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EFFECT OF ELECTRICAL ARC FURNACE DUST (EAFD) ON THE PROPERTIES OF ASPHALT CEMENT AND ASPHALT CONCRETE MIXTURES: STATE OF THE ART

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ABSTRACT

This paper aims at reviewing the effect of the Electric Arc Furnace Dust (EAFD) on the environment and the properties asphalt cement and asphalt concrete mixtures; by compiling the results of different researches conducted into the subject and comparing them with each other. Review analysis showed that although EAFD is classified as hazardous due to containing some heavy metals such as Zinc, Cobalt, Copper, Lead or Cadmium, the EAFD is considered to be safe for the environment according to the multiple conducted leaching tests. Also, previous research showed that mixing EAFD with asphalt cement increases its specific gravity, softening point and flash & fire points and decreases the values of penetration and ductility. As for asphalt concrete, previous results of conducted research, showed that it increased the value of flow, and there was an increase then a decrease in the values of stability, unit weight and the Voids Filled with Binder (VFB), and finally a decrease then an increase in the value of the Voids in Mineral Aggregate (VMA). From the environmental impact viewpoint, the EAFD is considered to be safe for the environment according to the multiple conducted leaching tests.

Key Words: Electrical Arc Furnace Dust (EAFD), Asphalt cement, Asphalt concrete, Road construction.

1. Introduction

2. An electric arc furnace (EAF)

The electric arc furnace technology is a furnace that heats material by means of an electric arc (see figure 1[1]). The use of this technology has been increasing over the last years, represents 34% of the steel production in Europe[2] and it is the most important process in scrap recycling where 100% steel scrap is the most used charge in developed countries[3]. Other than scrap recycling EAFs are used to recover internal wastes such as EAF dust, slag and refractory materials [3]. Steel making with EAF is done through several steps[2];

1. Storing and handling the raw material using cranes and storage facilities.
2. Loading the Furnace with scrap.
3. Melting the scrap in the furnace.
4. The melted steel is treated for quality adjustments.
5. The slag is removed.

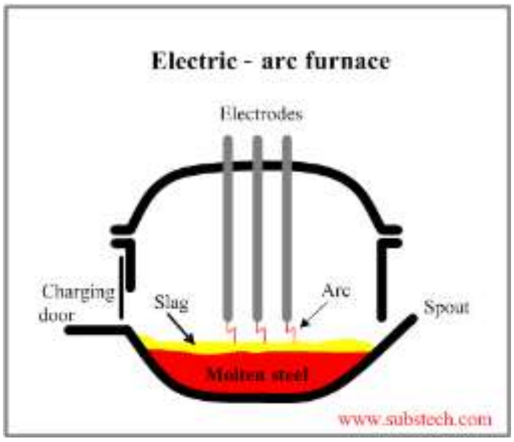

Figure 1: Electric Arc Furnace (source: https://www.substech.com/dokuwiki/doku.php?id=electric_arc_furnace_eaf).

The electric arc furnace dust (EAFD) (see Figure 2[4]) is a byproduct of steel making process. The generated amount of EAF dust produced per each ton of produced steel is estimated to 15-20 kg/ton, and the overall generated amount per year is around 3.7 million tons of EAFD around the world [5].

Figure 2. Electric Arc Furnace Dust
Source: https://www.ec21.com/product-details/EAF-Dust--9647892.html

EAFD is classified as a hazardous waste and therefore must not be disposed of in the environment; as the hazardous elements could leach into natural environment contaminating soil and water bodies. [6]. Recycling of the hazardous elements is reported to be quite costly, [7][8], thus immobilization techniques have been used to deal with them which includes [9], [10]:

1. Temporary containment.
2. Cost effective stabilization and solidification.
3. Permanent techniques.

EAFD is managed and treated in many ways, one of them which is the focus of this paper, is adding it to asphalt cement/asphalt concrete mixtures [8].known as the technology of stabilization and solidification, which aims to prevent the hazardous components of EAFD from negative environmental exposure by mixing the asphalt binder with EAFD, and studying its effect on asphalt cement and asphalt concrete mixtures through the results of different researches and comparing them with each other.

3. Electric Arc Furnace Dust (EAFD) characterization

3.1 Chemical and Structural Characterization

According to Sofilić et.al [12] who conducted research in 2004 , using different analytical methods, they concluded that the chemical composition of EAFD was found to include a lot elements such as ; Fe, Mg, Mn, Ca, Zn, Si, Pb, S, Hg, Cu, Al, Cd, Ni, C, As and Cr .EAFD was investigated using X-ray photoelectron spectroscopy (XPS) which showed that Zinc is present in the form of ZnO , and lead is present in the form of PbO.

Another research was conducted in 2006[13] , where a chemical and structural analysis was conducted on 2 samples of EAFD. The analyses included Optical emission spectroscopy via inductively coupled plasma (ICP), X ray diffractometry (XRD) and Mössbauer spectroscopy analysis.

According to XRD the sample was composed of the following compounds : ZnFe2O4 , Fe3O4 , MgFe2O4 , FeCr2O4 , Ca0.15Fe2.85O4 , MgO, Mn3O4 , SiO2 and ZnO.

Whereas the Mössbauer spectroscopy analysis showed the following compounds: ZnFe2 O4 , Fe3O4 , Ca0.15Fe2.85O4 and FeCr2O4.

The Royal Scientific Society of Jordan conducted a characterization analysis to find the composition of EAFD and the results are shown in Table 1 and figure 3.[14]

Component	Percentage (%)
Fe_2O_3	32
ZnO	29
NaCl	5.79
MgO	4.66
SiO2	4
$CaSO_4$	3.43
K_2O	2.7
$CaCl_2$	1.91
CaO	1.4
Al_2O_3	1.28
Cu_2O	0.7
Loss on ignition at 1000 °C	11.63
Others	1.5

Table 1: EAFD composition by weight %

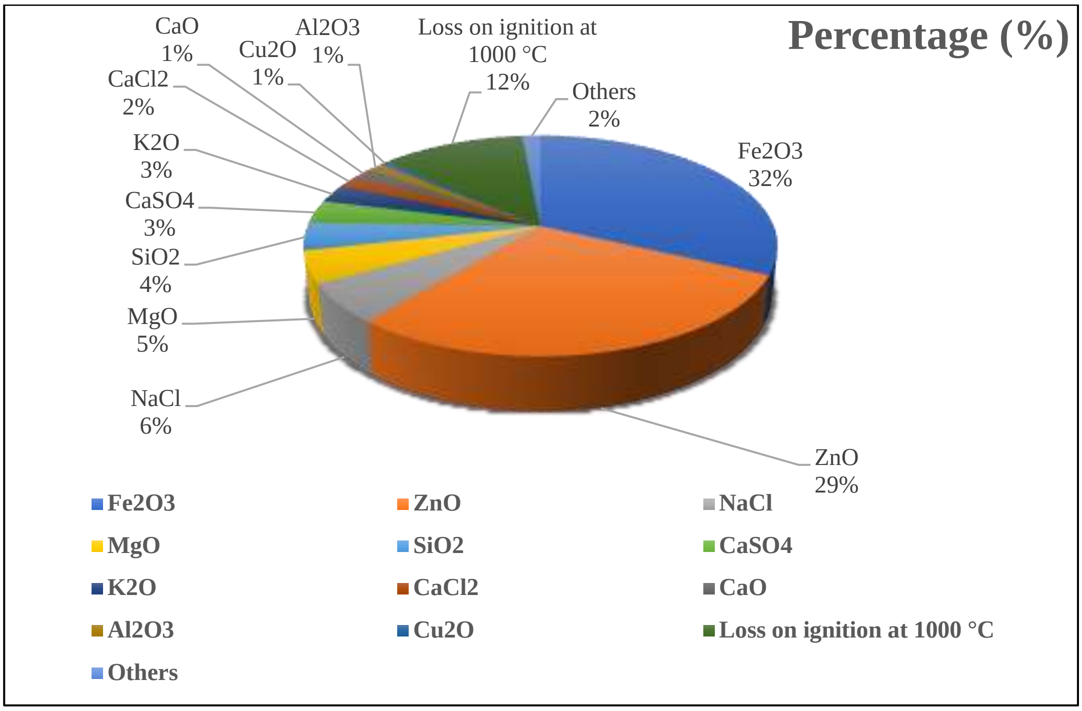

Figure 3: Electric Arc Furnace Dust composition.

We can conclude from all the mentioned findings that the main components of EAFD are Fe2O3 and ZnO and they had the highest percentage by weight of EAFD.

The differences in results between the previously mentioned studies might be due to the fact that they were done in different countries and the dust samples were collected from different types of factories in each case.

3.2 Micro-structure characteristics

Mohammad A. T. Alsheyab[15] conducted scanning electron microscopy analysis (SEM) on EAFD to study the micro-structural characteristics of EAFD.

Figure 4 above showed that EAFD is present in clots (points 3,4) and that its particles are spherical in shape (points 1,2) .

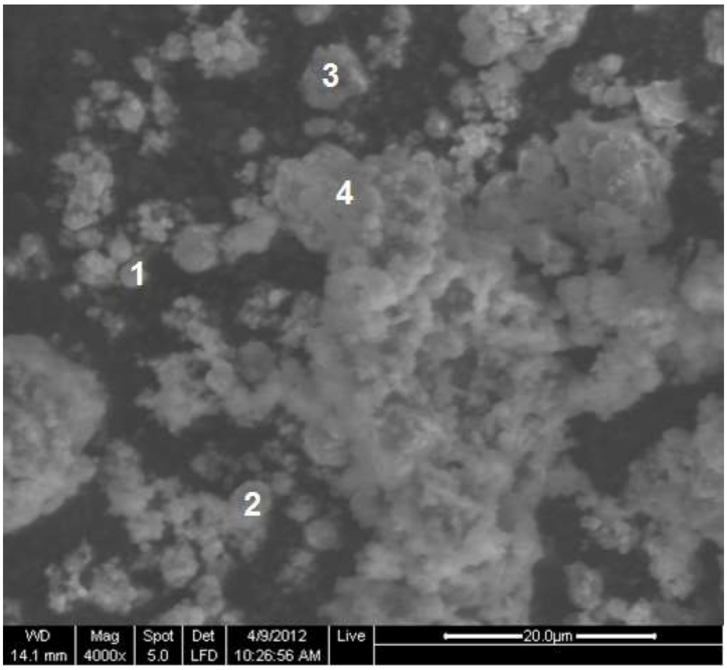

Figure 4: Metallographic structure of the EAFD particles, (x4000) Source:

Figure 5 shows that the air voids become less and less with the increase of EAFD , thus resulting in more adhesion between the binder particles.

It also shows that as the EAFD % increases more EAFD particles are going to appear on the surface , thus resulting in an irregularities in the mixture which leads to lowering the cohesion forces.

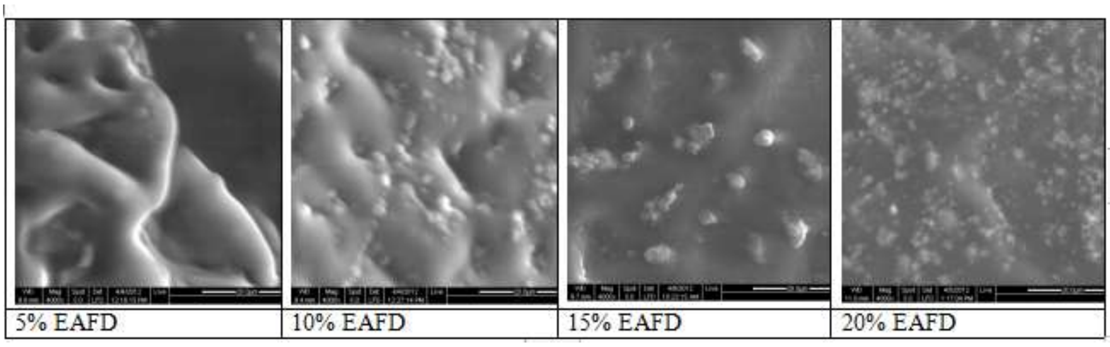

Figure 5: SEM analysis for asphalt-EAFD mixtures of volumes 5,10,15 and 20% volume of EAFD performed at x4000.

In conclusion the test results showed that the air voids in the asphalt binder are filled with small particles of EAFD, whereas the bigger particles are attached to the surface and the results were confirmed by the penetration and the specific gravity tests.

4. Environmental and Economic Aspects of Using electrical arc furnace dust (EAFD) in Road Construction

Regarding the effect of using the EAFD as asphalt binders and in HMA mixtures on environment, some researchers conducted research in that regards such as Milačič. El.al. [16] in 2011, where leachability test confirmed that it is safe to the environment and doesn't cause any environmental risk.

In 2017, Sayadi et.al., [17] conducted a research study on the effect of asphalt mix with EAFD on water resources in 2017, where it was concluded that these pavements are not a threat to surface or ground waters. Also, Toxicity Characteristic Leaching Procedure (TCLP) was conducted on flowing water by Sayadi et.al. [17]and it showed that the quantities of these heavy metals in the water samples were less than the regulatory levels; which supports the fact that EAFD is not hazardous for the environment when it's mixed with asphalt binders and HMA mixtures.

5. Effect Of Electric Arc Furnace Dust (EAFD) On Properties Of Asphalt Cement

5.1 Specific gravity

Specific Gravity is the ratio of the weight of a given volume of binder to the weight of an equal volume of water. In the case of EAFD the value it around 1.03.
Mohammad A. T. Alsheyab & Taisir S. Khedeywi[18] conducted a series of tests on asphalt cement specimens mixed with EAFD with 5 different concentrations (0%, 5%, 10%, 15% and 20%) by volume of binder.
The results showed the specific gravity increased with the increase of EAFD volume in binder. The highest specific gravity value was 1.348 at 20% EAFD.

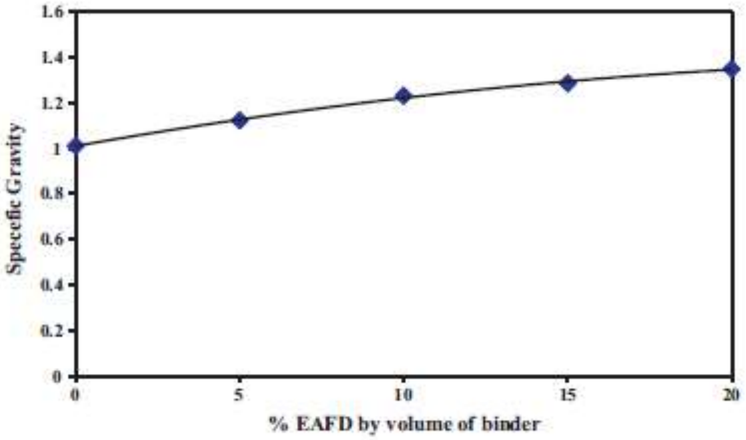

Figure 6: effect of EAFD percentage in asphalt mix on specific gravity.

In another research conducted by Mohammad A. T. Alsheyab[15];it was confirmed that the specific gravity increased with the increase of EAFD in the binder which supports the results of the previously mentioned research.

The increase in specific gravity can be explained by the fact that the voids within the binder become less with the increase of EAFD; because the EAFD particles fill these voids; that's why we call EAFD a filler material.

5.2 Effect on Penetration

Penetration is defined as the consistency of a bituminous material expressed as the distance in tenth of a millimeter that a standard needle vertically penetrates a sample of the material under known conditions of loading, time, and temperature. Penetration is recorded in 0.1 mm.

Alsheyab & Khedeywi[18] found that the penetration values decreased with the increase of EAFD volume in binder.

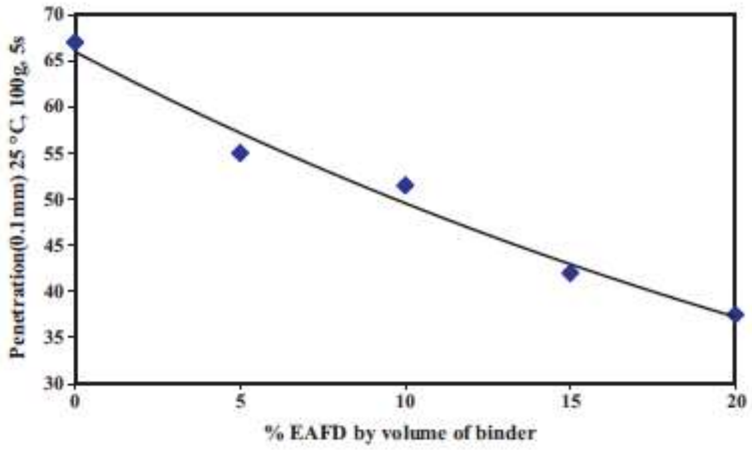

Figure 7: effect of EAFD% on penetration.

According to Mohammad A. T. Alsheyab[15] ; the penetration decreased with the increase of EAFD in the binder which supports the results of the previously mentioned research.

These results can be explained by the fact that the voids in the binder are being filled with EAFD and getting less; thus, the needle will be obstructed by more material; which makes the binder more resistant to penetration and more consistent.

Overall, the addition of EAFD to asphalt cement produced a mixture that is suitable for road construction since the values of penetration index for all samples were within ±2.

The penetration results of 15% and 20% EAFD showed that it can be used for crack filling of flexible and rigid pavements.

We can also conclude that the asphalt/EAFD mixture would be more suitable for cold weathers based on the decrease in penetration values.

5.3 Softening Point

Softening point test is defined as the temperature at which an asphalt cement cannot support the weight of a standard ball (3/8 in diameter and 3.5 g in weight) and starts flowing.

Alsheyab & Khedeywi[18] found that the softening point increases with the increase of EAFD percentage in the mix as shown in Figure 8.

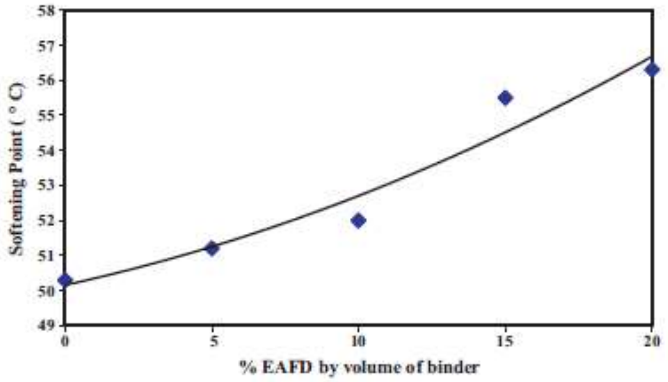

Figure 8: Effect of EAFD% on softening point of asphalt mix.

And this can be explained by the fact that the EAFD particles have high heat absorption capacity; which requires more energy (heat) to break the binder.

5.4 Ductility

The ductility of a bituminous material measures the distance to which material will elongate before it gets broken when two ends of a briquet specimen of the material, are pulled apart in water bath at a specified speed and at a specified temperature.

Alsheyab & Khedeywi[18] found that the ductility decreases with the increase of EAFD volume in binder as shown in Figure 9 shows this relationship:

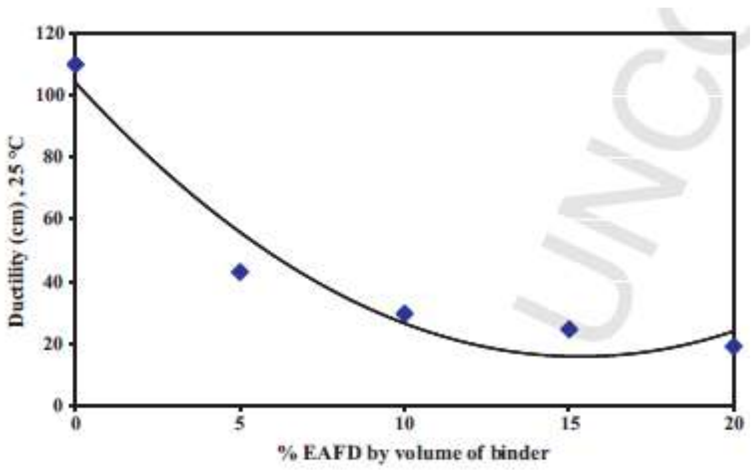

Figure 9: Effect of EAFD % on ductility of asphalt mix.

This can be explained by the fact that the EAFD addition causes an increase in the stiffness and hardness of the composite; thus, decreasing its ductility.

5.5 Flash & Fire Point

Flash point is the lowest temperature corrected to a barometric pressure of 101.3 kPa, at which application of an ignition source causes the vapors of a specimen of the sample to ignite and flash under specified conditions of test.

Fire point is the lowest temperature corrected to a barometric pressure of 101.3 kPa, at which application of an ignition source causes the vapors of a test specimen of the sample to ignite and sustain burning for a minimum of 5s under specified conditions of test.

Alsheyab & Khedeywi[18] found that both the flash and fire point increase with increase in EAFD volume in binder as shown in Figure 10.

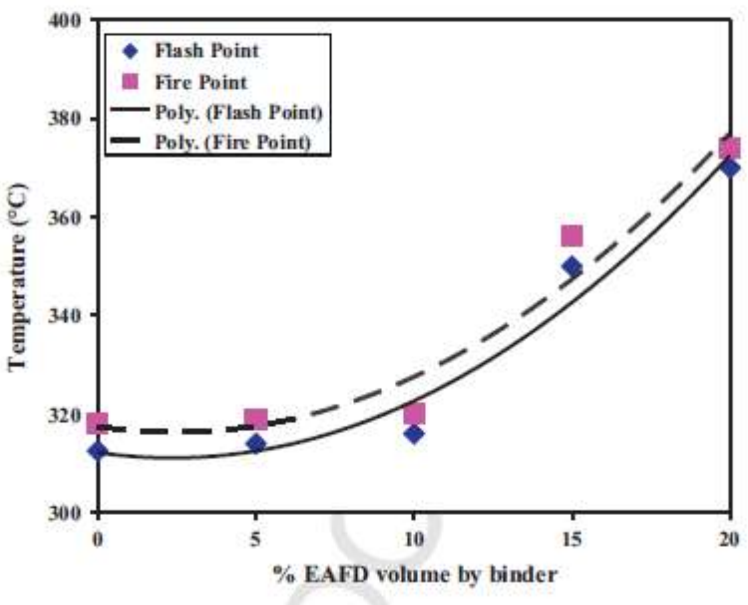

Figure 10: Effect of EAFD percentage on flash and fire points.

We can conclude that the use of EAFD/asphalt is safer than the use asphalt alone; since the flash & fire temperatures are higher. This increase in flash and fire points can be explained by the fact that the EAFD addition causes an increase of particles interlocked between each other; making it harder for the low-boiling point materials to evaporate.

5.6 Rotational Viscosity

The Rotational Viscometer (RV) is used to determine the viscosity of asphalt binders in the high temperature range of manufacturing and construction, Superpave specifies for the test to be conducted at 135° c. Alsheyab & Khedeywi[18] found that the rotational viscosity increases with the increase of EAFD volume in the Asphalt mix as shown in Figure 11.

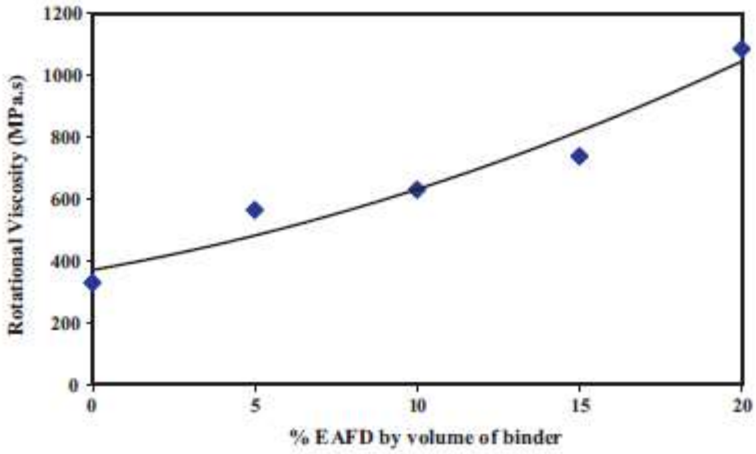

Figure 11: The effect of EAFD% on the rotational viscosity.

As previously mentioned, the EAFD addition causes an increase in particles interlock in the binder particles which increases the viscosity of the binder.

6. Effect of electric arc furnace dust (EAFD) on properties of asphalt concrete mixtures

6.1 Effect on Marshall stability

Stability is defined as the maximum load resistance (N or lb) that the standard test specimen will have at 60°C (140°F) when tested according to the standard procedure. A load is applied to the specimen at a constant rate of 51 mm./minute until failure occurs. The load at failure is recorded as the Marshall stability of the specimen.

According to Khedeywi & Alsheyab [14] , a test was conducted on asphalt concrete specimens with five different contents (0%, 5%, 10%, 15% and 20%) of EAFD by volume of binder, which concluded that the Marshall stability increases then decreases with the increasing of EAFD in the binder as shown in figure 12.

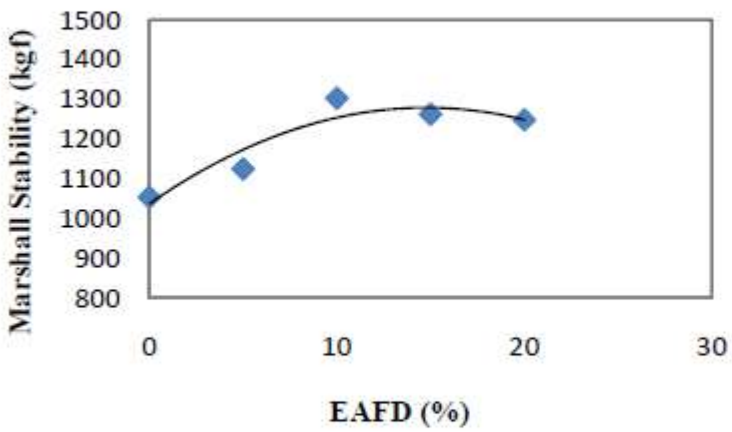

Figure 12: Effect of EAFD % on Marshall Stability.

Also, Yailuth Lopera and Henry A. Colorado[19] conducted multiple tests on asphalt concrete specimens with the addition of EAFD to the binder with different contents (1%, 5%, 10% and 20% of binder weight) ,and found that the Marshall stability increased with the increase of EAFD content .

Looking at the results of the previously mentioned two tests one might think that there is some difference in results ; but the decrease in stability that occurred in the first test was very slight and at the very end of the curve , so one can say that it is not significant , and the reason there was no decrease in stability in the second test was likely because the EAFD was added by percent of weight rather than volume , which meant less amount of EAFD added, thus they didn't reach the point where the curve goes downward.

The increase then decrease in stability can be explained by the fact that the EAFD addition causes an increase in the strength and stiffness of the binder by filling the voids in between which reflects on the HMA mix at the beginning, but after a certain point of adding the EAFD starts replacing the binder particles and causing them to be more distant from each other which leads to a decrease in binding ability and strength.

6.2 Effect on Marshall flow

Flow is defined as the total deformation (0.25 mm or 0.01 in) that occurs in the specimen between no load and maximum load during that stability test. The flow meter is held in position while the stability test is in progress. Once the maximum load is reached (at failure), the flow meter is removed. The reading of the flow meter is recorded. The flow is expressed in units of 0.25 mm (0.01 in).

Khedeywi & Alsheyab[14] found that the flow increases as the content of EAFD in the binder increases, almost in a linear relationship as shown in Figure 13.

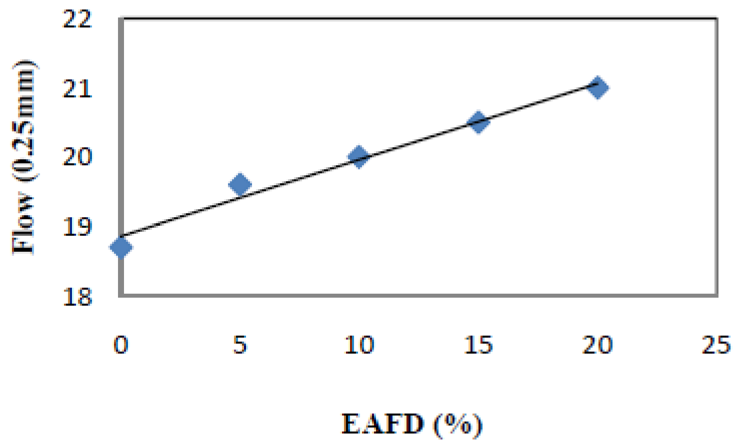

Figure 13: Effect of EAFD % on Marshall flow.

Yailuth Lopera and Henry A. Colorado[19] found that the flow decreased and then increased with the increase of EAFD content in the binder.

The increase in the flow value happens because of the decrease of the cohesion of the binder due to the increase of EAFD addition (Taisir S. Khedeywi & Mohammad A. T. Alsheyab).

6.3 Effect on Unit Weight

Unit weight is defined as the weight per unit volume of asphalt. In their research, Khedeywi & Alsheyab[14] found that the unit weight increased and then decreased with the increase of EAFD in the binder as shown in Figure 14.

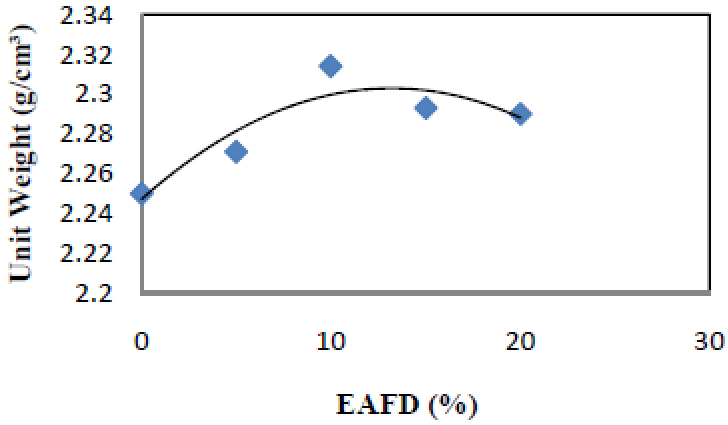

Figure 14: Effect of EAFD% on Unit Weight.

The increase of unit weight at the beginning can be explained by the fact that the EAFD particles fill the voids in the binder which increases the unit weight, but after a certain point of adding the EAFD starts replacing the binder particles and causing them to be more distant from each other which leads to a decrease in unit weight.

It was found that at 10% EAFD, less air voids in the mix will be filled and thus we get a lower unit weight value.

6.4 Effect on VMA (Voids in Mineral Aggregate) and air voids

Voids in the Mineral Aggregate (VMA) is defined as the volume of inter-granular void space between the aggregate particles of compacted paving mixture that includes their voids and volume of asphalt not absorbed into the aggregate (effective asphalt content). Whereas Air Voids (Va) is the total volume of the small pockets of air between the coated aggregate particles throughout a compacted paving mixture expressed as percent of the bulk volume of compacted paving mixture. And both of these values can be found in the volumetric analysis of the Marshall mix design.

Khedeywi & Alsheyab[14] found that VMA decreases then increases with the increase of EAFD content in the binder as shown in Figure 15.

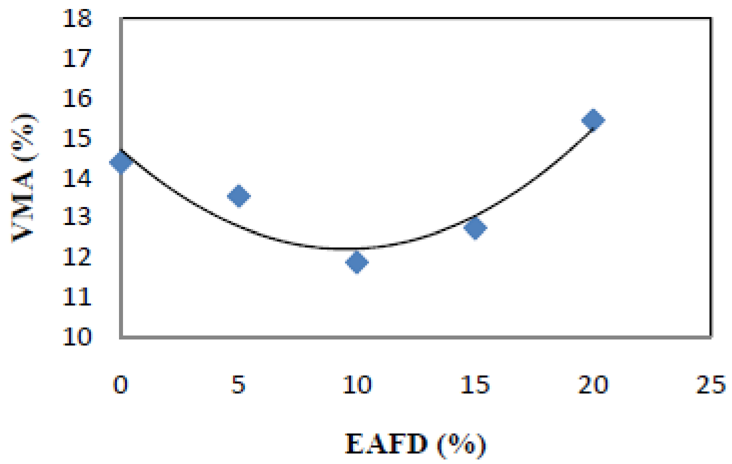

Figure 15: Effect of EAFD % on Voids in Mineral Aggregate (VMA).

They also found that similarly the Air Voids (VA) also decreases and then increases as the EAFD content increases in the binder as shown in Figure 16.

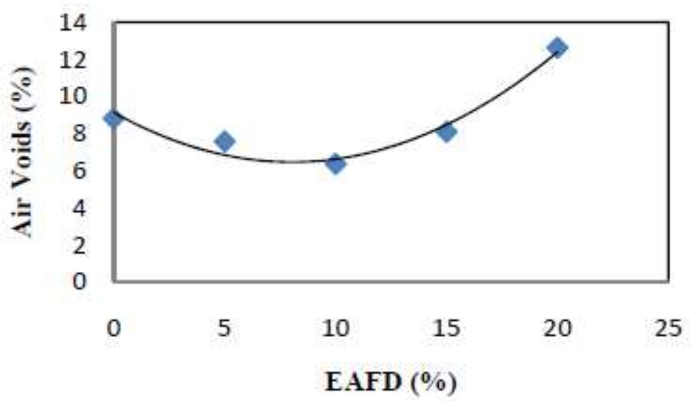

Figure 16: Effect of EAFD % on air voids.

Yailuth Lopera and Henry A. Colorado[19] found that the VMA increased and then decreased with the increase of EAFD in the binder.

whereas the Air voids VA increased as the EAFD content increased in the binder. The relationship between EAFD and VMA can be explained by looking at the following equation. VMA=100-(Gmb*Ps/Gsb).

From the equation we see that VMA is dependent on Gmb; which increases with the increase of EAFD which leads to a decrease in VMA.

6.5 Effect On VFB (Voids Filled With Binder)

Voids Filled with Asphalt (VFA) is defined as the percent of the volume of the VMA that is filled with asphalt cement (binder).

Khedeywi & Alsheyab[14] found that VFB increases slightly at the beginning then decreases with the increase of EAFD in the binder as shown in Figure 17.

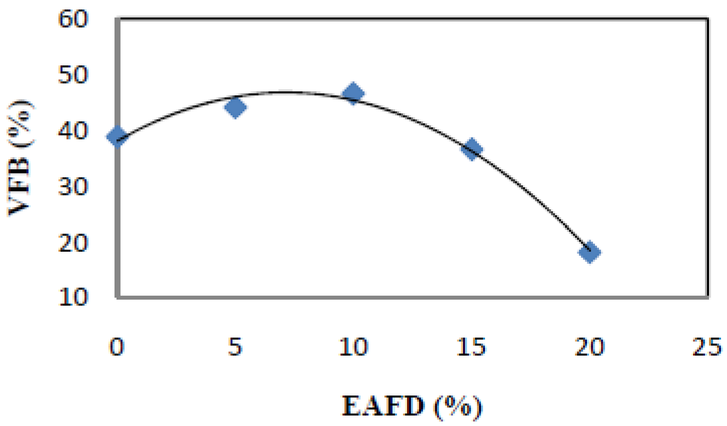

Figure 17: The effect of EAFD % on the VFB.

Yailuth Lopera and Henry A. Colorado[19] found that the VFB decreased with the increase of EAFD in the binder.

Thus one can conclude from the mentioned results that overall the VFB decreases with the increase of EAFD in the binder.

The relationship between EAFD and VFB can be explained by looking at the following equation. VFB=(VMA-VTM)/VMA

From the equation above we see that VFB is dependent on VMA and VTM. Resilient modulus Resilient Modulus is a fundamental material property used to characterize unbound pavement materials. It is a measure of material stiffness and provides a mean to analyze stiffness of materials under different conditions, such as moisture, density, and stress level. It is also a required input parameter to mechanistic-empirical pavement design method[20].

Alsheyab & Khedeywi[21] conducted research to measure the effect of temperature on the resilient modulus of EAFD/asphalt concrete.

The test was done at 25,40 and 55ºc and at loading frequencies of 1,4 and 8 Hz with five EAFD contents (0,5,10,15 and 20%) by volume of binder. The results showed that in most cases there was an increase then a decrease in the MR value with the increase of EAFD volume in the binder. But the MR value was increasing with the increase of EADF at frequency 4Hz when temperature was 40 ºc and at frequency 8Hz when temperature was 40 and 55 ºc.

The relationship between EAFD and MR can be explained by the fact that the increase of EAFD increases the stiffness of the binder and thus increases the stiffness of the HMA mixture, which leads to an increase in MR (MR is a measure of HMA stiffness).

7. Conclusion

a) Stabilization and solidification is a safe and effective method for the management of the hazardous waste of EAFD.
b) Using the EAFD with asphalt mix sounds promising method that achieves dual purpose; managing the waste in a safe way and using it in pavement.
c) The addition of EAFD to asphalt mix increases the specific gravity, softening point and flash & fire points, and decreases in the values of penetration and ductility.
d) The resulting asphalt cement/EAFD mixture was found to be suitable for road construction and makes it safer as it increases the flash &fire points temperatures.
e) The effect of EAFD on asphalt concrete includes (1) increasing and then decreasing the values of stability, unit weight and VFB, (2) Increases in the value of flow and (3) decreasing then increasing in the value of VMA.

References

1. "Electric Arc Furnace (EAF) [SubsTech]." https://www.substech.com/dokuwiki/doku.php?id=electric_arc_furnace_eaf (accessed Dec. 10, 2021).
2. T. Stengel and P. Schießl, "Life cycle assessment (LCA) of ultra high-performance concrete (UHPC) structures," *Eco-Efficient Construction and Building Materials: Life Cycle Assessment (LCA), Eco-Labelling and Case Studies*, pp. 528–564, 2013, doi: 10.1533/9780857097729.3.528.
3. J. Madias, "Electric Furnace Steelmaking," *Treatise on Process Metallurgy*, vol. 3, pp. 271–300, 2014, doi: 10.1016/B978-0-08-096988-6.00013-4.
4. "EAF Dust(id:9647892). Buy Iran EAF, EAF Dust - EC21." https://www.ec21.com/product-details/EAF-Dust--9647892.html (accessed Dec. 11, 2021).
5. D. G. Y. G. N and G.-E. V. B, "The situation of EAF Dust in Europe and the upgrading of the Waelz process.," *Global Symposium on Recycling, Waste Treatment and Clean Technology, 1999, Vol.2*, pp. 1511–1520, 1999, Accessed: Dec. 10, 2021. [Online]. Available: https://jglobal.jst.go.jp/en/detail?JGLOBAL_ID=200902125374127925
6. B. Cubukcuoglu and S. K. Ouki, "The use of alternative constituents in cement-based solidification/stabilization of electric arc furnace dust," in *Proceedings of the 7th international conference on sustainable management of waste and recycled materials in construction*, 2009, pp. 3–5.
7. M. Liebman, "The current status of electric arc furnace dust recycling in North America," in *4th Int. Symposium Recycling of Metals and Engineered Materials*, 2000, pp. 237–250.
8. A. D. Zunkel, "Electric arc furnace dust management: a review of technologies," *Iron and Steel Engineer*, vol. 74, no. 3, 1997.
9. B. Pavao, A. S. de Vargas, A. B. Masuero, D. C. Dal Molin, and A. C. Vilela, "Influence of electric arc furnace dust (EAFD) in alkali-activated fly ash binder," 2009.
10. J. N. Meegoda, A. S. Ezeldin, H.-Y. Fang, and H. I. Inyang, "Waste immobilization technologies," *Practice periodical of hazardous, toxic, and radioactive waste management*, vol. 7, no. 1, pp. 46–58, 2003.
11. T. Šturm *et al.*, "The use of EAF dust in cement composites: Assessment of environmental impact," *Journal of hazardous materials*, vol. 166, no. 1, pp. 277–283, 2009.
12. T. Sofilić, A. Rastovčan-Mioč, Š. Cerjan-Stefanović, V. Novosel-Radović, and M. Jenko, "Characterization of steel mill electric-arc furnace dust," *Journal of Hazardous Materials*, vol. 109, no. 1–3, pp. 59–70, Jun. 2004, doi: 10.1016/J.JHAZMAT.2004.02.032.

13. J. G. M. da Silva Machado, F. A. Brehm, C. A. M. Moraes, C. A. dos Santos, and A. C. F. Vilela, "Characterization study of electric arc furnace dust phases," *Materials Research*, vol. 9, no. 1, pp. 41–45, 2006, doi: 10.1590/S1516-14392006000100009.
14. T. S. Khedeywi and M. A. T. Alsheyab, "Laboratory Investigation to Evaluate the Effect of Electric Arc Furnace Dust (EAFD) on Properties of Asphalt Concrete," *Environment and Natural Resources Research*, vol. 4, no. 1, Dec. 2013, doi: 10.5539/enrr.v4n1p1.
15. M. A. T. Alsheyab, "SEM Analysis on Electron Arc Furnace Dust (EAFD) and EAFD-Asphalt Mixture," *Environment and Natural Resources Research*, vol. 3, no. 4, Nov. 2013, doi: 10.5539/enrr.v3n4p147.
16. R. Milačič, T. Zuliani, T. Oblak, A. Mladenovič, and J. Š. Ančar, "Environmental impacts of asphalt mixes with electric arc furnace steel slag," *Journal of environmental quality*, vol. 40, no. 4, pp. 1153–1161, 2011.
17. M. Sayadi and S. Hesami, "Performance evaluation of using electric arc furnace dust in asphalt binder," *Journal of Cleaner Production*, vol. 143, pp. 1260–1267, Feb. 2017, doi: 10.1016/J.JCLEPRO.2016.11.156.
18. M. A. T. Alsheyab and T. S. Khedaywi, "Effect of electric arc furnace dust (EAFD) on properties of asphalt cement mixture," *Resources, Conservation and Recycling*, vol. 70, pp. 38–43, 2013, doi: 10.1016/j.resconrec.2012.10.003.
19. A. Loaiza and H. A. Colorado, "Marshall stability and flow tests for asphalt concrete containing electric arc furnace dust waste with high ZnO contents from the steel making process," *Construction and Building Materials*, vol. 166, pp. 769–778, Mar. 2018, doi: 10.1016/J.CONBUILDMAT.2018.02.012.
20. "Resilient Modulus Testing." http://www.dot.state.mn.us/materials/mr/ (accessed Dec. 11, 2021).
21. M. A. T. Alsheyab and T. S. Khedaywi, "Analysis of the Effect of Temperature on the Resilient Modulus of Asphalt Concrete Mixed with Electric Arc Furnace Dust (EAFD)," *Water, Air, and Soil Pollution*, vol. 227, no. 3, Mar. 2016, doi: 10.1007/s11270-016-2776-4.