



Review

Assessment of Electric Arc Furnace (EAF) Steel Slag Waste's Recycling Options into Value Added Green Products: A Review

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Abstract: Steel slag is one of the most common waste products from the steelmaking industry. Conventional methods of slag disposal can cause negative impacts on humans and the environment. In this paper, the process of steel and steel slag production, physical and chemical properties, and potential options of slag recycling were reviewed. Since steel is mainly produced through an electric arc furnace (EAF) in Malaysia, most of the recycling options reviewed in this paper focused on EAF slag and the strengths and weaknesses of each recycle option were outlined. Based on the reports from previous studies, it was found that only a portion of EAF slag is recycled into more straightforward, but lower added value applications such as aggregates for the construction industry and filter/absorber for wastewater treatments. On the other hand, higher added value recycling options for EAF slag that are more complicated such as incorporated as raw material for Portland cement and ceramic building materials remain at the laboratory testing stage. The main hurdle preventing EAF slag from being incorporated as a raw material for higher added value industrial applications is its inconsistent chemical composition. The chemical composition of EAF slag can vary based on the scrap metal used for steel production. For this, mineral separation techniques can be introduced to classify the EAF slag base on its physical and chemical compositions. We concluded that future research on recycling EAF slag should focus on separation techniques that diversify the recycling options for EAF slag, thereby increasing the waste product's recycling rate.

Keywords: EAF steel slag; Malaysian steelmaking industry; recycle options of EAF slag

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 [5–20]. Studies have also shown that the recycling rate of steel slag is still generally much lower in Asian countries [2,21–34].

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]. Therefore, the present review serves to encourage the utilization of EAF steel slag in Malaysia. In order to provide a better understanding, the scope of this paper also includes a brief description of the Malaysian steel industry, the origin of slag from steel production, and different types of steel slags.

2. Production of Steel and Steel Slag

For the past five years, around 1.6 trillion tons of steel products have been produced worldwide. The total amount of steel products (i.e., carbon, stainless, and other steel alloys) produced from 2014–2019 in different regions of the world, as reported by the World Steel Association, is presented in Figure 1. In this figure, steel is dominantly produced in Asia, where China, Japan, and India are among the biggest steel-producing countries in the region [2]. The production of steel increased from 2013–2014, but reduced in 2015 due to slow economic growth in several major steel-producing countries such as China, the USA, and Japan. Nonetheless, steel production increased in 2016–2018, as these countries reeled from the economic slowdown. It is expected that steel production will continue to increase as long as the global economy continues to grow.

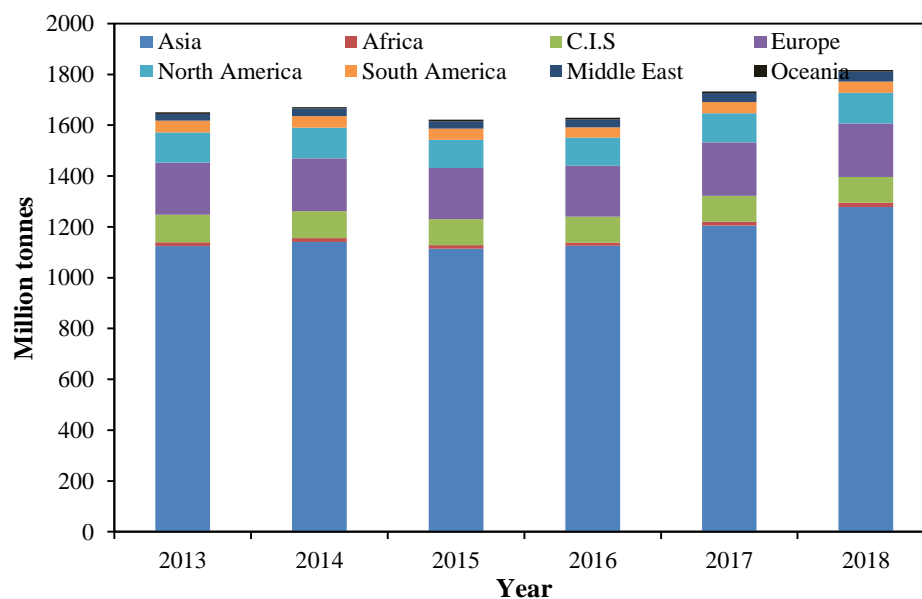


Figure 1. Total amount of steel products produced from 2013 to 2018 for different regions worldwide [3].

Steel is typically made from mixing iron with 0.05–2.5 wt.% of carbon. In some cases, a low amount of manganese, chromium, and copper is added to form steel with different properties. There are two methods that are commonly used for the production of steel: integrated facilities and electric arc furnace (EAF). The main difference between the two methods is that integrated facilities mainly use iron ore as its feed, while EAF uses scrap metal and pig iron [36]. While the integrated facilities method yields higher production with minimal labor requirements, EAF has proven to be the more sustainable steel production method. The EAF route also offers the advantages of lower capital cost, more flexible furnace size, and higher arcing temperature for melting purposes. However, this method may potentially suffer from stalling production time and output since it relies heavily on scrap materials that can be limited at times.

In general, steel is still mainly produced through the integrated facilities method, although EAF is becoming more popular in developed countries [3]. This is because EAF is generally a more environmentally friendly method and requires lower capital cost and operational cost [21,36,37]. Although there is another steelmaking method that utilizes an open hearth furnace, this method is considered to be outdated due to its slow operation, and hitherto has been widely replaced by integrated facilities or EAF [2].

For the integrated facilities method, a blast furnace is the most commonly used operational unit. Raw materials such as iron ore, coal (or coke), and limestone are fed into the blast furnace to produce pig iron. This pig iron is then fed into a basic oxygen furnace to produce molten steel. In comparison, molten steel can be produced by directly feeding steel scrap into the EAF. Regardless of the method used, slag is formed due to chemical reactions between liquid oxides of carbon, silicon, manganese, phosphorus, and iron with lime or dolomitic lime during the process of producing molten steel. It is estimated that approximately 10–15 wt.% of slag is generated per ton of molten steel [38,39]. After that, molten steel is tapped into a ladle while the slag is retained and subsequently tapped into a separate slag pot. The molten steel is later refined in a ladle and undergoes a continuous casting process to form semi-finished products such as bloom, billet, and slabs. These semi-finished products can be reheated, hot rolled, and further processed into the desired shapes for various applications. The overall process of steel production is represented in Figure 2.

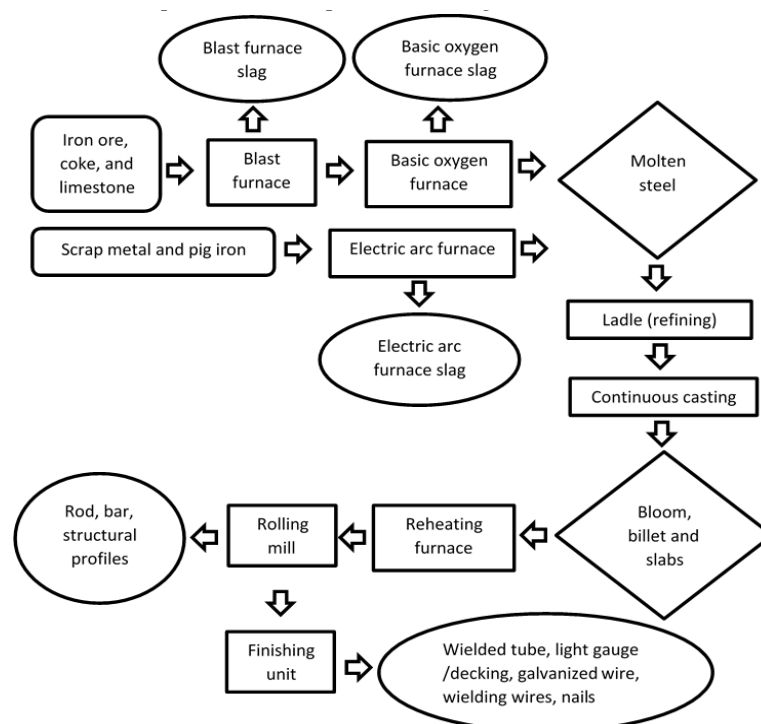


Figure 2. Typical steelmaking process through basic oxygen furnace and electric arc furnace (EAF).

2.1. Solid Wastes and By-Products Issues in the Steelmaking Industry

The steelmaking industry's solid wastes generally consist of steel slag, dust, sludge, and mill scale. These solid wastes are typically disposed of via landfilling or incineration, although neither disposal method has proved to be efficient [40–42]. Steel slag contains residues of toxic elements such as heavy metals, metalloids, alkalis, and anions, which might be released into its surroundings upon decomposition. Thus, the continuous opening of new lands for landfill would permanently damage the natural flora and fauna in the surrounding areas. Over the years, landfilling has become less favorable as it occupies a wide area of land that will eventually boost-up the disposal costs [43]. On the other hand, incineration is an extremely energy-intensive process that generates hazardous ash such as EAF dust, which negatively impacts humans and the environment [44].

Considering the limitations of the disposal methods, recycling has proven to be the more desirable solution to managing the huge amount of solid waste from the steelmaking industry. As one of the oldest steel industries worldwide, Germany has been recycling up to 94% of its steel slag, mainly as aggregates in civil engineering, feed material in steel production, and fertilizers in agriculture [45]. In addition, over 90% of dust emissions from the steelmaking industry has been reduced in the past two decades [45]. There are generally two factors that contribute to the high recycling rate of steel waste in Germany: the first factor is the government's role in imposing strict rules and regulations on recycling waste products from the industry; and the second factor is the initiative of private companies that supports the idea of waste recycling. For example, ThyssenKrupp Steel Europe AG reportedly invested over 300 million euros in studies related to recycling solid waste from the steel industry. In short, it is possible to fully utilize the solid waste from the steelmaking industry through cooperation between the government and private industry.

In Malaysia, however, the recycling rate is very low, leading to more and more landfills being commissioned. This shows that the solid waste keeps on expanding, while there is no real countermeasure applied. Thus, Malaysia needs to make recycling beneficial to both manufacturers and the environment. Initiatives may be taken toward a better Malaysia [22,29,30,34,43,46–48].

2.2. Steelmaking Industry in Malaysia

In Malaysia, steel is mainly produced through EAF, with steel scrap and pig iron as the raw materials. For the past five years, Malaysia has produced 2.5–5.0 million tons of steel annually, at the same time generating 0.2–0.6 million tons of steel slag [3]. According to the Malaysian Iron and Steel Industry Federation (MISIF), there are around 139 registered steel manufacturing and processing facilities in Malaysia, as of 2020 [49]. Major steel producing companies in Malaysia include Megasteel Sdn Bhd, Amsteel Mills Sdn Bhd, Ann Joo Steel Berhad, Southern Steel Berhad, and Antara Steel Mills Sdn Bhd. These companies mainly produce continuous cast steel products such as billets, bars, wire rods, pipes, tubes, coils, and sections [3,49]. In order to support the local steel demand, Malaysia imported approximately 7.9 million metric tons of steel in 2019 (i.e., semi-finished and finished steel products) from countries such as China, Japan, South Korea, and Taiwan [49].

3. 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.

3.1. 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 [39,50]. 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 [51]. One of these is to protect the electrodes and refractories in the furnace from thermal radiation by inhibiting oxidation [52]. 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.

3.2. Properties of EAF Slag

Raw EAF slag often appears as grey or black colored lumps, depending on its ferrous oxide content [53,54]. This type of slag generally has a rough surface texture, with a surface pore diameter of 0.01–10 μm [55]. Examples of EAF slag from different countries is shown in Figure 3. 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 [56]. 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 [57].

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 [58,59]. 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.

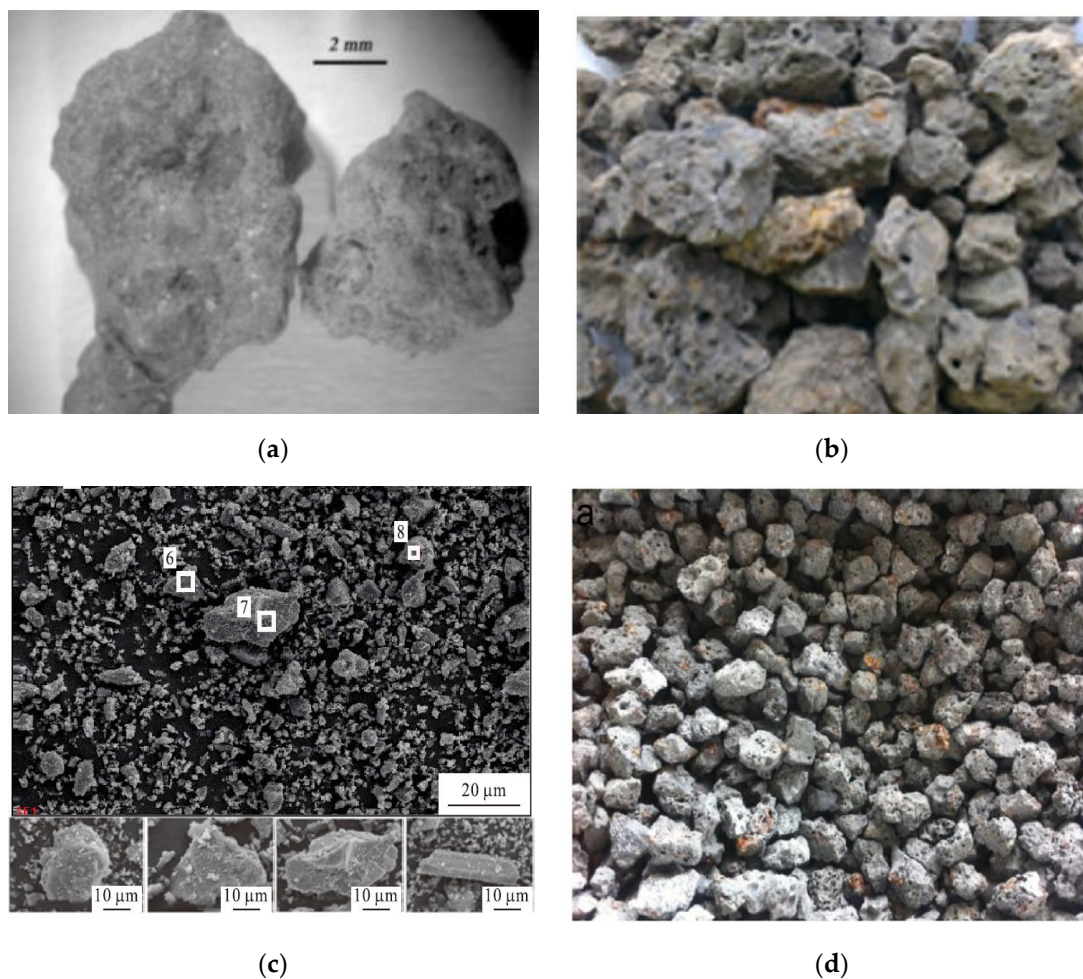


Figure 3. EAF slag samples from different countries. (a) Italy [56]; (b) Malaysia [60]; (c) China [27]; and (d) Spain [11]. Color variation of EAF steel slag is due to the different chemical compositions and oxidation conditions.

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	[46]
2.30–3.40	3.63–3.76	Italy	[55]
0.950	3.85	Italy	[41]
<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	[61]

3.3. 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, Fe₂O₃, or Fe₃O₄) 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 [19,51,62]. 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 ₂ O 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	[63]
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	[60]
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	[55]
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	–	[47]
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	[64]
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	[61]
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) [65]. In most cases, each of these minerals' XRD patterns overlaps with the other and needs to be appropriately identified [9,19,65]. 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	✓		✓			✓	✓	[54]
Italy			✓		✓	✓		[66]
Malaysia		✓	✓			✓		[22]
Italy			✓		✓	✓		[9]
Malaysia		✓	✓		✓	✓		[67]
Malaysia		✓						[47]
Malaysia			✓		✓	✓	✓	[61]

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 ₃ S, C ₂ S, and C ₄ AF	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 ₂ O ₅ , and FeO	Fertilizer and soil improvement

3.4. 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 [9,53,63,67–69].

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 [53]. 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 [70]. 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–CO₃–OH ion matrix solution that exhibits a pH of 10.0–12.5 [71,72]. 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 [73–75]. 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 [72,76]. Chaurand et al. (2007) reported the presence of vanadate (oxyanion of vanadium) under highly basic conditions [76]. 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 [72,77]. This would further highlight the drawbacks of EAF slag landfilling and the necessity to recycle the slag into new products.

4. Potential Recycling Options of EAF Slag

4.1. An Overview

Efforts of recycling steel slag can be traced back to the early 1970s, at which the iron content in steel slag is reclaimed through a series of crushing, grinding, magnetic separation, and screening process [33]. Nonetheless, in the last few decades, many studies have been conducted to examine the possibility of recycling EAF slag in an attempt to reduce the environmental impact caused by this by-product. In this section, a comprehensive assessment of EAF slag recycling options into a green product is presented. A product is considered 'green' if it is made from industrial waste, is non-hazardous, is recyclable, and cheaper in cost [78]. This particular review section will extensively focus on the recycling options of the EAF slag (including Malaysia), which include aggregates for the construction industry, filter, or adsorbent for wastewater treatment, and agricultural fertilizer as well as the ceramic product.

4.2. Aggregates for Construction Industry

Many breakthroughs have been made in the research of EAF slag waste utilization into aggregates for the construction industries. This can be proven by the enormous body of literature that has reported on this particular recycling option for EAF slag. According to Hosseini et al. (2016), steel slag is most commonly recycled into construction aggregates, particularly in concrete and road construction [39]. With the ever-growing construction industry, there is a constant high demand for construction materials. Recycled materials such as steel slag, geosynthetic aggregates, and recycled concrete have proven to be more reliable alternatives with the advantages of being less costly and potentially reduces the reliance on natural resources. Nonetheless, it is still necessary to evaluate if the steel slag (or particularly, EAF slag) possesses suitable physical properties and chemical compositions to completely or partially replace the construction materials for long-term use.

Several researchers have proposed the idea of using EAF slag as aggregates in the production of structural concrete [50,53,66,79]. Pellegrino and Gaddo (2009) demonstrated that the EAF slag aggregates incorporated into concrete had compressive strength and elastic modulus comparable to the commercially available concrete [53]. However, the drawbacks of this new concrete are that it suffers from volume instability and durability under extreme conditions. This issue was further studied by Ducman and Mladenovic (2011), where the performance of concrete incorporated with EAF slag was evaluated under temperatures of 700 °C–800 °C [50]. They reported that the mechanical properties of the concrete begin to drop at such temperatures due to phase transformation, which causes expansion and cracks. To overcome this issue, Ducman and Mladenovic (2011) suggested heat-treatment and aging to stabilize the EAF slag before it is added into the concrete [50].

In an attempt to improve the durability properties of concrete made with EAF slag aggregates, Pellegrino et al. (2013) investigated the mineral compositions of the EAF slag in order to identify the cause of volume instability [66]. They found that the EAF slag had limited free-oxides (e.g., CaO and MgO) that undergo hydration, eventually hindering the concrete's durability. Due to this, although EAF slag can replace traditional natural aggregates in the production of concrete conglomerates, treatments such as outdoor aging and exposure to moisture are necessary. The authors also claimed that while adding an air-entraining agent could increase the durability of the EAF slag included concrete, it is still vulnerable to repeated cycles of wetting and drying. In a separate study, González-Ortega et al. (2014) studied the radiological performance of the concrete incorporated with the EAF slag by measuring the attenuation coefficient of gamma rays [79]. In general, concrete with a greater attenuation coefficient have better radioactive radiation shielding capacity. Thus, in this study, they concluded that the concrete with EAF slag had an 11% higher attenuation coefficient than conventional concrete.

In Malaysia, several construction materials incorporated with EAF slag have been developed in the past few years. Preliminary work on supersulfated flowable mortars containing EAF slag as fine aggregates were proposed by Cheah and Jasme (2018) [64]. They observed a declining trend of workability as well as deteriorating compressive strength with an increasing amount of EAF slag

added and concluded that during moist curing, the ratio of EAF slag can be up to 40% as quarry dust replacement in the cementless mortar. In another study by Lim et al. (2019), EAF slag was used as a coarse aggregate to replace natural granite rock (NGR) in ternary blended concrete [61]. They found that the EAF slag managed to shorten both the initial and final setting times of concrete. However, more water was required to achieve the desired workability of the concrete. The compressive and flexural strength of the hardened concrete also increased with EAF slag added. They concluded that the recycling of EAF slag as coarse aggregate contributes to the optimum mechanical performance of the hardened concrete. This indicates that the EAF slag is feasible to be recycled as a coarse aggregate in concrete [61].

Many researchers have also suggested the usage of EAF slag aggregates as an alternative in road pavements [46,80–83]. According to Aziz et al. (2014), adding EAF slag into a hot bitumen mixture increases the skid resistance [80]. This is because EAF slag naturally has higher angularity and rougher surface textures. In the studies conducted by Ferreira et al. (2015) and Kavussi and Qazizadeh (2014), EAF slag and hot bitumen had higher internal friction angle and improved interlocking properties when compared to conventional aggregates [81,82]. In other words, the bitumen mixture more strongly adhered to the surface of the EAF slag. This could help in preventing the unexpected early stage damage of the road pavement through passivation of crack propagation, eventually increasing the life span of roads.

In Malaysia, Oluwasola et al. (2016) and Ali Jattak et al. (2019) revealed that the mechanical performance of road pavement incorporated with EAF slag aggregate would fulfill the requirements regulated by the Malaysian Public Works Department, although it had a slightly higher water absorption than conventional road pavement [46,84]. This is mainly because EAF slag aggregates simply have higher porosity when compared to conventional aggregates for road pavement (i.e., granite aggregates). In these studies, the authors also reported that EAF slag that underwent the aging process showed increased resilient modulus and dynamic creep modulus values. Nonetheless, further investigations are still necessary to attain the optimal weight percentage of an EAF slag-regular aggregate mixture for road pavement construction. In overall, the strength and limitations of recycling the EAF slag as aggregates for construction industry could be summarized as per presented in Table 5.

Table 5. Strengths and limitations of incorporating EAF slag in aggregates for the construction industry.

Application	Strengths	Limitations	References
Aggregates for construction industry	<ul style="list-style-type: none"> compressive strength and elastic modulus of concrete with EAF slag aggregates are comparable to the commercially available concrete, but is cheaper to produce concrete with EAF slag has 11% higher attenuation coefficient bitumen mixture with EAF slag aggregates is more durable resilient modulus and dynamic creep modulus values of EAF slag can be increased through aging process 	<ul style="list-style-type: none"> Concrete with EAF slag has volume instability and durability issues under extreme conditions Concrete with EAF slag is vulnerable to repeated cycles of wetting and drying EAF slag is generally more porous and have higher water absorption than conventional road pavement materials 	[46,50,53,66,79–82]

4.3. Filter or Adsorbent in Wastewater Treatment Plant

Another direct application of EAF slag is as a filter or adsorbent in wastewater treatment plants. This application utilizes the porous structure and water absorption properties of EAF slag to remove harmful substances in the wastewater such as Cd, Cu, P, and Pb [85,86]. Based on the research conducted by Drizo et al. (2006), EAF slag had a very high efficiency (close to 100%) in removing phosphorus from the investigated effluent [85]. The major mechanisms of phosphorus removal were reported to be related to adsorption and precipitation. The only drawback as such is that EAF slag has

limited adsorption sites that limit its usage for long-term treatment. To overcome this issue, Pratt et al. (2009) proposed several methods that included drying, agitating, and crushing to rejuvenate the EAF slag. Through these processes, fresh adsorption sites are constantly created. The authors claim that crushing is the most effective rejuvenation process [87].

In addition to removing pollutants, EAF slag can be used to reduce the acidity of wastewater. Many researchers have suggested that EAF slag can be used to remediate the soil and water resources in the surroundings of mining plants with acid mine drainage issues [73,74,88,89]. As the name implies, acid mine drainage refers to the acidic outflow from mines that are abundant in sulfide minerals such as Fe, Ni, Cu, Pb, and coal mines. In this case, EAF slag is used as an active treatment method, at which the slag is continuously added to the acidic outflow. EAF slag contains elements such as Fe and Ca, which could react with the acid (mainly SO_4^{2-}) to form gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$). This would effectively reduce the free acid in the wastewater. When compared to conventional materials for the active treatment of acid mine drainage (e.g., limestone and ammonia), EAF slag would serve as a cheaper alternative. The main drawback of using EAF slag, instead of conventional materials, would be the formation of unwanted precipitates that need to be disposed of separately [90]. Nonetheless, there is no doubt that EAF slag has great potential for treating wastewater from mines with acid mine drainage issues.

In Malaysia, several studies have reported on the application of EAF slag as an adsorbent for wastewater treatment [30,47,48,91,92]. Hosseini et al. (2015) agreed that the adsorption capacity, pH, particle size dosage, contact time, and initial concentration would affect the adsorption capacity of the EAF slag [91]. EAF slag was also found to be a more suitable adsorbent for nutrient removal compared to lime due to the presence of Si, Ca, Mg, and Fe, in addition to its surface porosity [92]. Phosphorus adsorption by EAF slag has shown that a smaller adsorbent size and a slightly acidic environment ($\text{pH} = 3$) are required for optimum adsorption [47]. Chemical treatment of EAF slag by using hydrochloric acid has proven to improve the adsorption of methylene blue by the slag due to the enhancement of the pores on the surface after removing impurities. The maximum adsorption capacity for treated EAF slag was 14.2029 mg/g, and raw EAF slag was 9.615 mg/g. The maximum removal percentage for treated EAF Slag was 71.01%, whereas raw EAF showed 37.19% removal at pH 10 [48]. In another study, Omale et al. (2019) investigated Malaysian EAF slag utilization for effective application in direct aqueous sequestration of carbon dioxide under ambient temperature and concluded that the maximum CO_2 uptake capacity was 5.836 wt%, resulting in sequestration of 58.36 g CO_2 /kg of steel slag and the sequestration efficiency of 32.53% [30]. In overall, the strength and limitations of recycling the EAF slag as filter or adsorbent for wastewater treatment plant could be summarized as per presented in Table 6.

Table 6. Strengths and limitations of incorporating EAF slag in filter or adsorbent in wastewater treatment plants.

Application	Strengths	Limitations	References
Filter or adsorbent in wastewater treatment plant	<ul style="list-style-type: none"> EAF slag can effectively remove phosphorus from effluent EAF slag can be processed to improve its adsorption capacity EAF slag can be used to reduce the acidity of wastewater 	<ul style="list-style-type: none"> EAF slag has limited adsorption capacity for long term usage Using EAF slag to treat acidic wastewater may produce unwanted precipitates that need to be disposed of separately 	[73,74,85,87–89]

4.4. Agricultural Fertilizer

Apart from being used to alter the acidity of soil and water resources, several researchers have reported that EAF slag can be used to replenish the nutrients in soil for agricultural purposes [26,89,93–95]. This is because EAF slag contains Fe, K, Mn, and P, which could sustain plant growth. However, most EAF slag also contains a low amount of harmful elements such as Cd

and Pb, and remediation procedures might be needed to reduce these elements to safe levels. One of the most straightforward applications of EAF slag is an inexpensive Fe fertilizer to treat calcareous soils that are deficient in Fe. In this case, EAF slag is simply crushed and mixed with the soil [93]. On a separate note, EAF slag can also be processed into higher added value phosphorus fertilizers. Separation techniques such as flotation, selective agglomeration, and magnetic separation can be used to extract phosphorus from the slag [26].

In some cases, it is possible to use EAF slag to reduce toxic elements uptakes of agricultural plants. In a research conducted by Gutierrez et al. (2010), steel slag was added to reduce the arsenic (As) uptake (i.e., phytoextractability) of radish plantation on As-contaminated arable soil [95]. Steel slag was crushed to <2 mm and added to an arable soil mixture consisting of mine tailings and loam upland soil. This soil was used for radish cultivation in Wagner pots. A comparison was made with similar procedures conducted on an As contaminated soil sample that was treated with Ca(OH)₂. The researchers found that radishes from the soil added with steel slag increased plant yield than those with the Ca(OH)₂ treatment. In other words, the steel slag suppressed radish As uptake more effectively than Ca(OH)₂, and this improved the radish plant yield. However, at this point, this finding is only applicable for radish cultivation in pots. Further evaluations are necessary to assess the extension of steel slag as a stabilizing agent for agricultural plants in outdoor field conditions.

In Malaysia, a study by Bankole et al. in 2011 found that by introducing 20% weight of K₂CO₃ to EAF slag, a modified slag system whose CaO/SiO₂ weight percent ratio was varied from 0.6 to 1.0 could be produced. This property suggests that EAF slag can be used as agricultural fertilizer [32,96]. In 2013, a statistical design analysis showed that the dissolution of Cr(VI), Ca, and Si was indeed affected by pH, mixing speed, particle size, and temperature. However, the most prominent effects can be observed by the mixing speed and size of the slag particles [63]. Moreover, in 2014, the Cr(VI) release rate from EAF slag was found to be safe for use as fertilizer as it was less than 0.1 mg/L in different lixiviants that were alkaline, deionized, and rain water [43]. A recent study on the potential of EAF slag as a nutrient source for mangrove seedlings suggested that the slow release rate of Ca, Si, Fe, Mn, K, Na, and Al through the leaching test showed its suitability as a slow-release nutrient source for the plant [97]. In overall, the strength and limitations of recycling the EAF slag as fertilizer for agriculture industry could be summarized as per presented in Table 7.

Table 7. Strengths and limitations of incorporating EAF slag in fertilizer for agriculture industry.

Application	Strengths	Limitations	References
Fertilizer for agriculture industry	<ul style="list-style-type: none"> EAF slag contains Fe, K, Mn, and P that could sustain plant growth EAF slag can also be processed into higher added value phosphorus fertilizer EAF slag have the potential to reduce toxic elements uptakes of agricultural plants 	<ul style="list-style-type: none"> EAF slag also contains low amount of harmful elements such as Cd and Pb remediation procedures might be needed to reduce harmful elements to safe levels 	[26,89,93–95]

4.5. Partial Replacement for Portland Cement

Since EAF slag contains a significant amount of CaO, some researchers have suggested that it can be used to replace part of the raw materials in Portland cement production. Shi (2004) reported that the presence of compounds such as C₃S (3CaO.SiO₂), C₂S (2CaO.SiO₂), C₄AF (4CaO.Al₂O₃.FeO), and C₂F (2CaO.FeO) in the slag contributed to its cementitious properties [51]. With this, EAF slag can be used as an alternative for regular clinker (i.e., alite, belite, and calcium aluminoferrite). However, since the C₃S content in the slag is lower than regular clinker, complete replacement is not possible. Instead, EAF slag can be mixed with other source materials that contain C₃S to form the desired mixture for Portland cement, hence the term partial replacement. In any case, including EAF slag into Portland cement production can be viewed as a more sustainable approach that reduces the reliance on raw

materials. In addition, partial replacement of raw material with EAF slag could potentially reduce the energy consumption for Portland cement production, as the firing process can be completed at a lower temperature [98,99].

Hekal et al. (2013) conducted a study to incorporate EAF slag from Egypt into the production of Portland cement [7]. The hydration characteristic of the Portland cement with EAF slag was evaluated and compared to regular cement, and they found that incorporating 5–10 wt.% of EAF slag produced Portland cement with compressive strengths that are comparable to conventional cement, even at the hydration age of 90 days. However, the cement's compressive strength reduced when the EAF slag was increased to 20 wt.%. Based on the XRD and thermal analysis (DTA) conducted, the cement with EAF slag showed no considerable pozzolanic reactivity.

Realizing that the successful utilization of granulated blast furnace slag in Portland cement was due to its excellent cementitious properties, Kim et al. (2015) proposed a method to alter the composition of the EAF slag so that it would possess similar cementitious properties as the granulated blast furnace slag before being added to the cement mixture [100]. The EAF slag was melted and the CaO–Al₂O₃ ratio of EAF slag was modified through the addition of Al-dross in a two-stage reduction procedure. This procedure also reduced the FeO content in the EAF slag to 2–5 wt.%. The molten modified slag was water-quenched so that it would form an amorphous structure that could be crushed and added into the cement mixture. The researchers found that the cement incorporated with the modified EAF slag showed a comparable compressive strength to the Portland cement incorporated with granulated blast furnace slag, despite requiring prolonged hardening time (28 days). However, since the overall process is rather complicated (i.e., involving two stages of heating and quenching), further investigations on the ideal chemical composition of the modified slag and optimal operational parameters are necessary.

Lu et al. (2019) modified the EAF slag by mixing with other wastes such as fly ash, coal gangue, and mine tailings to produce a modified-EAF slag that possessed similar chemical compositions as the blast furnace slag [101]. During the modification, the basicity index (CaO/SiO₂) of modified EAF slag was increased to increase the cementitious property. They found that the modified EAF slag with a basicity index of 1.67 showed excellent cementitious property and was the most suitable to replace Portland cement.

In Malaysia, limited study has been conducted on Portland cement replacement due to the abundance of Portland cement resources in Malaysia. Nevertheless, recently, Roslan et al. (2020) used ground EAF slag in concrete as a partial replacement for Portland cement [60]. Their study suggests that the replacement of up to 10% of EAF slag will give better strength than the control concrete. This is because the fine grains of EAF slag are able to fill in the void between Ca(OH)₂, ettringite, and hard phase. Moreover, the pozzolanic activity of the EAF slag at 90 days of curing also contributes to the strength. Nonetheless, further investigations are still necessary to attain the optimal replacement of EAF slag in Portland. In overall, the strength and limitations of recycling the EAF slag as partial replacement of Portland cement could be summarized as per presented in Table 8.

Table 8. Strengths and limitations of incorporating EAF slag in partial replacement for Portland cement.

Application	Strengths	Limitations	References
Partial replacement for Portland cement	<ul style="list-style-type: none"> EAF slag can be used as an alternative for clinker, due to its cementation properties EAF slag can potentially reduce the energy consumption for Portland cement production, by lowering the firing temperature 5–10 wt.% of EAF slag produces Portland cement with compressive strength that is comparable to conventional cement 	<ul style="list-style-type: none"> The chemical composition of EAF slag is often inconsistent Requires treatment before added into the cement mixture to obtain more consistent results 	[7,99,100]

4.6. Raw Material for Ceramic Products

The idea of incorporating EAF slag in the production of ceramic building materials originates from the fact that EAF slag contains minerals that are essential in the manufacturing of building materials. Unlike the previously discussed applications where EAF slag is used in its original state, incorporating EAF slag into ceramic building materials involves high-temperature sintering and crystalline phase transformation processes, in addition to crushing and grinding. There are also issues regarding the suitable amount of EAF slag that needs to be added to the ceramic building materials. Thus, this application is generally more complicated than other previously mentioned applications and requires more in-depth assessments. Nonetheless, this application is considered as one of the more constructive higher added valued options for EAF slag recycling, despite the complications. To date, ceramic tiles and bricks are two of the most common ceramic building materials that could include EAF slag in its production.

Badiee et al. (2008) were one of the earliest to propose the idea of incorporating EAF slag into the production of ceramic products [6]. A sample of 10–50 wt.% EAF slag from an Iranian steel production plant was crushed, ground, and mixed with other raw materials that consisted of ball clay, feldspathic sand, and silica sand. The firing process was completed at a temperature of 1140 ± 10 °C using an industrial roller kiln. They reported that the ceramic tiles added with 40 wt.% of EAF slag showed the most favorable properties with the highest bulk density, lowest apparent porosity, lowest water absorption, and highest modulus of rupture. The authors also reported that increasing EAF slag to 50 wt.% would produce ceramic tiles that were too brittle. Similar research works were conducted by [20–22,29,102–110], who mutually agreed that the optimal amount of EAF slag added was in the range of 30–50 wt.%. Meanwhile, the optimal firing temperature for the ceramic product incorporated with EAF slag was in the range of 1050 °C–1250 °C. Most of these studies were able to prove that the ceramic product incorporated with EAF slag had physical and mechanical properties comparable with commercially available products.

Undeniably, incorporating EAF slag into ceramic product/ building materials can help conserve the raw materials and reduce issues regarding waste disposal including in Malaysia. However, it would also alter some of the building materials' properties, which include water absorption, modulus of rupture, firing shrinkage, bulk density, and porosity. Thus, more evidence is needed to evaluate the durability of the EAF slag incorporated ceramic product, especially after long-term exposure to the outdoor environment. In addition, these products need to abide by the safety regulations, in the sense that they do not emit high levels of toxic heavy metals such as lead (Pb), cadmium (Cd), chromium (Cr), zinc (Zn), and mercury (Hg). These toxic elements are often present in EAF slag, although as trace amounts. Furthermore, the mechanism and interaction between different aspects that need to be looked into (e.g., optimal wt.% of EAF slag, firing temperature, possible treatment/curing procedures, etc.) would affect the properties of the ceramic building materials. With this, although many research efforts have been conducted to incorporate EAF slag into the production of building materials, this recycling option is hitherto confined to laboratory testing stages. However, with enough study and observation, there is no doubt that EAF slag can be included in the ceramic product's commercial production at an industrial scale, especially for developing countries such as Malaysia. In overall, the strength and limitations of recycling the EAF slag as raw material for ceramic building materials could be summarized as per presented in Table 9.

Table 9. Strengths and limitations of incorporating EAF slag in raw material for ceramic building materials.

Application	Strengths	Limitations	References
Raw material for ceramic building materials	<ul style="list-style-type: none"> • Ceramic tiles incorporated with EAF slag are cheaper to produce, while having properties that are comparable to commercially available tiles and are safe to use. • Optimal amount of EAF slag and firing temperature are 30–50 wt.% and 1100 °C–1250 °C, respectively. • Ceramic bricks produce with 10 wt.% EAF slag and firing temperatures above 1050 °C would fit the standard of CNS 3319 third-class brick • One of the higher added valued options for EAF slag recycling 	<ul style="list-style-type: none"> • Optimal EAF slag wt.% varies based on its composition from different sources • Operational parameters for producing the ceramic building materials needs to be carefully controlled so that the harmful elements that emits from the products are within safe level • Generally more complicated and requires more in-depth assessments on the different operational parameters (e.g., optimal wt.% of EAF slag, firing temperature, and possible treatment/curing procedures) 	[20–22,102–108]

5. Summary

The current work reviewed a wide range of commonly-known recycle options for EAF slag. The strengths and limitations of incorporating EAF slag in each application have been presented in the previous Tables 5–9 of Section 4 (Potential Recycling Options of EAF Slag). In general, the recycling options of EAF slag can be divided into two categories: lower added value applications and higher added value applications. Lower added value applications are basically direct applications that utilize the physical aspects of the EAF slag such as construction aggregates and filter/absorbent. On the other hand, higher added value applications utilize the chemical composition of the EAF slag and require further processing procedures. Examples of higher added value recycling applications for EAF slag are as raw material for ceramic building materials and Portland cement. To date, most of the successful recycle applications of EAF slag in the industry are only on the lower added value applications, as it is more straightforward and fewer complications are involved. The higher added value applications, on the other hand, mostly remain at the laboratory testing stage [26,71].

The main factor that is still preventing EAF slag from being effectively recycled into higher added value applications is its inconsistent chemical compositions. Since EAF slag is principally just a by-product, most steel production facilities would not impose any quality control procedure on the slag's chemical compositions. However, the physical properties of the EAF slag (i.e., porosity, grain size, etc.) can be controlled during the cooling process. Therefore, separation processes such as the one shown in Figure 4, are necessary to classify the EAF slag for different uses.

For applications such as construction aggregates and filters/absorbents for water treatments, only sieving is required to sort the EAF slag according to its particle size. In order to classify EAF slag for higher added-value applications that utilize the chemical compositions, crushing and grinding processes are necessary to liberate the entrapped minerals. After that, magnetic separation, flotation, and/or gravity separation can be used to further classify the EAF slag into magnetic minerals, valuable elements, and tailings. Magnetic minerals typically contain Fe that can be reclaimed. Valuable elements such as CaO, MgO, and SiO₂ can be used in the production of cement and ceramic building materials. Finally, the tailings from the separation process can be used as fertilizers and for water treatments. Overall, the classification process of EAF slag can be completed through straightforward means, and complicated chemical extraction methods such as leaching and solvent extraction are not necessary.

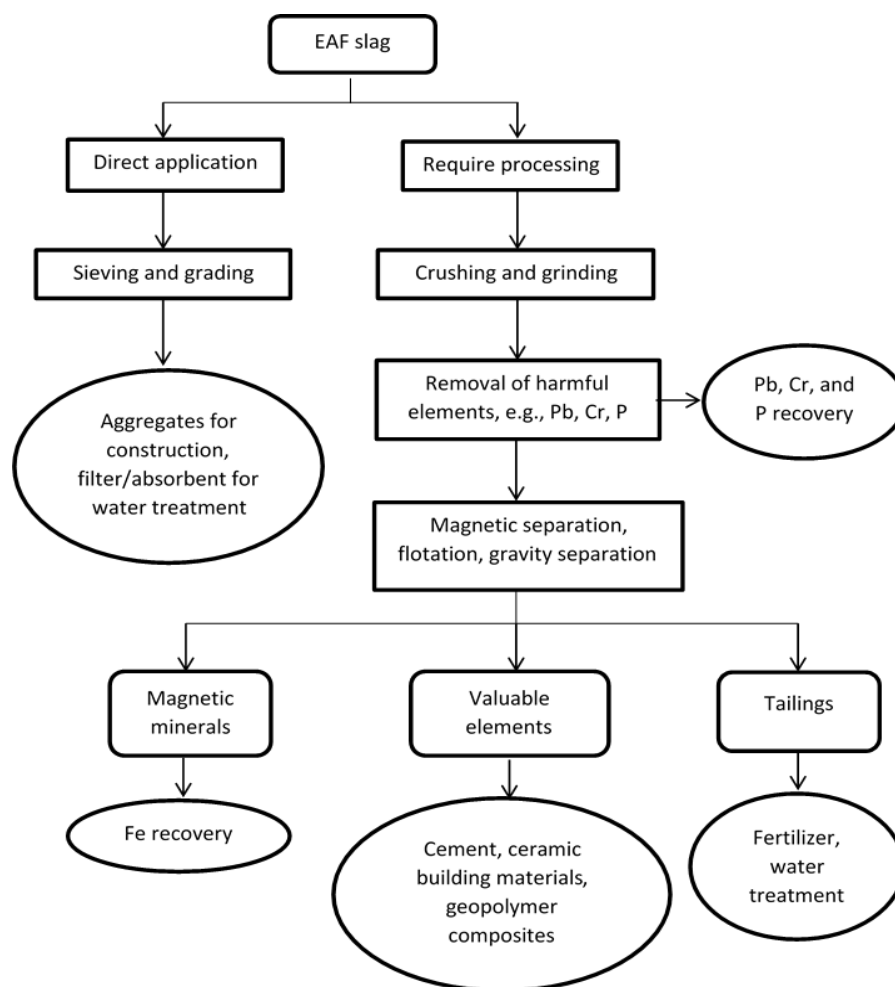


Figure 4. Possible separation processes to classify EAF slag for different uses.

6. Conclusions

In a nutshell, when compared to other developing countries, the recycling rate of steel slag in Malaysia (which is mainly EAF slag) is still very low. With the increasing cost of landfilling for EAF slag and land pollution in the country, recycling EAF slag should be made a necessity instead of just a complementary practice in the steelmaking industry. Efforts of recycling the EAF slag should be conducted based on large-scale utilization for multiple possible options, instead of centering on a single application. In addition, future research work should focus on the construction of functional EAF recycling plants that could satisfy the demand for multiple applications, rather than just exploring the possible recycling options of EAF slag. We can also conclude that future research on recycling EAF slag should focus on separation techniques that diversify the recycling options for EAF slag, thereby increasing the waste product's recycling rate.

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