Laboratory Characterization of Asphalt Mixtures Containing Steel Slag

دراسة معملية للخلطات الإسفلتية المحتوية على خبث الصلب

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الملخص

إن استخدام المنتجات الصناعية يتطلب معرفه جيدة لخواصها وسلوكها عند تعرضها للأحمال المرورية والظروف المناخية, فهذا البحث يقدم دراسة معملية شاملة لاختبارات الخلطة الإسفلتية المحتوية على خبث الصلب الناتج من افران القوس الكهربي كأحد المخلفات من مصنع حديد بمصر, ولقد تم اختباره للتعرف على خواصه الطبيعية والميكانيكية والكيميائية ومقارنه خواصه بالحجر الجيري , وكانت نسب الخلط المستخدمة بين الحجر الجيري وخبث الصلب عباره عن (0/100 , 80/20 , 60/40 , 100/0) **%** كركام مستخدم بالخلطة الإسفلتية المراد استخدامها كطبقه اسفلتيه رابطة , حيث تم تصميم الخلطة بطريقه مارشال المستخدمة لتحديد نسبة الاسفلت المثلى, وقد اوضحت النتائج انه بزياده نسبة خبث الصلب الناتج من افران القوس الكهربي يزداد كلا من ثبات الخلطة وكثافتها وتقل قيم الانسياب والفراغات بالمواد الصلبة.

Abstract

The use of industrial by-products needs better understanding of their characteristics and behavior when subjected to traffic loading and environmental conditions. This paper presents a comprehensive laboratory characterization testing of asphalt mixtures containing steel slag. Electric Arc Furnace Steel Slag (EAFS) products were chosen as one of the most significant types of non-hazardous metallurgical waste, which were sourced from a steel factory in Egypt. The routine tests were conducted on EAFS materials to examine the physical, mechanical, and chemical properties, which were compared with the virgin aggregate (limestone). Blends of limestone aggregates/EAFS with percentages of 100/0, 80/20, 60/40, and 0/100% were selected to be employed as binder course layer. Asphalt mixtures were designed by Marshall method to find the optimum binder content. Test results showed that as the EAFS percentage in the mix increased, both the stability and density of the mixes increased. In addition, the flow and voids in mineral aggregates (VMA) were found to decrease with an increase in the EAFS content.

Keywords

Electric Arc Furnace Steel Slag, characterization, Marshall, VMA, stability, flow.

Introduction

Slags are used in many applications, such as road construction aggregate, concrete, railway ballast, cement, mineral wool, etc. The old Romans used slag from furnaces for construction of the Roman roads in the Sussex District in England (Emery, 1984). Since the first half of the 19th century, USA have used slag in construction of roads (as bases and in bituminous mixtures), railways, and in cement manufacturing (Lewis, 1982).

EAFS is a by-product of the steel manufacturing process using high-power electric arcs, instead of gaseous fuels, to produce heat which melts recycled steel scrap and converts it to a high-quality steel (see Figure 1). EAFS products are recommended for use in Asphalt Concrete (AC) mixes as one of the non-hazardous metallurgical waste. Proper processing of steel slag and special quality control procedures are extremely important in selecting steel slag for use in HMA mixes.

Steel slag can be processed into coarse or fine aggregate material for use in dense-graded and open-graded HMA pavements (Norton, 1979) and in cold mixes or surface treatment applications (Noureldin, and McDaniel, 1990). Some types of slag are produced with high

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percentages of free lime and magnesium oxides, which cause hydration and expansion in humid environments (JEGEL, 1993). The free lime in steel slags can combine with water to produce calcium hydroxide (Ca (OH)2) solution. Upon exposure to atmospheric carbon dioxide, calcite (CaCO3) may precipitate in the form of surficial tufa and powdery sediment in surface water. Tufa precipitates have been found to block drainage paths in pavement systems (Shatnawi et al., 2008**)**. The free lime hydrates rapidly and can cause large volume changes (expansion) over a relatively short period of time (weeks), which may result in cracking of asphalt (Tarco, 2000).

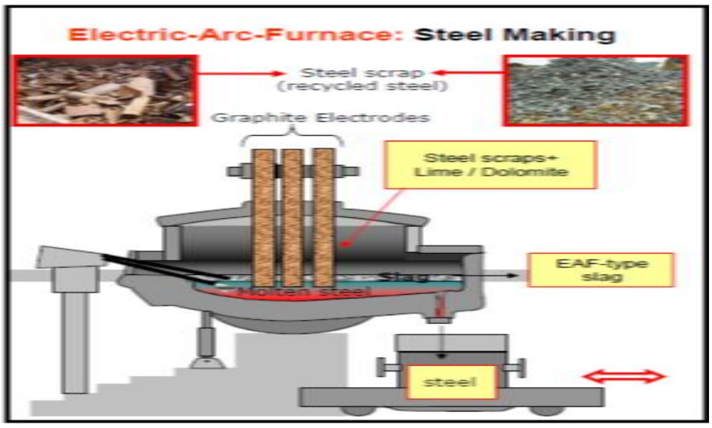

Figure 1. Schematic representation of the electric-arc-furnace steel making process (Yildirim and Prezzi, 2009).

Although, many of researchers have used steel slag in HMA, few researchers have used it in binder course layer, which are the focus of this research. Thus, the main objective of this study is to characterize the physical, chemical, and mechanical properties of the EAFS for application as HMA binder course layer

Literature Review

Numerous studies have been conducted on laboratory characterization of AC containing EAFS; some pertinent studies are presented in the following.

Khan et al. (2002) evaluated asphalt mixtures containing steel slag with percentage of 48% of total weight of virgin aggregates for wearing course asphalt mix. For base course asphalt mix, they used two different mixes with two different percentages of steel slag of 100% and 61% of the total weight of virgin aggregates. They concluded that the use of steel slag aggregate as a base or in asphalt layers minimized the use of natural aggregates, and hence can reserve the natural resources. They concluded also that the use of steel slag aggregate in asphalt mixes improve the resistance of surface skidding and increase the pavement fatigue.

Asi et al. (2007) replaced the limestone aggregates in asphalt mixes by the steel slag with percentages of 0%, 25%, 50%, 75%, and 100% of the total weight of aggregates. They also investigated the toxicity, chemical and physical properties of the steel slag. The effectiveness of the steel slag aggregate was characterized by a comprehensive testing i.e., indirect tensile strength test, resilient modulus test, wheel track test, creep test, and stripping resistance test. Asi et al. (2007) concluded that steel slag aggregate can be used in AC mixes, since its properties met both Superpave properties and Jordanian standards. They also found that replacing up to 75% of the limestone coarse aggregate by steel slag aggregate improved the mechanical properties of the AC mixes

Shatnawi, et al. (2008) compared the use of 100% steel slag in wearing course mix with the conventional wearing course mix using dense graded limestone at the same grading and bitumen contents. Shatnawi, et al.**,** 2008 concluded that steel slag mix yielded higher stability and higher resistance to rutting.

Fistrić, et al. (2010) investigated 75% steel slag aggregate with 25% limestone rock aggregate to be used in AC mixes. Results showed that the steel slag produced from water-cooled process yielded good resistance to permanent deformation, high stability with good flow properties and high resilient modulus. However, authors haven't compared the results of 75% steel slag mix with conventional asphalt mix.

Louzi, (2012) used steel slag in the AC mixtures with different percentages (15, 30 and 45%) of the total weight of coarse aggregates. Fatigue, indirect tensile strength, loss of indirect tensile strength and the resilient modulus laboratory tests were performed on all hot mixes. Louzi, (2012) concluded that steel slag improved the properties of asphalt mixtures in terms of fatigue life, indirect tensile strength, resilient modulus and stability.

Hainin, et al. **(**2012) compared the use of steel slag with two different nominal maximum sizes in AC mixes with the conventional AC mix. The Marshall Mix design system was used for samples preparation in accordance with Malaysian specifications. Samples of AC mixes were subjected to the resilient modulus test and creep test. Hainin et al (2012) concluded that steel slag mixes showed lower permanent deformation than conventional asphalt mixes.

Experimental Program

A schematic representation of the experimental program conducted in this research is shown in Figure 2. The laboratory work was divided into three phases as follows:

Phase I included collection and characterization of the limestone aggregates, bitumen and EAFS aggregates.

In phase II, four AC mixes were characterized. The percentage of EAFS in the investigated mixes was 0, and 100% of total weight of aggregates and 60, and 80% of coarse aggregate weight.

Phase III, included the evaluation and analysis of the four different mixes.

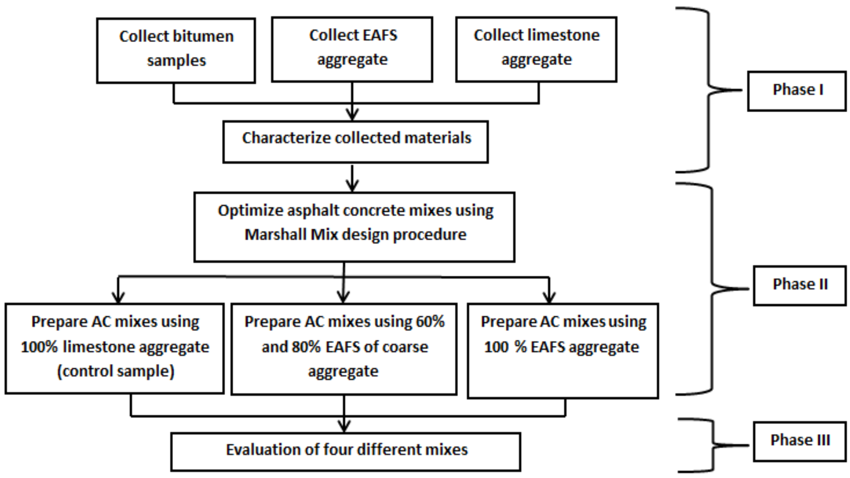

Figure 2. Flow chart of the experimental program

Materials Used

➢ Bitumen

There are three sources of bitumen in Egypt; Suez Oil Processing Co (SOPC), Alexandria Petroleum Co (APC), and Amreya Petroleum Refining Co (APRC). In this study, bitumen from only one source, which is the APRC was used. Penetration, specific gravity, softening point, flash point, and kinematic viscosity tests were conducted on the selected bitumen. Table 1 presents a summary of the results of the routine tests performed on the bitumen. It is noted from the table that all the bitumen properties comply with the Egyptian standards (ECP, 2008).

Table 1. Physical properties of the asphalt cement used in the study.

Properties	Standard	(ECP-2008) Limits	Measured values
Specific gravity	(ASTM D 70)	N/A	1.023
Penetration (*10 mm)	(AASHTO T49)	60-70	62
Softening point (°C)	(AASHTO T53)	45-55 °C	52
kinematic viscosity (cst/s)	(AASHTO T 201)	minimum 320cst/s	374
Flash point (°C)	(AASHTO T48)	minimum 250 °C	270°C

N/A, Not Applicable.

➢ Limestone and steel slag aggregates Gradation

Gradation of limestone and EAFS aggregates were fractionated to lie between the specification limits of the binder course (3d) in accordance with the Egyptian Specifications (ECP, 2008) as shown in Figure 3.

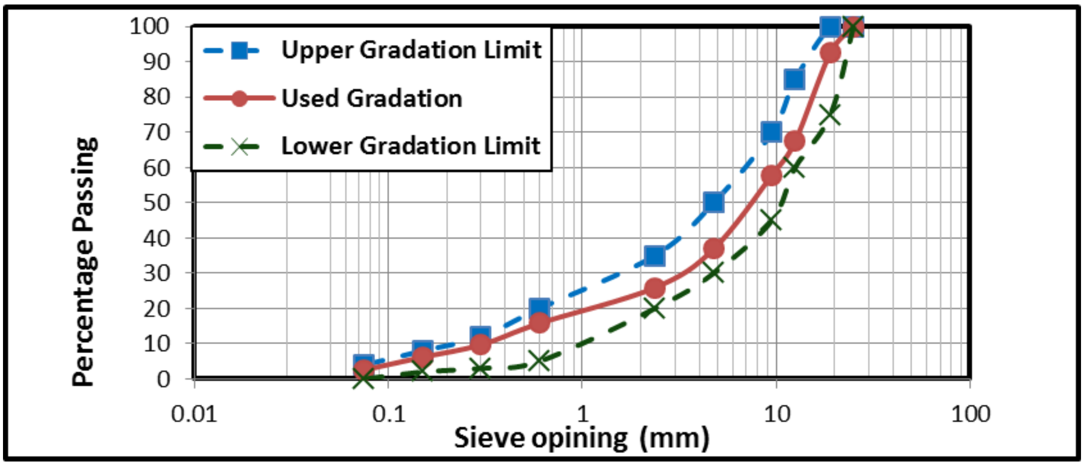

Figure 3. Job Mix Formula gradation for aggregates compared with the specification limits

➢ Physical and mechanical properties

Table 2 lists a summary of the physical and mechanical properties of EAFS and limestone aggregates. EAFS are angular in shape and have a rough surface texture compared to the limestone aggregate. EAFS showed higher bulk specific gravity, lower water absorption, and higher adhesion with bitumen compared with the limestone. Better abrasion resistance and soundness were noticed for the EAFS. The data in Table 2 showed that EAFS and limestone properties are within the specifications limits (ECP, 2008).

➢ Chemical properties

The chemical composition of the EAFS is usually expressed in terms of simple oxides calculated from elemental analysis determined by x-ray fluorescence. Table 3 presents the percentage of compounds exist in the investigated steel slag from the electric arc furnace. It consists primarily of CaO, MgO, SiO_2, and FeO. Of more importance is the mineralogical form of the slag, which is highly dependent on the rate of slag cooling in the steel-making process (Contra Steel Co, 2014).

EAFS contains free calcium and magnesium oxides with percentages of 37.9 and 7.53, respectively, which are not completely consumed in the steel slag. The hydration of free lime and magnesia in contact with moisture is largely responsible for the expansive nature of most steel slags. This needs appropriate processing in construction to prevent asphalt cracks as found in the literature.

Methods, Results, and Discussion

➢ Preparation of Marshall Specimens

Marshall Specimens were prepared and tested according to the AASHTO T 245. Aggregates and bitumen were heated at a temperature of 140ºC. The heated aggregates and the asphalt cement were mixed thoroughly in the mixer. The maximum specific gravity, Gmm of the loose mix was determined by Rice test in accordance with the AASHTO T 209 for all mixes. Fifteen specimens in total at different binder contents ranged from 3.5 to 5.5% were compacted by Marshall's hammer with 75 blows on each side to simulate heavy traffic. Specimens were extracted from the molds and kept at ambient temperature for one day. Bulk specific gravity, Gmb was measured for all mixes; summary of Gmb charts are shown in Figure 4. Specimens were kept in a water bath at 60^oC for 30 minutes, and then tested in Marshall's apparatus to obtain the stability and flow.

Table 2. Physical and mechanical properties of the limestone and slag aggregate used in the study.

Property	Standard	(ECP-2008) Limits	Limestone Aggregate	EAFS
Flat/elongated (1:5 ratio), %	(ASTM D 4791)	10% max	0%	0%
Sand equivalent, %	(ASTM D2419)	45% min	58%	88%
Coarse aggregate specific gravity	(AASHTO T 84)	N/A	2.535	3.300
Coarse aggregate absorption, %	(AASHTO T 84)	5% max	2.27%	1.38%
Fine aggregate specific gravity	(AASHTO T 85)	N/A	2.611	3.356
Fine aggregate absorption %	(AASHTO T 85)	5% max	3.45%	2.16%
Clay lumps and friable particles, %	(AASHTO T 112)	1% max	0.14%	0%
Stripping Value, %	(AASHTO T 182)	95% min	> 95%	> 95%
Abrasion loss (500 rev), %	(AASHTO T 96)	40% max	25.9%	21.8%
Soundness by (Mg SO4), % Soundness by (Na2 SO4), %	(AASHTO T 104) (AASHTO T 104)	18% max 12% max	3.50% 2.40%	2.10% 1.82%

N/A, Not Applicable.

Table 3.The chemical properties of EAFS in this study (Contra Steel Co, 2014)

Component	Percentage %
Free Lime (CaO)	37.9
Silicon dioxide (SiO2)	21.99
Manganese oxide (MnO)	2.24
Magnesium oxide (MgO)	7.53
Aluminum oxide (Al2O3)	7.9
T Fe	22.78

Percentage of air voids, Va%, VMA, and voids filled with asphalt (VFA) were calculated from the volumetric properties of the specimens. The OBC was determined based on the Marshall design charts (Bulk density, Marshall stability and Va). The OBC values for the different mixes were ranged from 4.5 to 4.85%. Marshall flow, VMA and VFA were checked based on the resulted OBC. Table 4 summarizes the Marshall properties for the different mixes. Marshall plots and the relationship between rigidity, which is the ratio of the stability over flow, and the percent of asphalt in the mix for the mixes containing different percentages of slag are shown in Figures 4 through 10.

Table 4. Marshall Properties for the different mixes.

	Control sample	60% EAFS of C.A*	80% EAFS of C.A*	100% EAFS
OBC %	4.85	4.73	4.62	4.50
Stability(Kg)	1100	1440	1570	1930
Bulk density	2.321	2.598	2.675	3.038
Air voids%	4.9	4.4	4.20	3.90
Flow(mm)	3.65	3.5	3.30	2.90
Rigidity(Kg/mm)	301	415	476	666
VMA (%)	15.4	15.1	14.6	14.3
VFA (%)	68.0	70.0	72.0	72.9

Analysis of Marshall Results

Figures 4 through 7 show the bulk density, stability, flow and rigidity values results for all mixes. It is clear from the figures that the 100 % EAFS mix had the highest bulk density, stability and rigidity compared with the other mixes. It is believed that the reason for this may be due to the high specific gravity and low Los Angeles Abrasion values of the EAFS, compared to limestone aggregates as given before in Table 2. ECP (2008) restricts the use of binder course asphalt mixes for heavy traffic roads that has a rigidity value greater than 700 kg/mm however all mixes prepared at OBC met this limit as presented in Figure 7. Slight decrease in the flow values with the increase of EAFS percentage in the mix was noticed as shown in Figure 6. Moreover, all specimens at OBC were within limits of flow of 2-4 mm for heavily trafficked roads as recommended by ECP, 2008. VMA values at OBC were also within specification limits as presented in Figure 9 except the 100% and 80% EAFS mixes. These mixes had a VMA value of less than 15%. However, the Asphalt Institute recommended that minimum, VMA for aggregates with nominal maximum size of 3/4" is 14%.

The percentages of Va, and VMA were found to decrease with the increase of EAFS percentage (Figures 8 and 9). It is believed that the reason for this is that EAFS form more angular in shape and the effect of aggregate interlock may increase the internal friction within the asphalt, which increase Gmm with the increase of EAFS (e.g., Topal and Sengoz, 2006; Park and Lee, 2002). In contrast, Figure 10 shows that the VFA increased with the increase of EAFS percentage. The reason for this that the steel slag aggregate had low absorption value.

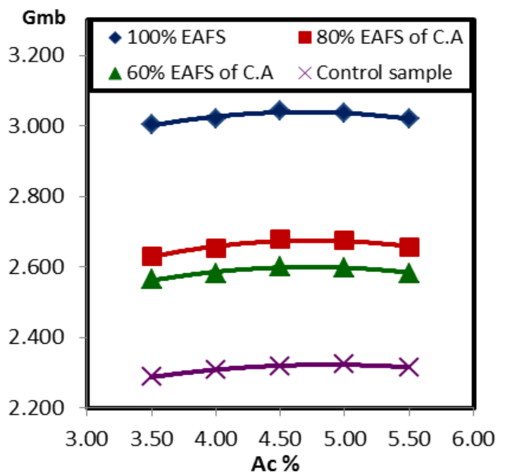

Figure 4.Corrected Bulk Density curves for different asphalt mixtures.

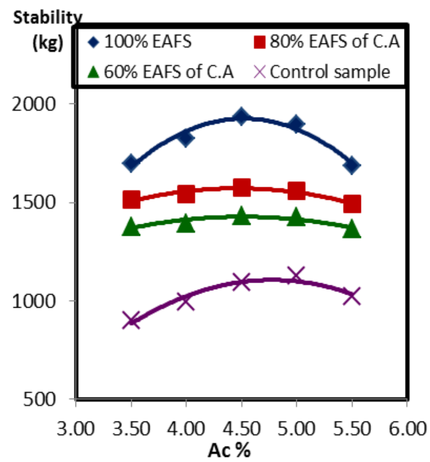

Figure 5.Corrected stability curves for different asphalt mixtures.

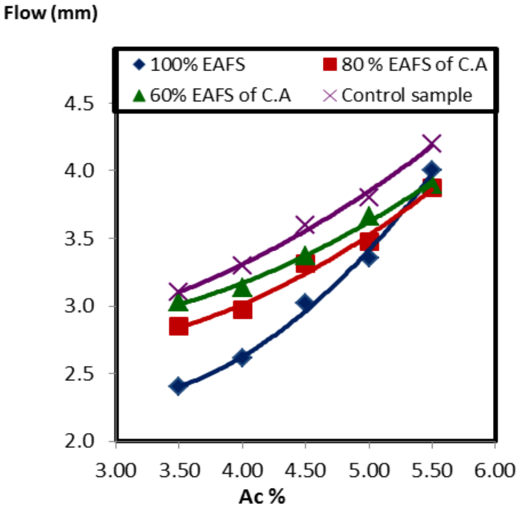

Figure 6.Corrected Flow curves for different asphalt mixtures.

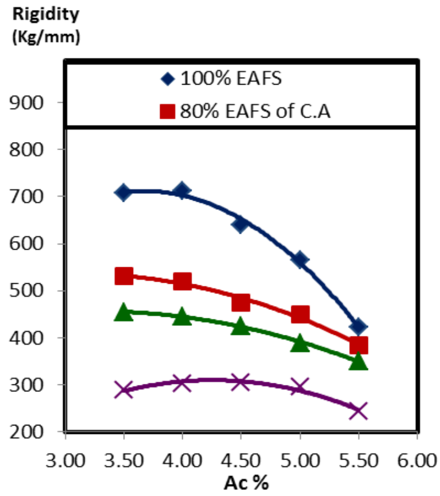

Figure 7.Corrected Rigidity curves for different asphalt mixtures.

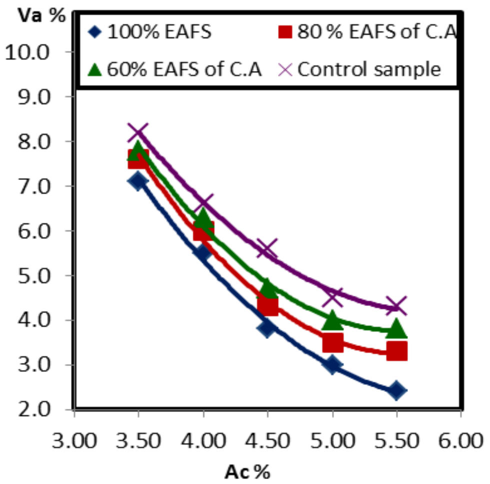

Figure 8.Corrected percentage of air voids curves for different asphalt mixtures.

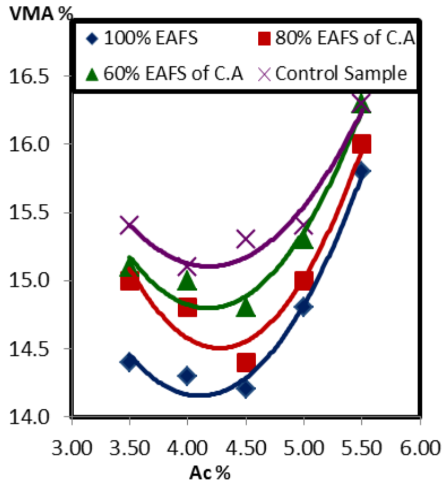

Figure 9.Corrected percentage of VMA curves for different asphalt mixtures.

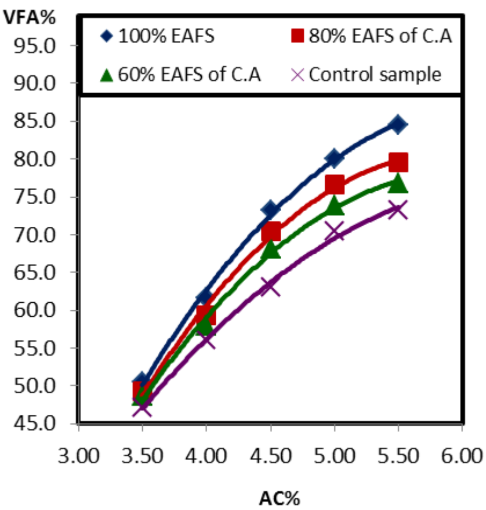

Figure 10.Corrected percentage of VFA curves for different asphalt mixtures.

Conclusions

- The engineering and ecological properties of steel slag aggregate have been accepted in many countries worldwide including Egypt and EAFS was widely utilized in the construction of pavements.
- The results of this study suggest that utilization of steel slag aggregate can benefit the environment and at the same time reduce the amount of limestone and dolomite application in highway construction.
- Research results showed that EAFS had particle properties such as high bulk specific gravity, low Los Angeles Abrasion values, low water absorption and high adhesion with bitumen that can improve the performance of asphalt concrete hot mixes.
- Test results showed that as the EAFS percentage in the mix increased, both the stability and density of the mixes increased. In addition, the flow and VMA decreased with an increase in the EAFS content.
- Further research in particular the determination of dynamic modulus, E* is still required to obtain new specifications for the use of EAFS in different fields of application to conserve Egypt's natural resources. Given the high strength of the materials and the potential employment creation benefits, the research on these materials is continuing.

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