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Chemical Composition of Electric Arc Furnace Slag – A Review

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***Abstract*: This study explores different studies to find out the chemical composition of steelmaking slag produced in electric arc furnace. The statistics in this study is gathered from a thorough review of the several papers in the literatures related to chemical composition of electric arc furnace slag. For this purpose, the paper represents data found from different study and includes data from a steelmaking plant in Bangladesh. Then an investigation is carried out focusing on the chemical compositions of different slags from different parts of the world. The paper finds the huge variability in chemical compositions of different slags under study or the same found from different studies. It is well understandable that chemical composition affects the properties of slag and the properties dictate the applications of the slag. This study has revealed the unique characteristic of electric arc furnace slag that the chemical compositions of these types of slags have lots of variations even between the batches of production in the same plant. It can also be concluded that all EAFS behave very differently, depending on their chemical composition, and must be treated and studied individually. This inherent variability of EAFS offers a vast area for researchers to study.**

***Keywords*: Steelmaking Slag (SS), Electric Arc Furnace Slag (EAFS), chemical composition.**

1. Introduction

There are several steelmaking processes in use throughout the world today. These are open hearth (OH), basic oxygen furnace (BOF), induction arc furnace (IAF) and electric arc furnace (EAF). Steelmaking slag (SS) is a non-metallic ceramic material and a byproduct of steel making processes. The secondary refining of SS through ladle furnaces is done in many occasions now-a-days. Day by day EAF is becoming popular worldwide.

1878 million tons of crude steel was produced in 2020 only. Out of the total production, 73.2% of steel were produced in BOF and 26.3% in EAF and rest 0.50% in OH process. Globally Bangladesh has become 28th steel producing country with a production of 5.5 million tons [1]. Present per capita consumption of steel stands at 45 kg considering the production of steel per annum, which was only 25 kg in 2012 in the country. Lower per capita consumption compared to global standard indicates huge industry prospect. As such the local steel market grew at a rate of 15%-20% in last two years from 8-10% per year previously. However, the per capita consumption is expected to be 73 kg by 2022 which to be met by currently existing more than 400 steel and re-rolling mills of the country [2].

A leading steel industry of Bangladesh produces approximately 200-250 tons of EAF slag (EAFS) per day. It is very likely that the production amount of EAFS will rise in the coming years with the increased production of steel. Steelmaking operations are specifically concerned about the generation of an enormous quantity of by-products. The amassing of a huge amount of EAFS has caused problems such as land occupation, environmental pollution, and waste of resources. Moreover, factories pay so much cost for the disposal of these materials [3].

Sustainable development of construction industry and conservation of natural resources need use of different recycled and industrial by-products in construction sector. The intention of using EAFS to replace natural aggregate in concrete is initially based on its availability and superb physical and mechanical features. The utilization of EAFS can be significantly beneficial in two main ways. Firstly, there will be a considerable reduction in environmental pollution due to changes in the traditional practice, where this is disposed of by dumping or stockpiling. Secondly, the use of EAFS will supplement, or replace, the need for using natural materials. It will also assist in protection in energy requirements associated with the processing of natural materials. Finally, there is huge opportunity of changing or modifying the physical, chemical, mineral and mechanical properties of the conventional concrete incorporating EAFS. Incorporation of EAFS depends on its inherent characteristics which again depend on chemical composition.

The objective of this review is to find out the uniqueness of EAFS based on the chemical compositions of investigated by different researchers in different countries.

2. Production Process of EAFS

The American Society for Testing Materials (ASTM) defines SS as 'a non-metallic product, consisting essentially of calcium silicates and ferrites combined with fused oxides of iron, aluminum, manganese, calcium and magnesium, that is developed simultaneously with steel in basic oxygen, electric arc, or open-hearth furnaces' [4].

EAFS is a liquid by-product generated during the melting of scrap while producing steel. During the separation of the liquid

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steel from impurities in steelmaking furnaces, EAFS is obtained in liquid state. The processing temperature in the EAF rises above 1600°C. The EAF is a kettle-shaped structure with a removable lid, as shown in Fig. 1. The three graphite electrodes that heat the furnace pass through the lid. An electric current is passed through the electrodes to form an arc. The heat generated by this arc melts the scrap. During the melting process, other metals ferro–alloys are added to the steel to give it the required chemical composition. Also, oxygen is blown in to the EAF to purify the steel. Phosphorus, sulphur, silicon and sometimes carbon are removed by lancing oxygen into the melt, forming a liquid oxide slag [5]. After a sample check the chemical composition of the steel, the EAF is tilted to allow the slag, which is floating on the surface of the molten steel, to be poured off into a desired pot.

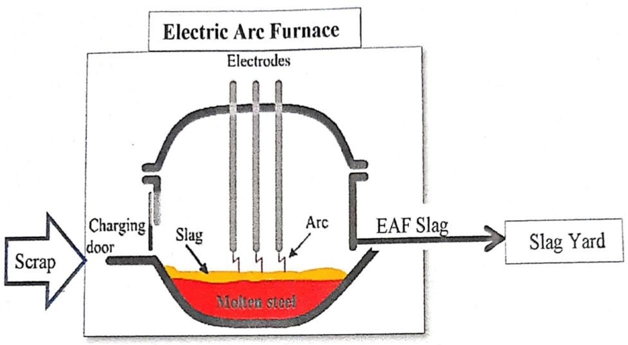


Fig. 1. Production and Processing of EAF Slag (EAFS)

3. Properties of EAFS

The mineralogical composition of SS plays a significant role in its utilization for various purposes [6]. EAFS, a by-product of steelmaking recovered after the oxidizing process [7]. Certainly, its quality depends on its origin. The chemical, mineralogical, and morphological characteristics of SS are determined by the processes that generate this material [8]. Therefore, knowledge of the different types of steelmaking and refining operations that produce SS as a byproduct is also required.

The chemical composition and cooling of molten SS have a great effect on the physical and chemical properties of solidified SS [9]. Also, the rate of cooling from a molten liquid to a solid mainly affects the physical properties of SS aggregate and as such, its chemical reactivity [10]. Similarly, utilization of EAFS is very closely interconnected to the properties of it. That is why knowledge of the physical, chemical, mineralogical, and morphological properties of EAFS is essential to know. Again, it is important to know their cementitious and mechanical properties.

Usually, the properties of the EAFS produced vary depending on the manufacturer, types of steel produced as well as cooling conditions of the slag. Therefore, before EAFS can be recycled into greener products or utilized in different products, it is essential to study and understand the slag properties. This includes how EAFS is formed, its chemical compositions, mineralogical behavior, and hazardous concerns. The frictional properties of EAFS are influenced by its physical features, morphology and mineralogy. Similarly, the volumetric stability of EAFS is a function of its chemistry and mineralogy.

A. *Physical and Mechanical Properties*

EAFS has very good mechanical properties: it is a crushed product with black colour stone appearance and a rough surface texture. It has high abrasion resistance, low aggregate crushing value (ACV) and excellent resistance to fragmentation. It is reiterated that raw EAFS often appears as black/oxidizing slag [11] or grey colored lumps, depending on its ferrous oxide content [12]. Those properties make EAFS particularly suitable in concrete applications, also for structural purposes. The use of steel slag as aggregate in RC structural elements, in principle, is possible, and the rate of substitution could reach the entire part of coarse aggregates [13].

Fig. 2. EAF Slag (EAFS)

EAFS shown in Fig. 2 is found from a steel plant of Bangladesh. It has a very rough surface with numerous of pores. The color of it is brownish black.

B. *Mineralogical Properties*

As the chemical composition of steel slag is highly variable, the mineral composition of steel slag also varies. Olivine, merwinite, C3S, C2S, C4AF, C2F, RO phase (CaOFeO–MnO–MgO solid solution) and free-CaO are common minerals in steel slag [14]. It depends largely on raw materials and slag cooling.

In the same way, final phase composition of the EAFS depends on the temperature at which the cooling occurs. By cooling the liquid EAFS very rapidly, there will not be sufficient time for the crystals to grow. As a result, crystals of the EAFS will be much smaller, resulting in a more homogeneous overall composition. The rapid cooling enables the possibility of having metastable phases at low temperatures.

During the rapid cooling with water, oxidation on the surfaces may occur, and thereby the formation of soluble phases. Side by side, fast cooling will result in an abrasive surface, due to the presence of smaller grains at the surface. An abrasive surface tends to be more reactive than a plane surface, due to the increase in vapour pressure that occurs over a convex surface. Thus, it will result in more grain boundaries due to the increase of small crystals in the material. Diffusion reactions are known to occur easier and faster along these boundaries [5].

Table 1
Chemical Compositions of EAFS (% by Mass of Main Constituents)

S.No.	Source	Chemical Composition of EAFS (% by Mass of Main Constituents)													
		CaO	SiO_2	MgO	MnO	FeO	Fe_2O_3	Fe	Al_2O_3	Free CaO	SiO_3	SO_3	Cr_2O_3	MnO_2	C
1	Australia [22]	45	15	7.50	7.50	18.5			2.0						
2	Chittagong, Bangladesh [23]	56.70	24.09	1.56	0.11		3.56		6.68			4.91			
3	Chittagong, Bangladesh [24]	32.56	14.92	9.34	4.76	17.27			9.56				1.59		
4	Chittagong, Bangladesh [25]	30.77	10.15	8.18	6.18	25.99			5.53				2.1		
5	Chittagong, Bangladesh [26]	28.51	13.47	9.86	5.11	24.8			6.83				2.02		
6	Hamilton, Ontario, Canada [9]	47.50	14.50	10.00	5.50	22.50			5.50						
7	Canada [27]	35.23	9.41	9.77			24.22		10.78						
8	China [20]	47.50	14.50	10.00	6.5	22.5			5.5						
9	China [28]	34.09	28.92	4.15	2.23	18		3.72	5.45		0.13				
10	China [29]	40.00	15.50	10.50	7.50	15	5.50		14.00						
11	China [30]	43.20	27.80	7.35	0.68	7.54	2.74								
12	Sisak, Croatia [31]	24.98	17.08	10.58	8.91		25.45		5.40			0.25			
13	Attaka, Suez, Egypt [32]	33.00	13.10	5.03			36.80		5.51			0.14	0.8		
14	Suez, Egypt [33]	33.00	13.10	5.03	4.18	36.80		5.51					0.775		
15	France [34]	41.70	34.70	9.06	2.15	0.54	6.26								
16	Sidenor, Greece [35]	35.70	17.53	6.45	2.50		26.36		6.25						
17	Hazira, India [36]	22.80	20.30	8.00			42.40		7.30						
18	Pune, India [37]	35.85	10.94	11.66	5.83		26.92		5.17						
19	Surat, India [38]	19.59	22.69	0.23	0.13		40.74		12.75	0.0012					
20	Ahvaz, Iran [39]	25.58	18.72	7.50	0.30		35.16		2.75						
21	Khuzestan, Iran [40]	30.35	15.45	7.78		41.19	2.05			0.3					
22	Iran [41]	34	14	14	2				5						
23	Iran [42]	33.30	19.50	4.25					4.88						
24	NE Part, Italy [43]	30.30	14.56	2.97	4.34	33.28			10.20				2.67		
25	Northern Italy [44]	29.60	13.02	3.65	5.09	32.84			9.3				4.03		
26		29.33	12.95	3.62	5.15	33.12			9.28				4.07		
27	Italy [45]	27.9	9.71	2.17	4.68				8.21						
28	Italy [46]	26.00	14	5	6				12						
29	Amman, Jordan [21]	53.50	10.00	1.50	4.50		11.50	17	1.05						
30	Jubail, KSA [47]	31.42	17.55	12.78	2.46	19.12			7.84						
31		30.53	17.43	13.19	2.66	18.33			7.85						
32	Penang, Malaysia [48]	29.93	21.41	4.89			22.01		9.60						6
33	Malaysia [49]	26.20	18.06	5.80	4.14		28.61		5.88						
34	Malaysia [50]	27.50	19.30	3.07	3.55				9.40						
35	Malaysia [51]	30.00	17.30	5.39	5.03				4.67						
36	Klang, Malaysia [52]	20.90	10.80	1.65					6.86						
37	Malaysia [53]	16.90	26.40	1.86	2.66	43.40		4.84							
38	Malaysia [54]	29.25	20.10	2.87	3.95				8.71						
39	Malaysia [55]	27.20	20.80	2.06	3.98				9.19						
40	Osun, Nigeria [56]	5.00	42.40				31.90		15.00						
41	Ota, Nigeria [3]	35.00	12.00	6.00	7.00	39.50			10.00	2.50					
42	Romania [57]	40.78	17.81	8.53	9.79	9.25	3.97	13	4.23			0.74	1.42		
43	Spain [58]	27.50	11.50	5.70	3.50	21	25.50		5.25	2.00					
44	Spain [7]	23.90	15.30	5.10	4.50				7.40						
45	Spain [59]	30.00	15.00	5.50	>6	33.50		6.50							
46	Spain [60]	27.70	19.10	2.50	5.30	26.80		13.70							
47		50.50	12.60	7.50	0.40		1.60		4.30	3.50					
48		57.50	19.80	11.90	0.50		3.30		18.60	19.00					
49	Spain [58]	32.90	20.30	3.00	5.10				12.20						
50	Spain [60]	26.70	20.90	3.20	4.60				12.10						
51	Spain [16]	24.40	15.40	2.90					12.20						
52	Sweden [14]	45.50	32.20	5.20	2.00	3.3	1.0		3.70						
53		38.80	14.10	3.90	5.00	5.6	20.3		6.70						
54	Trinidad and Tobago [10]	46.00	14.50	7.50			25.0		2.00					6.50	
55	US & Canada [9]	47.50	14.50	10	5.50	22.5			5.5						
56	US & Canada [61]	32.44	13.95	11.20	5.37	26.85			8.29				1.48		
57	USA [62]	32.10	19.40	9.40	6.80	26.40		8.60			0.6				
58	USA [63]	35.00		8.00	6.00		29.0		5.00		14.00	0.1			
59	Vietnam [64]	25.90	16.30	6.86	5.18	34.70		8.31							

C. *Chemical Properties*

The chemical properties of EAFS depend on the chemical composition which vary depending on the type of furnace, feed stock i.e., raw materials and slag formers used to produce the steel. Again, when dumped in the factory yards or any place, the chemical composition of the EAFS changes due to the exposure to environment of that place. So, the raw materials used for producing steel and exposure of EAFS to environment of the specific locality greatly contribute in varying the chemical composition leading to its chemical properties.

The main chemical constituents of EAFS can vary widely. The SS mainly consists of SiO_2, CaO, Fe_2O_3, FeO, Al_2O_3, MgO, MnO and P_2O_5 [15]. Typically, the FeO, CaO, SiO_2, Al_2O_3, and MgO contents of EAFS are in the 10–40%, 22–60%, 6–34%, 3–14%, and 3–13% ranges, respectively. Other minor components include other oxidized impurities, such as MgO, MnO, and SO_3. EAFS also contain free CaO and MgO along with other complex minerals and solid solutions of CaO, FeO, and MgO [8]. It is also indicated that the iron content can be up to 40% [16].

Due to the variation in steelmaking raw materials and smelting processes, the chemical composition and mineral phase, types of EAFS from different producing areas will be different. The EAF steelmaking process is essentially a steel scrap recycling process. The feed (charge) into the furnaces vary from one steelmaking plant to another, so variations in the chemical constituents of steel slags produced at different steelmaking plants are expected [8]. Therefore, the chemical composition of EAFS depends significantly on the properties of the recycled steel.

Again, the chemical composition of SS depends on the steelmaking process which is also an important factor for its CO_2 reactivity [17]. Even greater variation can be introduced by the composition of the Iron-bearing feed and the batch nature of the steelmaking processes. It is noteworthy that EAFS composition is dependent on the raw material source and its chemistry can vary from one batch to another.

4. Chemical Compositions of Different EAFS

It is known that EAF slag from different parts of the world and different manufacturers can exhibit a different appearance and physical properties, depending on the composition of steel scrap that is used as feed materials, the type of furnace, steel grades and refining processes.

The feature of the slag produced at each steel manufacturing facility will vary because it depends on the generation process of steel used. The quality and composition of SS depend on the steel scrap used as raw material, type and share in the heat of specific nonmetallic supplements, type and amount of ferroalloys, and other technological parameters [18].

From the review of several studies, factors on which the properties of the SS depend can be summarized. These are the furnace type and condition, source, type and chemical composition of steel scrap and other raw materials, type of process (batch process in which reactions are not always completed, thus resulting in a non-uniform slag), use of Dolomite, types of steel produced, type and rate of cooling, age of the SS, hazardous contents etc.

Table 2
Chemical Compositions of EAFS (% by Mass of Minor Constituents)

S.No.	Source	Chemical Composition of EAFS (% by Mass of Minor Constituents)													
		P_2O_3	P_2O_5	Na_2O	K_2O	TiO_2	Mn_2O_3	ZnO	ZrO_2	P	Cr	B_2	V	S	F
1	Australia [22]		1.25												
2	Chittagong, Bangladesh [23]		0.13	0.15	0.97	0.99									
3	Chittagong, Bangladesh [24]		0.42											0.10	
4	Chittagong, Bangladesh [25]		0.46											0.10	
5	Chittagong, Bangladesh [26]		0.52											0.10	
6	China [20]		1.5												
7	China [28]		1.01												
8	China [29]		3.50												
9	Sisak, Croatia [31]			0.12	0.13									0.10	
10	Attaka, Suez, Egypt [32]	0.7				0.60									
11	Suez, Egypt [33]					0.60									
12	Sidenor, Greece [35]			0.20	0.26	0.76		0.85							
13	Hazira, India [36]			0.63	0.82	0.32									
14	Pune, India [37]			0.50	0.5										
15	Surat, India [38]		0.60												
16	Khuzestan, Iran [40]			0.42	0.08	0.68									
17	Northern Italy [44]					0.35									
18						0.36									
19	Amman, Jordan [21]		2.75	0.03	0.03									0.11	
20	Jubail, KSA [47]											1.79	1.74		
21												1.75	1.73		
22	Malaysia [49]		0.71	0.30	0.19	0.64									
23	Osun, Nigeria [56]				2.05		0.20								
24	Ota, Nigeria [3]		2												
25	Romania [57]													0.30	
26	Spain [59]					0.30									
27			0.01			0.90									
28	US & Canada [9]									0.13	0.55			0.10	
29	US & Canada [61]				0.05	0.47			0.07	0.30				0.30	0.70
30	USA [62]					0.40									

The chemical composition of SS is most commonly analyzed using X-Ray Fluorescence (XRF) spectroscopy. It may be defined by different oxides present in SS. Mainly oxides like CaO, Al_2O_3, SiO_2, MgO, Fe_2O_3, FeO, MnO, P_2O_5, TiO_2 and Free CaO remain present in SS. Beside there may be other several oxides, metallic or nonmetallic chemical elements too. Now comparisons of some constituents of the EAFS from different parts of the world are described in the following paragraphs.

Unlike natural stone, steel slag contains excess free calcium oxide (f-CaO) or/and free magnesium oxide (f-MgO) on its surface. Volume expansion of SS is based on free lime [19] when it hydrates when it come in contact with water [20]. So, it is worth noting that this SS may be subjected to volumetric instability problems.

The presence of free lime and periclase (MgO) in SS affects the characteristics of it. Several factors contribute to the presence of free lime and periclase, dealing particularly with the steelmaking process and to the slag cooling, from furnace to environmental temperature. In the case of SS, the slag contains metallic elements such as iron in oxide form; however, because refining time is short and the amount of limestone contained is large, a portion of the limestone auxiliary material may remain un-dissolved as free CaO [21].

The main chemical components found in EAFS whose maximum average mass ranges more than 3.5% are listed below. There are total 14 elements, i.e. CaO, SiO_2, MgO, MnO, Fe, FeO, Fe_2O_3, Al_2O_3, Free Lime (CaO), SiO_3, SO_3, Cr_2O_3, MnO_2 and C are significantly found in SS. A summary of these elements found from 59 different studies carried out in 21 countries are shown in the table 1.

The chemical compositions (%) by mass found in maximum 3.5% are listed below. There are total 14 elements, i.e. P_2O_3, P_2O_5, Na_2O, K_2O, TiO_2, Mn_2O_3, ZnO, ZrO_2, P, Cr, B_2, V, S and F is seen to be scantily found in SS. A summary of these elements found from 59 different studies carried out in 21 countries are shown in the table 2.

5. Discussions

The main chemical constituents of EAF slags can vary widely. Based on the studies, the CaO, SiO_2, MgO, MnO, Fe, FeO, Fe_2O_3, Al_2O_3, Free Lime (CaO), SiO_3, SO_3, Cr_2O_3, MnO_2 and C contents of EAF slags are in the 5–57.50%, 0–42.40%, 0–13.19%, 0–9.79%, 0-17%, 0-39.50%, 0-42.40%, 1.05-18.60%, 0-19%, 0-14% 0-4.91%, 0-4.07%, 0-6.50% and 0-6% ranges, respectively. It shows CaO and Al_2O_3 are the common main constituents of EAFS in all the 59 studies. So, these are the main two elements which are found in EAFS.

From the studies, Maximum CaO% was found in the EAFS of a study carried out in Spain. Besides lowest CaO% was found in the EAFS of a study carried out in Nigeria. Free Lime (CaO) was found in EAFS of China, Nigeria and Spain significantly and very scantily in India. It is mentionable that the volume expansion of SS depends predominantly on Free Lime (CaO). MgO may also contribute to expansion of SS. A major disadvantage of SS, as utilized in the construction industry, is the likelihood of volume changes (expansion), considering that substantial proportions of free calcium and magnesium oxides (CaO and MgO) [65]. Maximum MgO% was found in the EAFS of a study carried out in Kingdom of Saudi Arabia. Besides lowest MgO% was found in the EAFS of a study carried out in India. MgO regulates and manages the crystallization, and further improves the sintering characteristics. It also increases porosity and bending strength of EAFS.

The oxides of Ca and Mg contents, contribute to overall basicity and cementitious strength. However, as-produced SS is chemically unstable as these oxides readily form hydroxides and carbonates through reaction with atmospheric gases. After a certain limit, both hydroxide and carbonate formation may produce substantial mechanical swelling, leading to heave failure in confined construction applications.

Maximum SiO_2% was found in the EAFS of a study carried out in Nigeria. Besides No trace of SiO_2% was found in the EAFS of a study carried out in USA and Canada. SiO_2 increases mechanical strength of the EAFS. SiO_3 was only found in the EAFS of a study carried out in USA and it was substantial. SO_3 was found in the EAFS studied in Bangladesh, Croatia, Egypt, Romania and USA. SO_3% was significantly found in a study in Bangladesh. However, it was scantily (<1%) found in the studies in China, Croatia, Egypt, Iran, Romania and USA. It may enhance the expansive performance of EAFS.

Maximum FeO found in EAFS in African countries like Nigeria is 39.50%. No trace of FeO was found in the SS of Croatia, Jordan, India and Greece. Fe_2O_3 increases specific capacity, density, electro- chemical properties and mechanical performance, but reduces pore size. The high iron oxide content of the aggregate results in very hard and very dense aggregate (20-30% heavier than naturally occurring aggregates such as basalt and granite) [66]. It has rough surface texture as it is very angular, roughly cubical pieces with a flat or elongated shape and porous (as shown in Fig. 2). It is also observed that the flakiness index value for slag was generally low which attributes to the rounded shape of SS. SS aggregate (SSA) are hard and durable and resistant to abrasion.

Maximum MnO% was found in the EAFS of a study carried out in Romania. No MnO trace was found in EAFS in Trinidad and Tobago. MnO shows high adsorption ability of EAFS. Again, maximum Al_2O_3% was found in the EAFS of a study carried out in Spain. The lowest Al_2O_3 trace was found in EAFS in Jordan (1.05%). It removes most of the oxygen in the EAFS and produces deoxidized steel. Thus, provides abrasive property through hardness and strength through densification and mechanical strength.

Cr_2O_3 is responsible for the color of the EAFS when present. It may also provide some resistance to acid. Maximum Cr_2O_3% was found in the EAFS of a study carried out in Italy (4.07%). Some trace of Cr_2O_3 was also found in the EAFS of Bangladesh, Canada, Egypt, Romania and USA. MnO_2 in a good percentage was found in a study carried out in Trinidad and Tobago only. Some of the known heavy metals that might be present in EAF slag are Cd, Cr, Cu, Mn, Pb, and Zn. Although these heavy metals often appear only as trace elements, they may very well serve as the factors of pollution and toxicity. Like soil pollution by heavy metals is particularly concerning owing to its toxicity. The toxicity and mobility of these harmful elements depends on factors, such as oxidation state, molecular geometry, and environmental conditions [67].

The Fig. 3 below gives a representation of the oxides of EAFS only found commonly where studies were conducted in the 21 source countries. The percentage of average of mass indicates the average of any element found in studies carried out in the particular country.

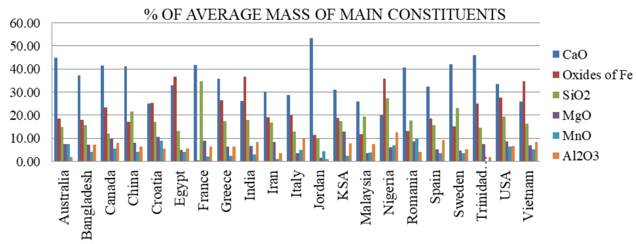


Fig. 3. Chemical compositions of main constituents of EAFS (% of Average Mass)

Based on the averages, the CaO, SiO_2, MgO, MnO, all Fe ($Fe+FeO+Fe_2O_3$) and Al_2O_3 are common among the 21 countries. In China, all the eight oxides are found shown in the Figure 3. The main constituents of EAFS in China are shown in the Fig. 4.

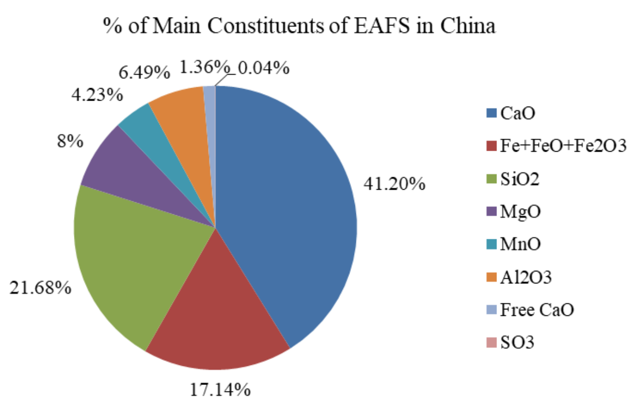


Fig. 4. Percentages of main constituents of EAFS in China

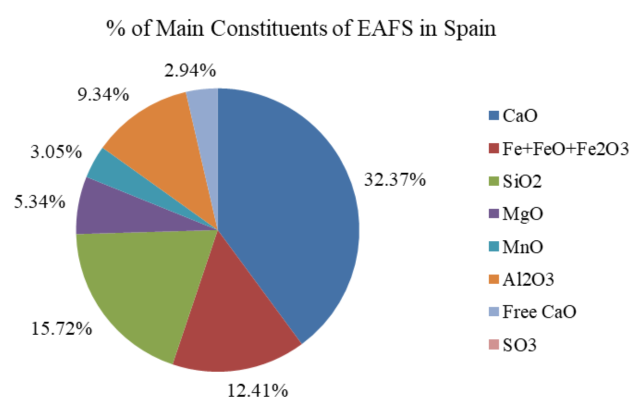


Fig. 5. Percentages of main constituents of EAFS in Spain

Again, seven elements were found in each of Bangladesh, Croatia, Egypt, India, Iran, Nigeria, Romania, Spain and USA. Considering the amount of the free CaO and SO_3, the constituents are shown in the Fig. 5.

It is noteworthy that EAFS composition is dependent on the raw material source and its chemistry can vary from one batch to another. The rate of cooling from a molten liquid to a solid mainly affects the physical properties of SS and as such, its chemical reactivity.

Based on the studies the ranges of P_2O_3, P_2O_5, Na_2O, K_2O, TiO_2, Mn_2O_3, ZnO, ZrO_2, P, Cr, B_2, V, S and F are 0-0.70%, 0-3.50%, 0-0.63%, 0-2.05%, 0-0.99%, 0-0.20%, 0-0.85%, 0-0.07%, 0-0.30%, 0-0.55%, 0-1.79%, 0-1.74%, 0-0.30% and 0-0.70% respectively.

P_2O_3% was found in a little percentage in the EAFS of a study carried out in Egypt only. Besides Maximum P_2O_5% was found in EAFS in China is 3.50%. However, no trace of P_2O_5 was found in the EAFS of Canada, Croatia, France, Greece, Iran, Italy, Romania, Sweden, Trinidad and Tobago, USA and Vietnam. P_2O_3 increases flame retardancy and P_2O_5 increases thermal stability, conductivity, and mechanical flexibility in a composite material. P_2O_3 and P_2O_5 might show some hazardous characteristics when present in the EAFS.

Maximum Na_2O% was found in the EAFS of a study carried out in India (0.63%). No trace of Na_2O was found in the EAFS of Australia, Canada, Egypt, France, Italy, Kingdom of Saudi Arabia, Nigeria, Romania, Sweden, Trinidad and Tobago, USA and Vietnam. Na_2O manages the crystallization, and further improves the sintering characteristics and also increases porosity in a composite material.

Maximum K_2O% was found in the EAFS of a study carried out in Nigeria (2.05%). No trace of K_2O was found in the EAFS of Australia, Canada, Egypt, France, Italy, Kingdom of Saudi Arabia, Nigeria, Romania, Sweden, Trinidad and Tobago and Vietnam. It improves densification and mechanical strength of a composite material.

Mn_2O_3 trace was found in a study in Nigeria only. It may increase the surface area, specific capacity, adsorption efficiency and electro- chemical properties of EAFS. Maximum TiO_2% was found in the EAFS of a study carried out in Bangladesh (0.99%). No trace of TiO_2 was found in the EAFS of Australia, Croatia, France, Jordan, Kingdom of Saudi Arabia, Nigeria, Romania, Spain, Sweden, Trinidad and Tobago and Vietnam. It improves crystallization, viscosity, and mechanical properties of a composite material.

ZnO trace was found in EAFS of Greece only. It may improve the interfacial bonding and hence, may develop tensile strength of EAFS. ZrO_2, Cr, F and P traces were found in EAFS of Canada and USA only. ZrO_2 improves microstructure properties and solubility. Again it protects composite structure from crack propagation. Cr enhances mechanical performance (tensile strength), interfacial bonding strength, and thermal conductivity of EAFS. Compressive strength decreases with increasing F content.

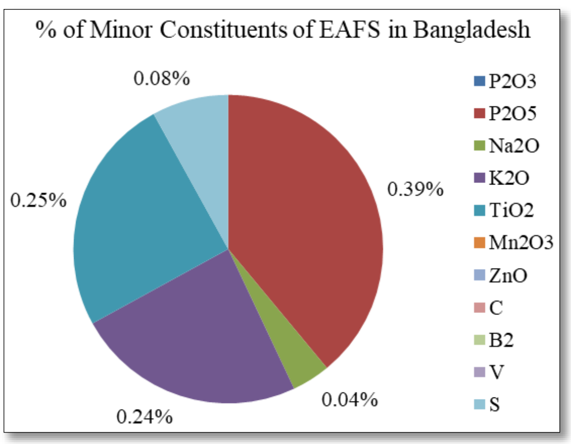
C trace was found in EAFS of Malaysia and Romania. B_2 and V traces were found in EAFS of Kingdom of Saudi Arabia only. B_2 may influence the hardness and tensile strength of EAFS. V has the capability of influencing the hardness and wear resistance of EAFS. S traces were found in EAFS of Bangladesh, Canada, Jordan, Romania and USA. Country wise

Table 3
Chemical Composition of Minor Constituents of EAFS (% of Average Mass)

Serial	Source Country	Chemical Composition (% of Average Mass) of Minor Constituents										
		P_2O_3	P_2O_5	Na_2O	K_2O	TiO_2	Mn_2O_3	ZnO	C	B_2	V	S
1.	Australia		1.25									
2.	Bangladesh		0.39	0.04	0.24	0.25						0.08
3.	Canada		-									
4.	China		2.00	0.25	0.25	0.25						
5.	Croatia			0.12	0.13							0.10
6.	Egypt	0.35				0.60						
7.	Greece			0.20	0.26	0.76		0.85				
8.	India		0.20	0.34	0.44	0.11						
9.	Iran			0.14	0.02	0.17						
10.	Italy					0.14						
11.	Jordan		2.75	0.03	0.03							0.11
12.	KSA									1.77	1.74	
13.	Malaysia		0.09	0.04	0.02	0.08			0.75			
14	Nigeria		1.00		1.03		0.10					
15.	Romania								1.00			0.30
16.	Spain					0.13						
17.	USA					0.20						

averages of minor elements found in EAFS are presented in the Table 3.

Based on the averages of Table 4, out of 14 elements, maximum of five elements were found in the EAFS of Bangladesh and Malaysia in very less percentages. P_2O_5, Na_2O, K_2O, TiO_2 and S are in EAFS of Bangladesh and P_2O_5, Na_2O, K_2O, TiO_2 and C are in EAFS of Malaysia. These are shown in the Fig. 6.



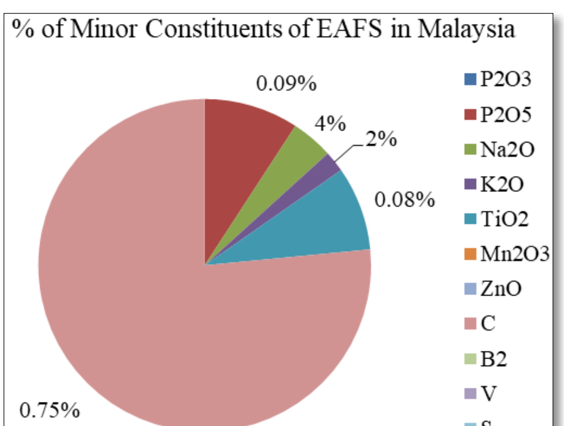


Fig. 6. Percentages of minor constituents of EAFS in Bangladesh and Malaysia

6. Conclusion

This paper summarizes the findings acquired from a wide-ranging literature review focused on the chemical compositions related to different types of EAFS as well as identifying corresponding areas of study for future viewpoints. The comprehensive review implies that the variations of the EAFS are based on the significant differences in chemical compositions of EAFS. It is evident that different types of chemical compositions result in different properties of EAFS. This also has a great influence on the applications of EAFS.

EAFS is a complex solution of silicates and oxides that solidifies during cooling. There is typically a large variation in the physical, chemical, and mineralogical properties of all types of EAFS being produced in different parts of the world. This difference depends on the steel-making plant, steel-making process, raw materials of the plants, and types of furnace, processing, the grade of steel produced, and storage strategies. For this reason, the behaviors and characteristics of EAFS is very different from one to another. Thus, EAFS must be considered with recognition of the inherent variability. This is the uniqueness of EAFS.

Furthermore, the chemical composition of EAFS varies from country to country and even within the same country region to region and further due to every single factor related with the production system. The variation is for the differences in the composition of raw materials used, for the differences of types of furnaces used or in operating procedures in batching or in others in the plant. Thus, variations can even be seen from factory to factory, plant to plant and even batch to batch. Even the process, rate and speed of cooling matters in producing slag.

It can also be concluded that all EAFS behave very differently, depending on their chemical composition, and must be treated and studied individually. This inherent variability of EAFS offers a vast area for researchers to study. This huge research field may be explored and studied thoroughly to utilize EAFS in all the possible sectors for the development of the human civilization. Hence this warrant independent research on each and every type of EAFS.

The generation of an enormous quantity of EAFS as by-products of steelmaking operations has become a great concern for the steel industry. The amassing of a huge amount of EAFS has caused and causing several problems also. If these EAFS are suitably utilized, problems of steel industry would be reduced to a bearable one.

Finally, the review conducted on the different kinds of EAFS studied by several researchers can be concluded like this. Considering the variety of the chemical compositions of EAFS, each type of EAFS requires separate research to be able to understand the chemical characteristics of EAFS and related engineering properties for its applications.

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