Electric Arc Furnace Slag

Subjects: Ergonomics

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EAF slag is a non-metallic by-product that consists mainly of silicates and oxides formed during the process of refining the molten steel. Raw EAF slag often appears as grey or black colored lumps, depending on its ferrous oxide content. This type of slag generally has a rough surface texture, with a surface pore diameter of 0.01–10 μm.

Keywords: EAF steel slag waste ; Steel making industry

1. Introduction

Steel is one of the most popular construction materials in the world. This alloy is typically used as support for structural frameworks of all sorts of constructions, ranging from skyscrapers to highway construction. The main reason why steel is so commonly used is simply due to its unique combination of strength, durability, workability, and cost. However, while being one of the world's largest industries, the steelmaking industry is known to have significant negative impacts on the environment [1][2]. Although steel can be produced through recycling scrap iron, researchers have estimated that about two billion tons of iron ore and one billion ton of metallurgical coal are used in the global steel industry every year [3]. In addition to the raw material requirement, there are also issues regarding the steel slag by-product disposal. Based on previous reports, around 190–290 million tons of steel slag are generated every year [4]. Most of the global steel slag ends up being disposed of, with only a small portion recycled [5][6][7][8][9][10][11][12][13][14][15][16][17][18][19][20]. Studies have also shown that the recycling rate of steel slag is still generally much lower in Asian countries [2][21][22][23][24][25][26][27][28][29][30][31][32][33][34].

With the Earth’s ability to sustain life eroding every day, there is an urgent need to reduce the waste produced and preserve the non-renewable resources. Thus, the present review’s main goal was to assess the EAF steel slag's recycling potential, especially for the Malaysian steelmaking industry. Possible steel slag recycling options were evaluated based on the engineering properties. Moreover, as sustainable development has been highlighted these past few years, it is generally known that countries with higher human development tend to have extreme environmental problems [35].

2. Characterization of Steel Slag

Generally, the properties of the steel slag generated varies depending on the manufacturer, types of steel produced as well as cooling conditions of the slag. Therefore, before steel slag can be recycled into greener products, it is essential to investigate and understand the slag properties. This includes how steel slag is formed, its chemical compositions, mineralogical behavior, and hazardous concerns. The scope of discussion in the present review will focus on EAF steel slag, which is the most common steel by-product in Malaysia.

2.1. Formation of Electric Arc Furnace (EAF) Slag

EAF slag is a non-metallic by-product that consists mainly of silicates and oxides formed during the process of refining the molten steel. As mentioned previously, the feed materials for EAF are mainly steel scrap and pig iron. It is generally known that steel scrap contains impurities such as phosphorus (P), aluminum (Al), manganese (Mn), and silicon (Si). The presence of these impurities deteriorates the mechanical properties of the steel product. Thus, it is essential to perform additional refining or treatment processes to remove the impurities from the molten steel. During this refining process, oxygen gas is injected directly into the molten steel to oxidize the impurities that are present. These oxidized impurity compounds combine with the lime added during the refining process, forming a layer of molten slag. The molten slag has a lower density than the molten steel and will remain on top of the molten steel [36][37]. Upon completion of the melting process and the steel has achieved its desired chemical composition, the slag and molten steel will be discharged separately [19]. Thus, the EAF slag might contain a low amount of iron oxide that originates from iron oxidation when oxygen is injected.

The EAF slag actually plays several other roles in refining the molten steel, in addition to its main function of absorbing deoxidation products and impurities from the molten steel [38]. One of these is to protect the electrodes and refractories in the furnace from thermal radiation by inhibiting oxidation [39]. The slag also protects the molten steel against re-oxidation and acts as a heat insulator to prevent heat loss to the surroundings. This would serve to increase the thermal efficiency in EAF by refining the furnace heat-up rate, maximizing the active power of the transformer and better electrical stability.

2.2. Properties of EAF Slag

Raw EAF slag often appears as grey or black colored lumps, depending on its ferrous oxide content [40][41]. This type of slag generally has a rough surface texture, with a surface pore diameter of 0.01–10 μm [42]. Examples of EAF slag from different countries is shown in Figure 1. EAF slag is generally categorized as aggregates with a particle size range of 5–40 mm, and has a similar appearance to aggregates that are commonly used in the construction industry [43]. It is known that EAF slag from different regions 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. Nonetheless, EAF slag typically has Mohs hardness values in the range of 6–7, regardless of the differences in chemical compositions [44].

The water absorption and density of EAF slag from different sources (including Malaysia) are presented in Table 1. From this table, the water absorption of EAF slag is around 0.5–4.0%, while its density is in the range of 2.8–3.9 g/cm^3. There is no clear connection between the water absorption and density of EAF slag. Water absorption is an essential property for the EAF slag, as it represents the ability of fluids penetrating the slag body and causes degradation. It is reported that degradation such as carbonation occurs when EAF slag with high basic (alkaline) contents (i.e., Ca and Mg oxides) is exposed to an acidic source (i.e., CO_2 or H_2CO_3). The process of acidic source neutralization forms a decomposed carbonate phase [45][46]. Although it is generally agreed that more porous EAF slag would have higher water absorption values, this does not necessarily translate to a higher density. Instead, EAF slag with a higher iron content could potentially have a higher density.

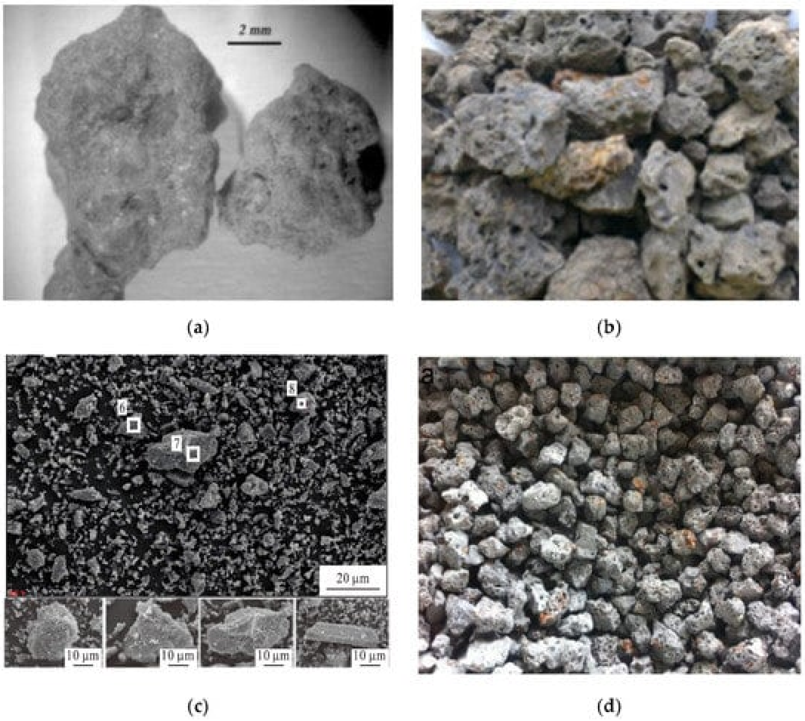

Figure 1. EAF slag samples from different countries. (**a**) Italy [43]; (**b**) Malaysia [47]; (**c**) China [27]; and (**d**) Spain [11]. Color variation of EAF steel slag is due to the different chemical compositions and oxidation conditions.

Table 1. Water absorption and density of electric arc furnace (EAF) slag as reported in various studies.

Water absorption (%)	Density (g/cm^3)	Sources	References
–	3.30–3.60	China	[33]
2.00	1.54–2.90	India	[23]

2.60	2.80	France	[10]
3.90	2.82–3.05	Malaysia	[48]
2.30–3.40	3.63–3.76	Italy	[42]
0.950	3.85	Italy	[49]
<4.00	3.40	Spain	[11]
1.12–3.55	3.51–3.64	Spain	[12]
1.12	3.42	Spain	[13]
2.93	3.40	Vietnam	[28]
–	2.84	China	[27]
1.50	3.56	Malaysia	[50]

2.3. Chemical Composition and Mineralogy of EAF Slag

The chemical composition of EAF slag is most commonly analyzed using x-ray fluorescence (XRF) spectroscopy. The weight percentage of each element present in the EAF slag, as reported by several sources including Malaysia, is presented in Table 2. In this table, the different types of iron oxides (i.e., FeO, Fe_2O_3, or Fe_3O_4) in EAF slag are represented as total Fe (FeOx). The main elements in the EAF slag are iron (Fe), calcium (Ca), silicon (Si), and aluminum (Al) oxides, while the minor elements in the EAF slag are magnesium (Mg) and manganese (Mn) oxides, although it should be mentioned that trace elements in the EAF slag with wt.% of <1.0% such as lead (Pb), phosphorus (P), and fluoride (F) were not included in Table 2. It is believed that the compositions of EAF slag from different sources would vary often, based on the composition of the scrap steel materials used for the steel production, the grade of steel produced, and the condition of the EAF refractory lining [19][38][51]. The inconsistent chemical composition issue is one of the main reasons that prevent EAF slag from being effectively recycled into new products at an industrial scale. Thus, in order to ensure a thorough representative of the slag sample and reproducibility of the analysis, a proper sampling method has to be performed prior to its recycling.

Table 2. Typical chemical composition of EAF slag reported by several researchers.

EAF slag Source	**Type of steel**	Chemical composition						Reference
		CaO	Total Fe	SiO_2	Al_2O_3	MgO	MnO	
Iran	–	34.0	25.0	14.0	5.00	14.0	2.00	[6]
India	–	22.8	42.4	20.3	7.30	8.00	–	[21]
China		30.0–50.0	5.00–22.0	11.0–20.0	10.0–18.0	8.00–13.0	5.00–10.0	[33]
Malaysia	–	27.5	33.3	19.3	9.40	3.07	3.55	[52]
Egypt	–	33.0	36.8	13.1	5.51	5.03	–	[7]

Malaysia	–	29.0–29.5	31.7–32.5	19.7–20.5	8.83–8.58	2.60–3.13	3.94–3.95	[22]
Italy		27.9	37.5	9.71	8.21	2.17	4.68	[9]
Malaysia	Carbon steel	16.9	43.4	26.4	4.84	1.86	2.66	[47]
Malaysia	–	27.2	33.3	20.8	9.19	2.06	3.98	[29]
France	Stainless steel	41.7	0.540	34.7	6.26	9.06	2.15	[10]
Italy	–	26.0	35.0	14.0	12.0	5.00	6.00	[42]
Spain	Carbon steel	27.7	26.8	19.1	13.7	2.50	5.30	[12]
Spain	Carbon steel	25.0–35.0	17.0–50.0	10.0–20.0	3.00–10.0	2.00–9.00	<6.00	[11]
Spain	–	32.9	22.3	20.3	12.2	3.00	5.10	[13]
Malaysia	–	29.9	22.0	21.4	9.60	4.89	–	[53]
Vietnam	Carbon steel	25.9	34.7	16.3	8.31	6.86	5.18	[28]
China	Stainless steel	43.2	7.54	27.8	2.74	7.35	0.680	[27]
Spain	–	26.7	24.5	20.9	12.1	3.20	4.60	[15]
Malaysia	–	26.2	28.6	18.1	5.88	5.80	4.14	[54]
Malaysia	–	20.9	43.0	10.8	6.86	1.65	–	[30]
Malaysia		30.0	27.3	17.3	4.67	5.39	5.03	[50]
Iran	–	33.3	25.9	19.5	4.88	4.25	–	[17]

EAF slag is well known for its highly complex crystallinity due to the presence of several mineral phases [9]. The mineral phases present in EAF slag from different sources, identified through x-ray diffraction (XRD) analysis, are shown in Table 3. According to Chiang and Pan (2017), the crystalline phases in EAF slag can be divided into those that consist of iron oxides (i.e., wustite, magnesioferrite, magnetite, and hematite), silicates (i.e., larnite, bregedite/merwinite, and gehlenite), and manganese oxides (i.e., birnessite, hausmannite, rutile/hollandite, and groutellite) [55]. In most cases, each of these minerals' XRD patterns overlaps with the other and needs to be appropriately identified [9][19][55]. The mineralogy and crystalline phases in the EAF slag are dependent on the chemical compositions of the molten slag and the cooling process. Both of these factors will result in the variation of crystalline phases being formed in the slag. It is known that each chemical composition in the EAF slag exhibits specific properties that would serve to provide different functions when recycled into new products, as described in Table 4 [26][33].

Table 3. Typical crystalline phases present in EAF slag proposed by various researchers.

EAF slag source	Crystalline phases							Reference
	Bredigite	Gehlenite	Larnite	Merwinite	Hematite	Wustite	Magnetite	

Sweden			✓	✓	✓			[5]
Iran	✓					✓		[6]
India	✓	✓				✓		[21]
UAE	✓		✓			✓	✓	[41]
Italy			✓		✓	✓		[56]
Malaysia		✓	✓			✓		[22]
Italy			✓		✓	✓		[9]
Malaysia		✓	✓		✓	✓		[57]
Malaysia		✓						[53]
Malaysia			✓		✓	✓	✓	[50]

Table 4. Chemical composition in the EAF slag and possible recycle functions.

Chemical composition	**Possible recycle functions**
FeO_x	Iron reclamation
CaO, MgO, FeO, MgO, MnO	Fluxing agent
C_3S, C_2S, and C_4AF	Cementation composition in cement and concrete production
CaO, MgO	Carbon dioxide capture and flue gas desulfurization
FeO, CaO, SiO_2	Raw material for cement clinker
CaO, SiO_2, MgO, P_2O_5, and FeO	Fertilizer and soil improvement

2.4. Leaching Behavior and Hazardous Concerns of EAF Slag

The leaching behavior assessment is often conducted to measure the amount of heavy metals released when EAF slag is exposed to a water source. This assessment would serve as a guideline to ensure that EAF slag is non-hazardous, environmentally friendly, and safe to be incorporated into new products. The experimental methodology for the leaching assessment of EAF slag reported in most literature is based on the EN 12457 European Standard [9][40][52][57][58][59].

Through the leaching assessment, concentrations of toxic heavy metals leached from the EAF slag are evaluated and benchmarked with the regulations specified by the Department of Environment of respective countries [40]. 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 serve as key factors in pollution and toxicity [60]. Researchers have suspected that the presence of these heavy metal impurities originated from the scrap steel feed materials for steel production. However, most literature has reported that the concentrations of these heavy metals are kept within the safety limit as regulated by the respective country, and therefore, are safe to be recycled.

EAF slag is considered basic (alkaline) by nature, mainly due to its large amount of CaO. When exposed to a water source, EAF slag undergoes a hydrolysis reaction, forming a Ca–CO_3–OH ion matrix solution that exhibits a pH of 10.0–12.5 [61][62]. The basicity of EAF slag is comparable to concrete and can be used to increase soil pH. Some researchers have also suggested using EAF slag to neutralize environmental issues such as acid mine drainage [63][64][65]. Nonetheless, the relatively high basicity of EAF slag could cause several complications. First, it is reported that the high pH condition stimulates the mobility of various oxyanion-forming contaminations such as vanadium, chromium, barium, and molybdenum [62][66]. Chaurand et al. (2007) reported the presence of vanadate (oxyanion of vanadium) under highly basic conditions [66]. Second, the basic condition also leads to the precipitation of carbonate minerals in water sources such as rivers and lakes. Long-term effects in the increment of pH in these water sources would lead to water quality deterioration, eventually diminishing the diversity of the invertebrate and fish [62][67]. This would further highlight the drawbacks of EAF slag landfilling and the necessity to recycle the slag into new products.

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