure (ASTM D1559) was followed as a part of this study (Asphalt Institute, 2008). Three specimens at each asphalt content (4.0, 4.5, 5.0, 5.5, and 6.0%) were tested for stability, flow, air voids, unit weight, and voids in mineral aggregate.

The optimum asphalt content, which was the average of asphalt contents that meet optimum stability, maximum unit weight, and 4% air voids, was determined. The value of the optimum asphalt content found to be 5.4% by total weight of asphalt concrete mixture.

To determine the optimum asphalt content for the mixture, the procedure indicated by the standard American Institute MS - 2 Manual (Asphalt Institute, MS - 2, 1988) and ASTM D1559 was followed.

1) Aggregate was washed, dried, and sieved according to MPWH specifications. Approximately 1,200 gm of aggregate was taken to prepare Marshall specimen. The aggregate was heated to 149°C (300°F) for 24 hours in an oven.

2) Molds and collars were heated to 149°C (300°F) for 24 hours in an oven.

3) The asphalt was heated to 149°C (300°F) for one hour.

4) The hot aggregate and hot asphalt were mixed until full coating is achieved.

5) The prepared mixture was placed in a Marshall mold.

6) Each specimen was compacted 50 blows on each face to represent a medium traffic.

7) Three samples from each asphalt level (4.0, 4.5, 5.0, 5.5, and 6.0%) of the total weight of the mix were prepared.

8) Specimens were extruded from the Marshall molds after 24 hours. Height and weight measurements were conducted to determine unit weight of each specimen.

9) Specimens were submerged in water at 60°C for 40 minutes before testing.

10) Specimens were tested by using Marshall apparatus to determine stability, and flow values.

The optimum asphalt content was found to be 5.4% by total weight of mixture.

3.3 Measurement the Marshall Properties of Asphalt – EAFD Concrete Mixes

To determine the Marshall properties of the asphalt – EAFD concrete, the Marshall test method procedure was used to prepare specimens for the EAFD content of 0, 5, 10, 15, and 20% by volume of binder. All of tests specimens were tested for Marshall stability, flow, unit weight, voids in mineral aggregate, air voids, voids filled with binder and Marshall stiffness. The tests were conducted according to Asphalt Institute Manual, MS - 2, (1988) and ASTM D1559.

4. Test Results and Discussion

4.1 Effect of EAFD on Marshall Stability

Figure 1 shows the effect of EAFD on Marshall stability of asphalt concrete mixtures for each EAFD concentration. Figure 1 shows that the Marshall stability increases then decreases with the increasing of percentages EAFD in the binder.

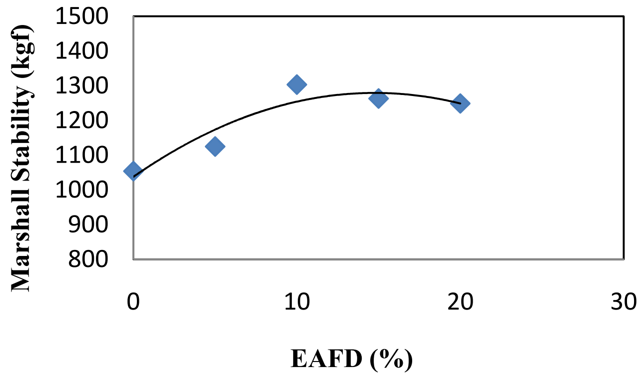

Figure 1. Relationship between Percent EAFD and Marshall stability

Based on the data given in Figure 1, the following equation was developed:

$$Y_1 = -1.1086x^2 + 32.731x + 1037.8 \quad (R^2 = 0.8797) \tag{1}$$

Where

Y_1 = Marshall stability of asphalt concrete mixtures.

x = % of EAFD by volume of binder.

4.2 Effect of EAFD on Flow

Figure 2 shows the effect of EAFD on Marshall flow of asphalt concrete mixtures for each EAFD concentration. Figure 2 shows that the Marshall flow increases with the increasing of waste concentration in the binder. This is due to that the cohesion of the binder decreases and hence, the mixture trends to flow more.

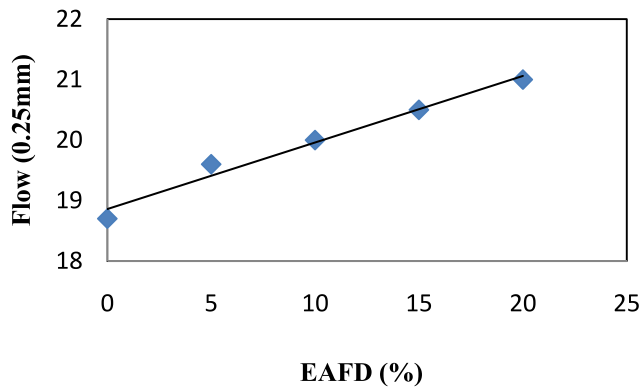

Figure 2. Relationship between percent EAFD and Marshall flow

Based on the data given in Figure 2, the following equation was developed:

$$Y_2 = 0.11x + 18.86 \quad (R^2 = 0.9783) \tag{2}$$

Where

Y_2 = Flow of asphalt concrete mixtures.

x = % of EAFD by volume of binder.

4.3 Effect of EAFD on Unit Weight

Figure 3 shows the effect of EAFD on the unit weight of asphalt concrete mixtures for each EAFD concentration. Figure 3 shows that the unit weight increases then decreases with the increasing percentages of EAFD in the binder. At 10% less air voids in the mix will be filled with binder and hence, lower unit weight will result.

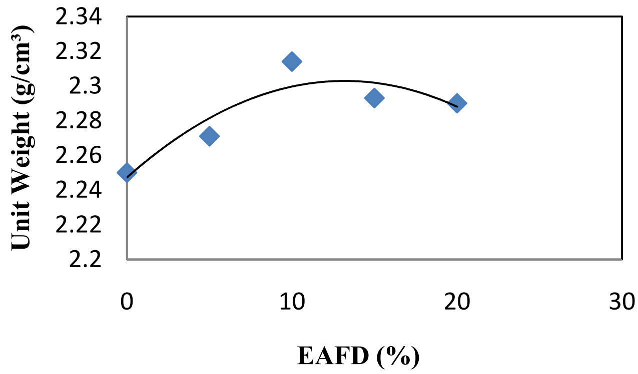

Figure 3. Relationship between Percent EAFD and unit weight

Based on the data given in Figure 3, the following equation was developed:

$$Y_3 = -0.0003x^2 + 0.0084x + 2.278 \quad (R^2 = 0.8271) \qquad (3)$$

Where

Y_3 = Unit weight of asphalt concrete mixtures.

x = % of EAFD by volume of binder.

4.4 Effect of EAFD on Voids in Mineral Aggregate (VMA)

Figure 4 shows the effect of EAFD on voids in mineral aggregate of asphalt concrete mixtures for each EAFD concentration. Figure 4 shows that voids in mineral aggregate decreases then increases with the increasing of EAFD concentration in the binder.

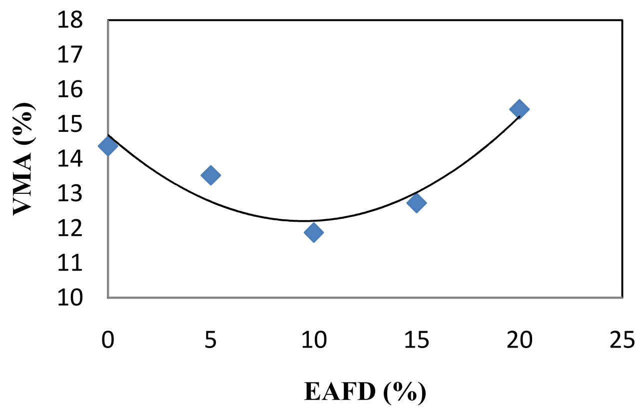

Figure 4. Relationship between percent EAFD and voids in mineral aggregate (VMA)

Based on the data given in Figure 4, the following equation was developed:

$$Y_4 = 0.0274x^2 - 0.521x + 14.693 \quad (R^2 = 0.8784) \qquad (4)$$

Where

Y_4 = VMA of asphalt concrete mixtures.

x = % of EAFD by volume of binder.

4.5 Effect of EAFD on Air Voids

Figure 5 shows the effect of EAFD on air voids of asphalt concrete mixtures for each waste toner concentration.

Figure 5 shows that the air voids decreases then increases with the increasing percentages of EAFD in the binder.

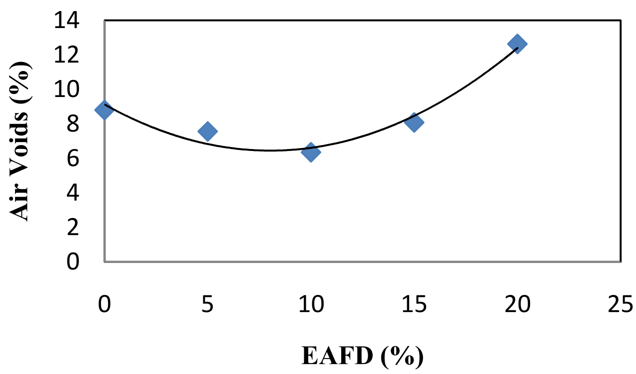

Figure 5. Relationship between Percent EAFD and air voids

Based on the data given in Figure 5, the following equation was developed:

$$Y_5 = 0.0415x^2 - 0.6661x + 9.1223 \quad (R^2 = 0.9590) \tag{5}$$

Where

Y_5 = Air voids of asphalt concrete mixtures.

x = % of EAFD by volume of binder.

4.6 Effect of EAFD on Voids Filled With Binder (VFB)

Figure 6 presents the effect of EAFD on VFB of asphalt concrete mixtures for each EAFD concentration. Figure 6 shows that the VFB increases then decreases with the increasing of EAFD concentration in the binder.

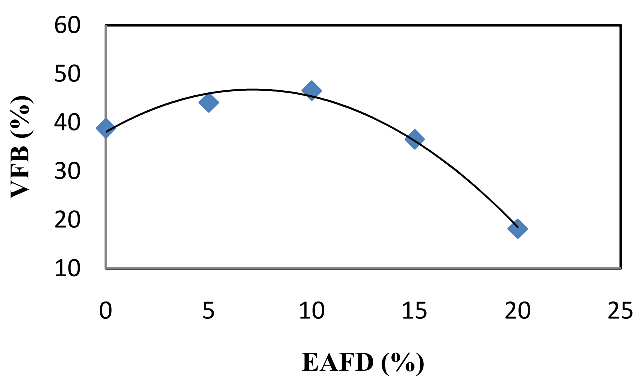

Figure 6. Relationship between Percent EAFD and VFB

Based on the data given in Figure 6, the following equation was developed:

$$Y_6 = -0.17097x^2 + 2.4403x + 38.06 \quad (R^2 = 0.9888) \tag{6}$$

Where

Y_6 = VFB of asphalt concrete mixtures.

x = % of EAFD by volume of binder.

4.7 Effect of EAFD on Marshall Stiffness

Figure 7 presents the effect of EAFD on Marshall stiffness of asphalt concrete mixtures for each EAFD concentration. Figure 7 shows that the Marshall stiffness increases then decreases with the increasing of waste toner concentration in the binder.

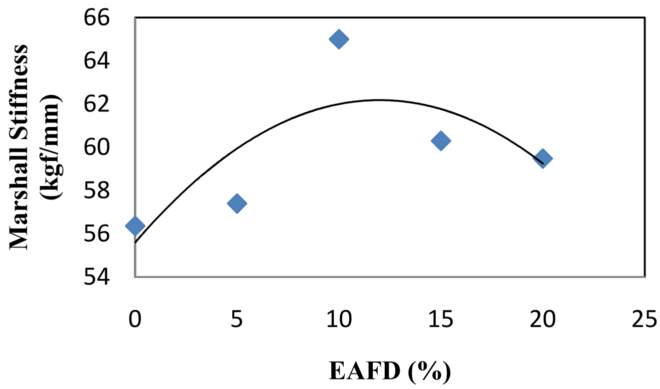

Figure 7. Relationship between percent EAFD and Marshall stiffness

Based on the data given in Figure 7, the following equation was developed:

$$Y_7 = -\ 0.04587x^2 + 1.0982x + 55.591 \quad (R^2 = 0.5938) \tag{7}$$

Where

Y_7 = Marshall stiffness of asphalt concrete mixtures.

x = % of waste toner by volume of binder.

5. Conclusions

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

1) Marshall stability, unit weight, voids filled with bitumen (VFB) and stiffness increase then decrease with the increasing % EAFD in the asphalt concrete mixtures.

2) Flow increases with the increasing % EAFD in the asphalt concrete mixtures.

3) VMA and air voids decrease then increase with the increasing % EAFD in the asphalt concrete mixtures.

4) A 5% EAFD content by volume of binder is found to meet the criteria of Marshall properties of asphalt mixtures.

5) Finally it has been concluded that the results are promising for dual achievement (a) to solve an environmental problem and (b) to use the dust for road construction.

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