Recycling Perspectives of EAF Slag in the United States: A Review

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This work is dedicated to Prof. Em. Seshadri Seetharaman on the occasion of his 80th birthday.

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This article presents a comprehensive review of Electric Arc Furnace (EAF) slag recycling in the United States, examining its classification and the associated challenges and opportunities of its industrial use. The study affirms EAF slag's non-hazardous status. The main challenges identified in EAF slag applications include substantial variations in composition and volume instability during/after hydration. Analysis of the U.S. recycling practices reveals that EAF slag is predominantly reused, with minimal landfill disposal. However, its prevalent use as a low value-added aggregate in construction applications underscores the industry's ongoing challenge to get additional value from EAF slag recycling.

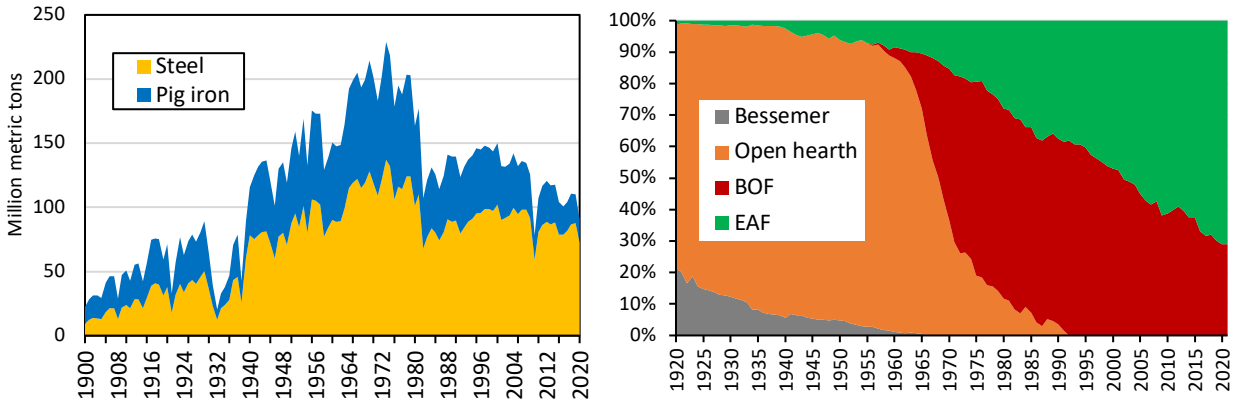
Despite these challenges, the study highlights a great potential for increased value extraction from EAF slag recycling. Beyond conventional applications as a clinker material for the cement industry, the review explores modern technologies for steelmaking slag recycling, revealing options for recovering valuable metals such as Cr, V, Mo, and Fe through methods such as leaching, reduction, and oxidation.

1. Introduction

Steel, renowned for its versatility, strength, and durability, stands as one of the most widely used construction materials worldwide. In the year 2022, the production of crude steel in the world was 1,885.4 million tonnes (Mt) and the contribution in the U.S. was 80.5 Mt, landing the U.S. as the fourth largest producer only behind China, India, and Japan.[1]

The majority of the steel in the world is produced from virgin iron-bearing materials – iron ores – via the Blast Furnace (BF) – Basic Oxygen Furnace (BOF) route (so-called integrated steel plants). The recycled steel production via the Electric Arc Furnace (EAF) route (in mini- and micro-mills) accounts for 31% of the total steel production worldwide whereas BF-BOF accounts for 69%.[1] Only a handful of countries solely produce steel from EAFs, including Bulgaria, Croatia, Greece, Luxembourg, Portugal, Slovenia, Venezuela, Saudi Arabia, and Egypt.[1,2]

The EAF was first implemented in the United States in the late 19th century. Since then, it has gradually become the main steelmaking method in the U.S., accounting for nearly two-thirds of steel production. EAFs have seen an increase in usage in the U.S. since the 1960s, but the rest of the world still primarily utilizes basic oxygen furnaces (BOFs) (See **Figure 1**). EAFs are now present in over 130 facilities across the U.S.[3] The wide adoption of EAF by the steelmaking industry in the USA happened due to several reasons, e.g., the high abundance of domestic scrap resources, the advantages of EAF in terms of capital cost, raw materials flexibility, and energy consumption.[4]



a) b)

Figure 1. US iron and steel production in 1900-2020 (a) and share of US steelmaking processes in 1920-2020 (b).[4,5]

It is important to estimate the real volumes of EAF slag generated in the USA. During the steelmaking process via EAF production route, the amount of slag generated can be within the range of 70 kg/$t_{liquid\ steel\ (LS)}$ to 150 kg/t_{LS}.[6] Furthermore, for the year 2023, USGS estimated production of all steelmaking slags as 7.04 Mt for the whole stock of steelmaking furnaces, (e.g. EAF, BOF, ladle furnaces, etc.).[7] However, these data should be considered with some interpretations. Real specific slag amounts coming directly from the EAF are lower than the average. Typical slag yields of scrap-based heats in EAF are around 100 kg/t_{LS}.[6,8] Therefore, considering the EAF share of steel, slag volumes that can be attributed to electric arc furnaces specifically in the U.S. should not exceed 5-6 Mt annually.

In recent times, as the world's capacity to sustain life faces mounting challenges, it has become paramount to conserve non-renewable resources. The worldwide demand for raw materials is experiencing exponential growth as a result of urbanization and technological advancements. However, this escalating consumption poses both economic and environmental threats. The scarcity of critical materials poses an economic risk, while the generation of a substantial volume of coproducts contributes to environmental concerns. In response, industries are aiming to enhance material efficiency by utilizing resources in a sustainable manner while minimizing environmental impact.

The focus of this review article lies in exploring the recycling prospects of EAF steel slag, in the United States specifically. As a pivotal player in the global steel industry, the U.S. holds a vital role in shaping sustainable steel production practices and mitigating environmental repercussions. Steelmaking slag recycling is in the focus of extensive research efforts. Some recent reviews have covered recycling research of ferrous and non-ferrous metallurgical slags with the focus on the U.S.,[9] of iron- and steelmaking slags with a focus on China,[10–12] and EAF slags with the focus on Malaysia.[13] The present review aims to comprehensively assess the recycling potential of EAF steel slag within the U.S. It serves as a catalyst to promote and encourage the beneficial utilization of EAF steel slag, thus enhancing the circular economy within the steel industry and tending to contribute to a more sustainable and resource-efficient future for the U.S. steel industry, paving the way for improved waste management practices and reduced environmental impact through the recycling of EAF steel slag.

2. Formation of EAF slag

During steel production via the EAF route, an electric arc is used to melt some combination of recycled steel scrap and in some cases Ore-Based Metallics (OBMs) such as direct reduced iron (DRI) or pig iron. The process utilizes a combination of electrical and chemical energy inputs to produce molten steel at approximately 1600°C.[14] As the raw materials undergo high-temperature reactions, impurities in the scrap metal, fluxes, and other additives combine to form molten slag.

The slag formation process involves the following stages: 1) Charging: scrap metal and other raw materials including lime or dolomitic lime (slag formers) are loaded into the electric arc furnace. 2) Melting: an electric arc is created between the electrodes and the metal charge, generating intense heat that melts the materials. 3) Chemical reactions: during the melting process, various chemical reactions occur between the impurities and fluxes present in the scrap, leading to the formation of slag and the removal of carbon from the liquid bath (See **Figure 2**). 4) Slag separation: the molten slag, which is less dense than the molten steel, floats to the surface and is separated from the steel.

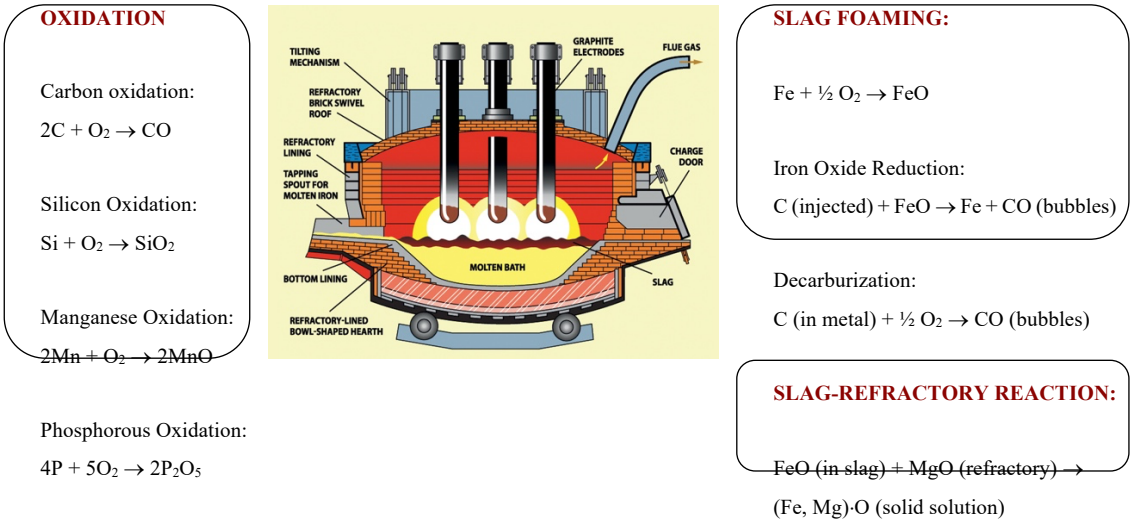


Figure 2. Chemical reactions in electric arc furnace. Adapted with permission.[15] Copyright 2023, Shutterstock.

The chemical and mineralogical composition of EAF slag can vary depending on the raw materials used and the steel grade to be produced. When solidifying during cooling, crystalline and glassy phases are formed depending on the chemical composition of the slag and its cooling history.[16] Generally, EAF slag consists of the following components: FeO (10–40%), CaO (22–60%), SiO_2 (6–34%), Al_2O_3 (3–14%), and MgO (3–13%).[17] These ranges of constituents of EAF slag are consistent with the typical EAF slag composition from flat as well as long product producers, provided by an industry contact in the U.S.[18] Such typical EAF slag composition can be found in **Table 1**. Different plants will have varying levels of chromium oxide of up to 2 wt.% depending on its content in the scrap charge. Other slags from long product producers in the U.S. may have chromium levels as high as 3 wt.%.

Table 1. Typical EAF Slag Composition.[18]

Slag constituents, wt.%	Sheet mills	Bar mills	Origin of constituents[19]
MgO	11.60	12.50	Flux (dolomite)/ Refractory material
Al_2O_3	4.50	6.00	Scrap/ DRI
SiO_2	12.60	17.00	Iron Ore/ Pig iron/ Flux/ DRI
P_2O_5	0.55	0.30	Iron Ore/ Scrap / DRI
S	0.10	0.40	Coal/ Coke/ Iron ore/ Steel/ DRI
CaO	28.50	32.50	Flux (lime)
TiO_2	0.60	0.40	Iron ore/ Scrap

Cr_2O_3	0.90	1.50	Scrap
MnO	3.20	4.50	Scrap
FeO_x	37.20	25.00	Iron Ore/ Pig iron/ Scrap/ DRI

Differences in EAF slag compositions from sheet and long products mills stem from varying inputs of direct reduced iron (DRI), flux additions, and charge carbon, and the required level of phosphorus in the liquid steel. Sheet mills typically require lower levels of copper and therefore, more often utilize OBMs as a charge material. Many steel grades (particularly in sheet steel production) require low carbon levels, necessitating higher dissolved oxygen content in the steel and thus, higher FeO levels in the steelmaking slag. Long product mills may utilize more carbonaceous materials such as anthracite coal, a charge carbon with an ash content consisting primarily of SiO_2 and Al_2O_3. Long products production typically uses higher levels of obsolete scrap, which will have higher levels of oxide gangue, principally SiO_2 and Al_2O_3.[20] The higher silica content in bar mill slag can be attributed to an increased utilization of these materials.

Ultimately the percentage of FeO in the EAF is in a pseudo-equilibrium with the dissolved carbon content in the liquid steel bath.[21] This FeO originates from two sources. Some FeO is brought into the EAF through the materials charged. Rusted scrap and ore-based metallics with unreduced iron contribute FeO to the EAF directly. The formation of FeO occurs from metallic iron reacting with injected oxygen, oxidizing the iron, and forming FeO. To control the level of FeO in the slag, EAF operators inject powdered or granulated carbon to react with the FeO, reducing the FeO to iron and leaving a second product of CO in the form of bubbles. These gas bubbles are the driver of slag foaming in the EAF, a process that greatly increases the stability and efficiency of melting. [22,23]

EAF slag often contains calcium silicate phases, such as dicalcium silicate (Ca_2SiO_4) and tricalcium silicate (Ca_3SiO_5). Depending on the furnace operation, additional minerals like calcium aluminate ($CaAl_2O_4$) and magnesium aluminate ($MgAl_2O_4$) may be present. Magnesiowüstite solid solution, (Fe,Mg)·O, forms due to the reaction between FeO and MgO at the slag/refractory interface. The formation of magnesiowüstite, acting as an intermediate protective layer, prevents the immediate dissolution of the refractory. The presence of magnesiowüstite in MgO-saturated slags improves slag foaming and reduces refractory wear.[24,25] Slag with calcium oxide saturation will precipitate Ca_2SiO_4 solid phase. Under the conditions of MgO and CaO-saturated slags, the

slag is considered to be dually saturated with the precipitation of dicalcium silicate and magnesiowüstite. EAF slag can also contain minor amounts of impurities, such as sulfur, phosphorus, and trace elements of chromium, molybdenum, titanium, and vanadium from the raw materials.

3. Industrial applications of EAF slag in the U.S.

Slag is a multifunctional material used in various applications. For example, ironmaking slag from blast furnaces in the USA is almost exclusively (99.8%) used in Portland cement production. Currently, Blast Furnace Slag (BFS) is a high-value coproduct of steelmaking with prices around 100-120$/t.[26] BFS contains major constituents of 20-30% SiO_2, , 30-40% CaO, 10-20% Al_2O_3, 5-15% MgO, 1-10% MnO, and other trace oxides of FeO, TiO_2, ZnO, SO_3, K_2O, V_2O_5, P_2O_5, SrO and Cr_2O_3.[9] BOF slags stand out mainly by their higher CaO and FeO content -major constituents range from 40-50% CaO, 10-20% SiO_2, 10% MgO, 15-30% FeO/Fe_2O_3, 10% MnO, 2-5% Al_2O_3.[9] On the contrary to ironmaking slags, BOF and EAF steelmaking slags (SS) are regarded as a "poor relation" with almost negligible sales price of 7-10 $/t. Primary reasons for such market valuation are the enrichment of steelmaking slags with FeO and entrapped metallic iron particles. Another reason is a certain volume instability of the slag due to the presence of free lime. If free lime is present in the slag, it can hydrate which will cause the slag to swell. In road fill applications this would be problematic. EAF slag is frequently "weathered" so that no further swelling will occur. Depending on the chemical composition and cooling rates, slags have different crystallinity levels. For cement applications, an amorphous phase is preferred, which is easier to grind. EAF slags are more likely to crystallize with higher iron oxide content what creates stronger particles. The high diffusivity of the Fe^{2+} cation is believed to accelerate the formation of crystal phases such as Fe-containing akermanite ($(Ca,Na)_2(Al,Mg,Fe^{2+})(Si_2O_7)$) in the melilite mineral group, wüstite, or magnetite when the concentration of FeO is high in the slag.[27] However, a small portion of iron oxide is desirable in Portland cement at typical levels of 0.5-6% which is considerably lower than in EAF slag 25-37%, as seen in **Table 1**. MgO levels in slags can also be a limiting factor due to the expansion caused by the very slow hydration of magnesium oxide (periclase) crystals causing cracking and reduction of strength of the Portland cement. Free CaO and MgO hydrate under the influence of moisture, leading to large volume changes. Free CaO hydrates quickly, and this causes large volume changes during the first few weeks. MgO on the other hand hydrates slowly,

promoting expansion in the long term, even for several years.[27] Aside from weathering, one of the options to fight the volume instability of the EAF slag is the modification of slag during/after tapping with silica or alumina[28,29] that convert some of the responsible phases (free lime and periclase, dicalcium and tricalcium silicate) into stable ternary oxides (belonging to melilite series).

However, the low market evaluation does not mean the complete absence of utility of steelmaking slags. EAF slag finds extensive use as a substitute for traditional aggregates in the production of construction materials such as concrete and asphalt. EAF slag is commonly referred to as having an angular shape or rough texture with many angles and edges compared to common aggregates in concrete.[13] The slag's unique properties, including its hardness and angularity (coarse shape), contribute to enhanced bonding and mechanical strength of concrete.

EAF slag is also utilized as a cost-effective material in road construction and maintenance projects.[18,30] It can be employed as a base or sub-base material, providing stability and improving load-bearing capacity. The United States Geological Survey, the main source of statistics on minerals and materials in the U.S., does not differentiate steelmaking slags on BOF and EAF. In 2021, asphalt concrete and road bases or surfaces accounted for a large portion (12.3% and 44.7% respectively) of the total steel slag reutilization in the U.S.[26] Another 12.9% of steelmaking slag was used simply as a filling material in construction projects. Production of clinker from steelmaking slag has halved now compared to during the years 2003-2008, when it was almost 7% (**Figure 3**). However, it is not clear if both BOF and EAF slag are used in clinker production.

In the cement industry, EAF slag can act as a supplementary cementitious material. When finely ground, it can be blended with clinker to produce Portland slag cement (PSC).[31] PSC offers improved durability, reduced heat of hydration, and reduced carbon dioxide emissions compared to ordinary Portland cement. An addition of steelmaking slag reduces the clinkering temperature during production thus, lowering process heat requirements usually covered with natural gas or coal.[31] The integration of EAF slag in cement production also diminishes the requirement for raw materials, making it an eco-friendly alternative. To put it into context, the U.S. cement industry produces between 80 and 100 Mt of cement per year. Therefore, potentially the whole EAF slag can be consumed solely for cement production as a 5-10% blending for clinker, which is

considered as a very tolerable blending amount. In world practice, steelmaking slags are used in cement production either as a raw material in a clinkering process step or as a blending of final cement composition - in the fine milling of clinker together with gypsum. For example, in China a steelmaking slag (SS) Portland cement has been available on the market with 30% SS, 30% BFS, and 35% clinker.[31]

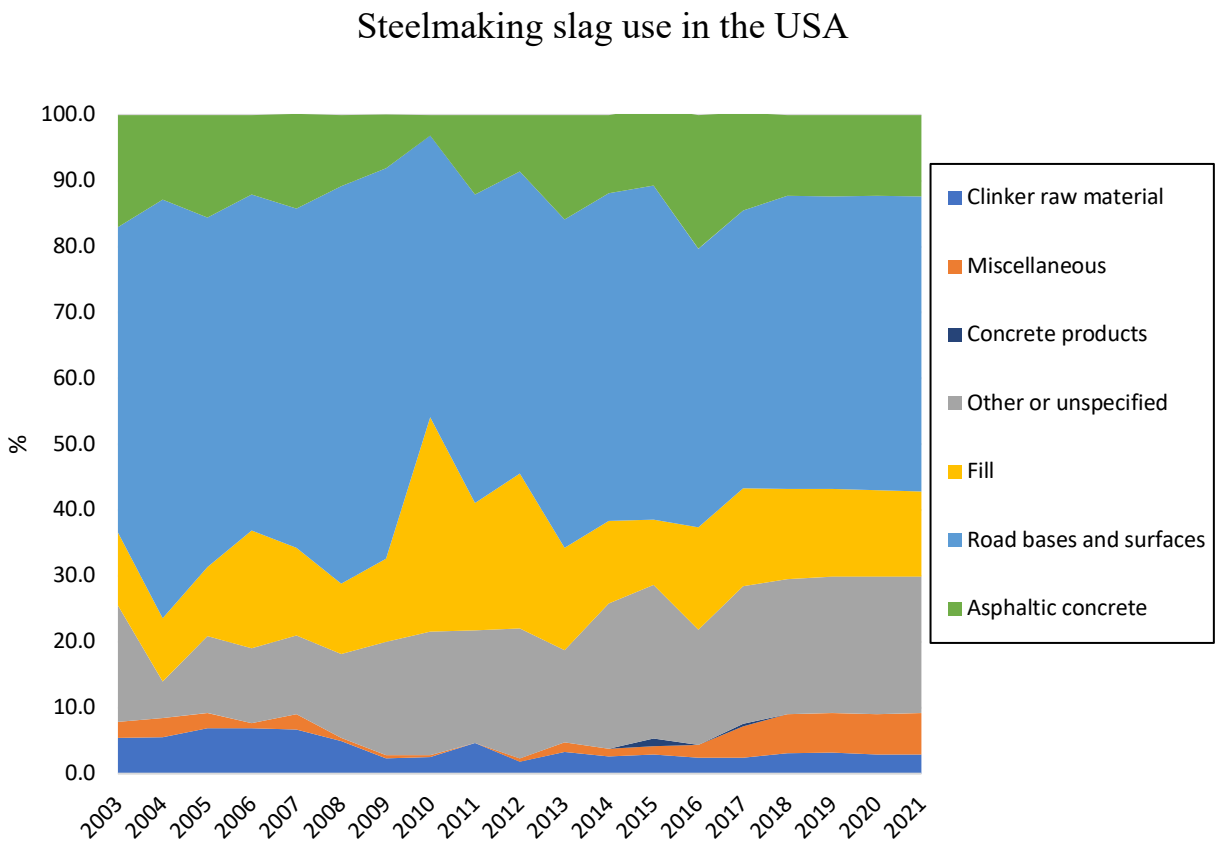


Figure 3. Statistics on BOF and EAF steelmaking slags usage in the USA in 2003-2021, based on USGS data.[32]

About 6% of "miscellaneous" uses of slags are mineral wool, railroad ballast, roofing, and soil conditioner. Nevertheless, statistics on 21% of steelmaking slags remain unclear, since it is reported as "other uses". According to some estimates, about 15% of steel slag was landfilled in 2013.[11]

From the above data, it is quite clear that the dominant application of steelmaking slags in the U.S. is low-value substitutes of natural sands and aggregates such as crushed stone. Overall, it helps to decrease an environmental impact by reducing the need for conventional virgin material aggregates. Thus, it can lead to lower greenhouse gas emissions and a smaller carbon footprint compared to traditional disposal methods. Utilizing slag in various applications reduces the need for energy-intensive processes involved in the extraction and production of virgin materials, such as rock grinding. Amani et al.[33] investigated the CO_2 footprint of concrete mixtures with varying levels of naturally fine and coarse aggregate and EAF slag fine and coarse aggregate. The largest CO_2 emission, 311.4 kg CO_{2eq} per cubic meter of concrete, stemmed from the mixture with the combination of natural fine and natural coarse aggregate. The smallest level of CO_2 emission, 136.9 kg CO_{2eq} per cubic meter of concrete, contained a mixture of natural fine aggregate and EAF coarse aggregate.

However, two important aspects of slag utilization for construction must be taken into account. First, total annual steelmaking slag production is at least two orders of magnitude smaller than the transportation industry or total aggregates consumption[34,35] in the U.S., and thus, cannot be regarded as a significant factor at scale. Second, low prices of both slag and natural aggregates (in the range of 10-20$/t) make a selection between them for the construction project more a matter of transportation cost and local availability.

Our private communication with the industry representative confirmed the following information: in the U.S.-based metallurgical company EAF slags are sent directly to a slag processing company such as the Edw. C. Levy Company for processing, repurposed in-house as either road aggregates or make-shift retaining walls for preventing the erosion of different soils and muds, or sold to companies to be used as a road aggregate in driveways in rural parts of the U.S.[18] The average EAF slag composition at these industrial plants is within the range reported in Table 1 and contains high levels of FeO making them unfit for cement applications.

In some states, the EAF slag is used in landscaping.[3] According to preliminary research by the U.S. Environmental Protection Agency, EAF slag is marketed as a gravel alternative for residential unencapsulated use (used as lose ground cover, not encapsulated by concrete, asphalt, or similar

cover) in many states across the U.S. The handling of the use and disposal varies greatly from state to state.

3.1. Challenges and Limitations of EAF Slag Usage

Despite the utilization of EAF slags in construction, there are some challenges and limitations in its usage.

3.1.1. Chemical Composition Variability

EAF slag's chemical composition can vary significantly based on factors such as the type of steel produced, scrap materials used, the choice of operating practices, and the operating conditions of the electric arc furnace in the particular heat.[13,36] This variability can influence its suitability for different applications and may require additional testing and customization.

3.1.2. Leaching Potential

EAF slag may contain trace amounts of heavy metals and other potentially harmful elements. If not properly managed or used in appropriate applications, there is a risk of leaching, which could lead to environmental contamination and pose potential health hazards. Chromium (Cr^{6+}), vanadium (V^{5+}), lead (Pb), mercury (Hg), molybdenum (Mo), barium (Ba), and cadmium (Cd) are of particular concern due to their high toxicity to both human health and the environment, although mercury, lead, barium, and cadmium are not commonly found in typical EAF slag compositions[37,38] due to high temperatures of EAF operation, which drive those elements in vapor phase.

3.1.3. Technical Compatibility

While EAF slag can be a suitable substitute in certain applications, its physical and chemical properties may not always align perfectly with those of conventional materials, potentially affecting the performance of the end product. An especially sensitive characteristic of EAF slag is its volumetric expansion due to hydration.[36]

3.1.4. Quality Control and Standardization

Ensuring consistent quality and performance of EAF slag products may be challenging due to the varying composition and processing methods. The lack of standardized quality control measures can hinder wider adoption.

3.1.5. Abrasion and Durability

In some construction applications, EAF slag may exhibit higher abrasion characteristics compared to natural aggregates, which can affect the durability and long-term performance of structures if not adequately addressed.[39]

3.1.6. Regulatory and Permitting Challenges

Compliance with environmental regulations and obtaining necessary permits for using EAF slag in certain applications can be time-consuming and resource-intensive, posing barriers to its implementation.

3.1.7. Research and Development

Continuous research and development efforts are needed to explore new and optimize the potential uses of EAF slag in various industries.

Addressing these challenges requires collaboration among stakeholders, including steel producers, recyclers, regulators, and end-users. Research efforts focused on optimizing EAF slag properties and identifying new applications can further enhance its usability and promote sustainable resource management practices. Additionally, raising awareness about the benefits of slag recycling and responsible use of EAF slag can contribute to its wider acceptance and integration into various industries.

4. Potential Alternative EAF Slag Applications

4.1. Soil Improvement

Hiroyuki Matsuura[40] conducted a study of the valorization of ferrous pyrometallurgical slag. Author reported the main utilization of EAF slag in road materials being around 44.3% and roughly 5.7% of EAF slag ends in a landfill in Japan. Globally, 14% of the EAF slag produced is

landfilled.[41] Throughout history, iron ions have been naturally transported from the land into the ocean from rivers and streams through a process of complex chelating by soil fulvic or humic acids which are both organic acids. Due to continued land development leading to increased deforestation in Japan, the stock of organic materials produced and processed through the natural circulation system has decreased. Additional contributions to the decline of the marine environments along the Japanese coastline include global climate change and sea desertification. Recent research has utilized EAF slag as a rehabilitation material for marine habitats along the coast of Japan. The ions in iron are an essential micronutrient required for the proliferation of phytoplankton and for the growth of different species of seaweed. Therefore, the utilization of EAF and other steelmaking slags as a supply of iron ions is being studied with hopes of being applied not only in Japan, but the United States, and around the world in general.

EAF slag can be utilized as a soil amendment to improve soil fertility and structure.[42] Its high calcium content enhances soil pH and nutrient availability, promoting plant growth. The increase of soil pH is attributed to the high basic oxide content, primarily free calcium oxide, due to their easily dissolvable nature in the aqueous solution of the chosen soil. The presence of highly dissolvable basic oxides results in a release of hydroxide ions from the solution, thus contributing to a higher alkalinity of the soil. Furthermore, the slag's porous structure aids in moisture retention and prevents soil erosion, contributing to sustainable agriculture practices. According to the USGS,[43] the high calcium content present in slag can neutralize acid, similar to the effect of an antacid taken to alleviate indigestion after a heavy meal. Furthermore, slag can even mitigate accumulated acids in soils. There exists a significant potential for utilizing slag to address acid soils or acid mine drainage within the Chicago-Gary region of Illinois and Indiana.[9,43] Such an application would not only offset the expenses involved in restoring abandoned mine areas but would also provide a beneficial use for slags from steel manufacture.

An inclusion of EAF slag as a material for the full replacement of soils due to its benefits in environmental considerations and improvements in the engineering properties of soils was investigated by Mahmudi et al.[44] EAF slag was used as a substitute for clay soil within the range of 30% to 50% ratios to measure the geotechnical properties, extensive mechanical properties, and strength parameters of clay soils and EAF slag admixtures of clay through. Four different samples of clay, EAF slag, 70% clay-30% EAF slag, and 50% clay-50% EAF slag were tested. Due to the

non-plastic nature of the properties of the slag particles, the liquid limit and plasticity index decreased with the increase in overall EAF slag content. Results from the shear tests concluded the mixtures with 50% slag exhibited greater resistance to the higher levels of stress than the natural clay and 30% slag mixture. Upon formation between the clay particles and EAF slag aggregates, a strong structure was formed and increased resistance to constant normal stress, shear stresses, and normal stresses as the content of EAF slag was increased. Based on these tests and their results, the implementation of EAF slag is a stabilizing material with low cost leading to profitable implementation and desirable soil properties as clay-slag mixtures. Although these mixtures showed promise for their applications in ground improvement purposes, their utilization is currently limited to shallower, subbase applications. When implemented into deeper layers of the soil, additional specialized mixing techniques and equipment are required.

4.2. Filter Material

Metallurgical slags have long been tested as filter materials [9,45] in various applications due to their porous structure, which allows for high surface area and effective filtration and high calcium content able to neutralize acids. Slag's porosity enables it to trap and remove impurities, such as heavy metals, organic compounds, and other contaminants from different types of liquids and gases. As the composition of slags can vary, it leads to a diverse range of materials suitable for specific filtration tasks.

Steelmaking slags were tested for phosphorus removal from wastewater[46] and fish farm sludge,[47] for nitrogen removal from the wetlands[48] and heavy metals removal – As,[49] Cd,[50,51] Mn,[52] Pb.[51]

EAF slag presents a potential solution to address the issue of excessive phosphate in the water within the Chicago-Gary region. Phosphate, a crucial nutrient for plants and a major component in fertilizers, can become problematic when overused, leading to its discharge into local streams or lakes. The surplus phosphate in the water contributes to harmful algal blooms and can create dead zones. The high calcium content of ferrous slag, responsible for its ability to neutralize acids, may also enable the slag to absorb the excess phosphate from the water.[43] Barca et. al.[53] in the study of BOF and EAF slags reported the main mechanism of phosphorus removal from

wastewater was the precipitation of hydroxyapatite (HAP), the most stable of the investigated calcium phosphate complexes. The main influences on the removal of phosphorus were the pH of the wastewater and the initial concentrations of phosphate and calcium due to the present Ca^{2+} ions readily available for HAP precipitation. HAP precipitation is additionally favorable when the pH of the solution is increased, further enhancing the CaO dissolution. Given the substantial concern over excess phosphate in water within the Chicago-Gary area, this advantageous property of slag could offer an additional application for the material, reducing the necessity to mine new natural materials for water treatment purposes.

It has been shown in lab-scale trials in Sweden by De Colle et al.[54] that EAF slags from high-alloyed steels can successfully be used as a substitute for limestone for the neutralization of acidic wastewater produced by the rinsing of steel after the pickling process in a steel mill. In the trials, two out of the four tested slag samples reached the desired pH value compared to the neutralizations made with lime. Chemical analysis of the cleaned water both from the neutralizations using lime and slag showed that the neutralization with slag yielded similar results to lime in terms of hazardous elements concentrations. Moreover, the increased concentration of valuable alloying elements since the wastewater contains Cr, Ni, Mo, Fe and F. These elements can end up in the slag if the neutralization process works. If the reacted slag can successfully be reprocessed to remove these elements, the circularity of resources will be improved. Furthermore, De Colle et.[55] tested the approach of treating industrial wastewater with stainless steel slags in pilot-scale trials and proved its reliability in adequately treating wastewater.

4.3. Composites Production

Gobetti et. al.[56] investigated a new application for EAF slag as a filler for nitrile butadiene rubber (NBR), utilized in numerous parts in the automotive industry, by evaluating the mechanical and physical properties of an advanced sustainable composite material. To evaluate the potential implementation of EAF slag, four different calendered and compression-molded compounds with varying amounts of filler of 5, 10, 20, and 30%v/v (volume concentration of a solution) were tested with reference to a standard NBR which was only compression-molded and an NBR 0% which was calendered and compression-molded. The compounds containing greater amounts of slag in NBR increased the viscosity moderately. Additionally, the crosslinking kinetics were expedited

for the compounds with greater amounts of slag which decreases production time and lowers the cost of production. However, slag additions lead to a higher risk of producing non-compliant rubber parts. For compounds containing EAF slag at 30%v/v the compression modulus with an increase of 50% from the standard reference NBR which concludes that the compounds will have an increased deformation resistance when increasing the amount of slag. The hardness results, followed a similar trend to the compression modulus as the hardness value increased with the addition of more filler. Based on these results, utilizing EAF slag as a filler for NBR proves to be a promising slag application to enhance the composite properties.

Another interesting application of EAF slags is ceramic tiles and bricks production.[13] Currently, only lab-scale tests are reported. Badee et al.[57] were one of the first to test floor tiles production with up to 50% steel slag. Other researchers[58–61] later explored slag application in tiles production. A series of works[62–64] confirmed the successful application of steelmaking slag in ceramic bricks production. In most cases, sintered ceramic products can have between 30 and 50% of slag. However, an application of slag can be considered only if it does not create any health hazards associated with heavy metals content. To date, ceramic products for indoor application have not received the necessary certifications.[13]

5. EAF Slag Classification and Characterization

According to the United States Environmental Protection Agency (EPA)[3] and a Safety Data Sheet (SDS),[65] EAF slag is comprised of primarily oxides of iron, calcium, silicon, manganese, and magnesium; with additional varying amounts of additional metallic oxides with specific components which are hazardous under OSHA's Hazard Communication Standard (29 CFR 19120.1200).[66] Outlined in the Nucor SDS, the specific hazard effects associated with EAF slag are limited to the lungs, central nervous system, skin irritation, and eye irritation and do not include environmental or physical risks. The specific health classifications of the Globally Harmonized System (GHS)[67] are classified as the following: eye irritation in Category 2B, skin irritation in Category 2, specific target organ toxicity within single exposure in Category 3, and specific target organ toxicity of repeated exposure in Category 1. The main avenues of exposure leading to potential health effects stem from eye contact, and inhalation stemming from the potential hazards of EAF dust/fumes. Precautions discussed in Nucor's SDS[65] include safe handling of materials,

avoidance of inhaling dust and fumes, continued and thorough washing of hands and exposed skin, wearing of necessary protective clothing, gloves, eye and face protection.

According to the EPA,[3] the main risks associated with exposure to EAF slag dust stem from high pH levels, and concentrations of manganese (Mn) and hexavalent chromium, Cr (VI), in EAF slag. Prolonged exposure and inhalation of EAF slag dust risk is associated with skin irritation and respiratory system. Hexavalent chromium has been found to cause cancer, and manganese can affect the nervous system. When chromium is present, Cr (III) and Cr (VI) are the most common forms. Trivalent chromium is low in reactivity and relatively immobile while also being a necessary element in the human metabolism found in low dosages. Cr (VI) is extremely mobile, and soluble in water. The mobility of Cr (VI) enables easy penetration into cell membranes while maintaining a strong oxidizing power, both contributing heavily to its toxicity.[68] According to standards set by the Occupational Safety and Health Administration (OSHA),[66] the specific permissible exposure limits (PEL) of Cr (VI) are established as 5 $\mu g/m^3$ and the Action Level is set at 2.5 $\mu g/m^3$, both set over an eight-hour time-weighted average (TWA). If exposure occurs above the PEL, periodic monitoring for three months is required. Periodic monitoring is required every six months if the measured exposures average at or above the Action Level. Exceptions to these limits are exposure that occurs from the usage of pesticides, exposure to Portland cement, and when an employer possesses objective data that demonstrates the material possessing Cr (VI) does not emit fumes, dusts, or mists with Cr (VI) equal to or above 0.5 micrograms per cubic meter over an eight-hour TWA. Exposure to Cr (VI) is considered as contact to the skin or orifices and inhalation of Cr (VI) as a dust, fume, or mist. Although stringent levels of action have been established by OSHA,[66] current leaching studies and discussions with multiple industry partners show chromium being present in EAF slag up to 2 wt. % and as trivalent chromium rather than hexavalent chromium, making the need for caution when handling EAF slag less than previously anticipated. [18,37,69,70] Due to the high basicity of slag, hexavalent chromium is not a stable phase in typical steelmaking conditions.[70] At the same time, Cr leaching is significantly hindered under basicities below 2.0.[71] Some studies report the formation of unstable $CaO{\cdot}Cr_2O_3$ at basicities higher 2.0, which is prone to Cr leaching. Dissolved Cr(III) can be oxidized in alkali environment and form Cr(IV).[72,73] Besides, high-quality and stainless steel production yields a slag with much

higher Cr content. In the cases of high-Cr steel grades production, slag can form hexavalent Cr under certain conditions, which is discussed further.

From EAF slag, increased exposure to manganese on the human body has negative effects on the nervous system while increased exposure to hexavalent chromium can lead to cancer with children being more susceptible to the negative effects than adults. The more severe effects of exposure to chromium stem from delayed, long-term effects. Additional risks of long-term exposure include chronic exposure to manganese and manganese salts which can affect the lungs, kidney, brain, central nervous system, and blood or blood-forming organs. Although the EPA outlines potential hazards from manganese exposure, the risk is negligible due to its tendency to bind with iron in the slag, i.e. iron-containing oxides such as wüstite, ferrite, and spinel. Also, the risk of manganese leaching is low due to the low concentration of manganese oxide in the iron-containing oxides and these solid solution phases being stable during weathering.

Crystalline silica exposure in the form of chronic respiratory exposure may lead to lung disease with systems ranging from shortness of breath and coughing to heart enlargement and heart failure. Additional effects of crystalline silica exposure can lead to carcinogenic effects causing a disease referred to as silicosis. Crystalline silica has been classified by both the International Agency for Research on Cancer (IARC) and the National Toxicology Program (NTP). The IARC classified crystalline silica[74] as carcinogenic to humans and the NTP classified crystalline silica as respirable silica as a known human carcinogen.[65] The risks associated with the presence of crystalline silica are mitigated due to the silicon oxide in the slag existing in the form of silicate, a binary, ternary, or quaternary compound. However, there is an exception that would result in crystalline silica existing in the slag. If the chemical composition correction is not fully functional, quartz will be added to the bath. The inserted quartz is unable to dissolve fully into the liquid slag, resulting in a formation of pure quartz clusters that can potentially lead to exposure to crystalline silica during the processes of slag crushing and milling.

The Leaching Environmental Assessment Framework (LEAF) is a leaching evaluation system that is applied to create screening level assessments of constituent release or to generate more precise estimates of release in particular use or disposal scenarios.[3,75] LEAF consists of four different

leaching methods combined with data management tools and scenario assessment approaches which offer information pertaining to constituents of potential concern (COPCs).

The leachability of chromium from stainless steel slag was investigated by Yu et al.[76] under specific atmospheric conditions and temperatures. The authors performed experiments in an oxidizing atmosphere in a muffle furnace and in a reducing atmosphere in an induction furnace. The results indicated that an oxidizing atmosphere intensifies the leachability of chromium, Cr^{6+} and the degree of leaching increases with temperature. The leaching of chromium is restrained in a reducing atmosphere. To prevent the formation of hexavalent chromium, it is necessary to utilize a reducing atmosphere since it is difficult to completely reduce chromium Cr^{6+} to Cr^{3+}.

Leaching characteristics of chromium in EAF stainless steel slag, which typically has much higher Cr content than dominating carbon steel EAF slags, were investigated by Wang et al.[69] from the perspective of mineralogical control. The main mineralogical phases which were identified by X-ray Diffraction (XRD) were spinel ($Mg(Cr,Al)_2O_4$), merwinite ($Ca_3Mg(SiO_4)_2$), perovskite ($CaTiO_3$), magnetite (Fe_3O_4), calcium aluminosilicate ($Ca_2Al_2Si_2O_8$), dicalcium silicate (Ca_2SiO_4), and eskolaite (Cr_2O_3), commonly referred to as trivalent chromium (Cr (III)). Concentrations of trivalent, hexavalent, and total chromium content in the leachates were measured in mg/L from EAF stainless steel slag utilized as the admixture in cement. Due to the reduction properties and high alkalinity of the leachate, chromium remaining in the leachate primarily existed as trivalent chromium. The origins of the trivalent chromium stemmed from the chromium-bearing minerals present in the EAF slags, primarily in silicates, Fe-Cr alloy, and spinel-type phases. The spinel-type phases are insoluble in neutral and alkaline solutions; however, chromium is dissolvable in Ca-Mg silicates in neutral and alkaline solutions. Ca-Mg silicates are commonly referred to as pseudo-binary phases and the swift dissolution of these phases contributed to the fluctuations in the level of trivalent chromium during the first few days of leaching. The sequential leaching process proved successful in separating the primary chromium bearing minerals from the difficult to dissolve secondary phases generated in the EAF slag. Amorphous or crystalline secondary phases were formed by primary phases undergoing either hydrolysis, dissolution, or precipitation. The overall concentration of chromium in the leachates was less dependent on the dissolution of the primary minerals with chromium than the dependence on the diffusion rate of chromium passing through the secondary phases. Therefore, based on the stabilization of chromium

concentrations under different liquid/solid (L/S) ratios, the chromium leaching of EAF slag is controlled concretively by the precipitation of the secondary phases and the dissolution of the primary chromium bearing phases.

Bankole et al.[68] investigated the leachability of hexavalent chromium taken from acidic EAF slag with basicity of 0.96 based on modified European batch leaching tests conducted over sixteen days. Three different lixiviants of de-ionized (DI) water, alkaline water, and rainwater were compared for a batch of 50 grams of EAF slags with a particle size between 1-4 mm. The pH levels were high in alkaline water, enabling a steady leaching of Cr (VI) with a slow initial reaction and DI water had the lowest leachate pH value. The overall pH of the leachates was alkaline and was observed within the first day of initial contact with the lixiviant. The amount of Cr (VI) leached was higher at the start until decreasing later and can be viewed as the reduction of Cr (VI) due to the precipitation of a reductant mineral. Fe (II) can be used as a reductant to Cr (VI) whereas a more soluble, acidic solution will oxidize Fe (II) to Fe (III). This would lead to a lower potential for Cr (VI) reduction, allowing for more Cr (VI) to be left in the solution. Therefore, Cr (VI) leaching is ultimately correlated to the redox reaction occurring in the leaching process. Increasing the stirring speed led to an increase in the amount of Cr (VI) leached, with 0.006 mg/L leached at 0 rpm and 0.032 mg/L leached at 50 rpm, observed within the first 24 hours and are lower than the established PEL-TWA.[66] This increase in leaching can be attributed to more contact between the lixiviant and the slag samples upon increasing the stirring speed and is possibly indicative of the release of Cr (VI) being controlled by diffusion. The L/S ratio also affected the leachability of Cr (VI) as the concentration of leached Cr (VI) increased with a decreasing L/S ratio.[68]

Cirilli et al.[16] studied the stability of V oxides in the morphological structure in EAF slags and consequent leachability. Both synthetic and industrial slags were investigated. The researchers concluded that V tends to concentrate in the $3CaO{\cdot}SiO_2$. Although the formation of tricalcium silicate can be promoted by adding CaO at high temperatures to the slag, tricalcium silicate will not be easily formed in EAF slag other than in cases where the basicity ranges between 2.5 and 3.0.[77] This measure drastically reduced V in the eluate of the reported leaching tests.[16] However, for the basicity range of 2.5 to 3.0, the formation of brownmillerite (C_4AF) or gehlenite (C_2AS) occurs instead of $3CaO{\cdot}SiO_2$ due to the presence of Al_2O_3 and FeO_x and lower thermodynamic potentials of brownmillerite and gehlenite. Other studies[38] pointed out the effect of Ba on the

leaching of V, suggesting the negative correlation of leaching Ba on the leaching of V and vice versa. The least amounts of leached Ba, Cr and V were detected in samples with kirschsteinite.

A study conducted by Iwama et al.[78] focused on the sequestering of phosphorus from steelmaking slag as it reduces the mechanical properties of the steel but at the same time is commonly utilized as a fertilizer. Phosphorus is transferred from molten iron into the slag during the steelmaking process. Phosphorus is commonly found in the C_2S-C_3P phase ($2CaO{\cdot}SiO_2$-$3CaO{\cdot}P_2O_5$) and is soluble in water. Additional elements present in different mineral phases have a wide array of water solubilities. Due to the differences in solubility in water for the C_2S-C_3P phase and other mineral phases, a selective acid leaching method was applied to sequester phosphorus and study the effect of treating the slag by oxidation and slow cooling before selective separation. After selective leaching of the phosphorus-enriched phase in the slag, an increase in FeO as Fe_2O_3, MgO, MnO, and Al_2O_3 and a decrease in CaO, P_2O_5, and SiO_2 was observed. Increasing the yield of Fe and Mn coupled with lowering the phosphorus content in the slag is advantageous for the reuse of slag. This study concluded that phosphorus can be effectively selectively sequestered from the slag with oxidation treatment and slow baking, producing residues which can be utilized in the steelmaking process.

Another interesting approach to utilizing phosphorus from steelmaking slags was proposed by Peter Drissen.[79] Instead of removing phosphorus from the slag, he suggested dissolving in the slag additional amounts of P_2O_5 from phosphorus-containing wastes, such as sewage sludge and ashes from bone incineration. The resulting slag got an increase in P_2O_5 content from 2.1 to 5.1%. Moreover, 95% of this phosphorus became available for plants consumption. Application of such modified slag for growing plants showed mass gain comparable to commercial phosphate fertilizer and well-exceeded compost or sewage sludge. The advantage of such method is the utilization of chemical and thermal energy of the liquid slag. The only drawback is the need to add some extra equipment that would facilitate the liquid slag enrichment – blowing lance or other feeder.

6. Recycling Technologies and Methods

As EAF slag contains a range of valuable metals, their recovery using various traditional techniques is a viable option for slag treatment and metal reusability. To harness the potential of

steel slag as a resource, various mineral processing techniques, including crushing, grinding, magnetic separation, eddy current separation, flotation, leaching, and roasting, can be employed to recover these metal constituents.

Generally, the slag recycling processes depend on the slag classification and its further use (See **Figure 4**). When using the slag for construction aggregates and as filters and absorbents in water treatment processes, only rough crushing and sizing are required. In contrast, for more advanced applications that rely on its chemical composition, it becomes imperative to crush and grind EAF slags aiming at liberating the minerals confined within. Subsequently, magnetic separation, flotation, and/or gravity separation methods further differentiate the EAF slag into distinct categories, including magnetic minerals, valuable elemental constituents, and residual materials. Magnetic minerals, rich in iron, can be effectively recovered. Valuable elements like calcium oxide, magnesium oxide, and silicon dioxide find application in the production of cement and ceramic building materials. Finally, the by-products resulting from the separation processes can be repurposed for applications such as fertilizers and water treatment.

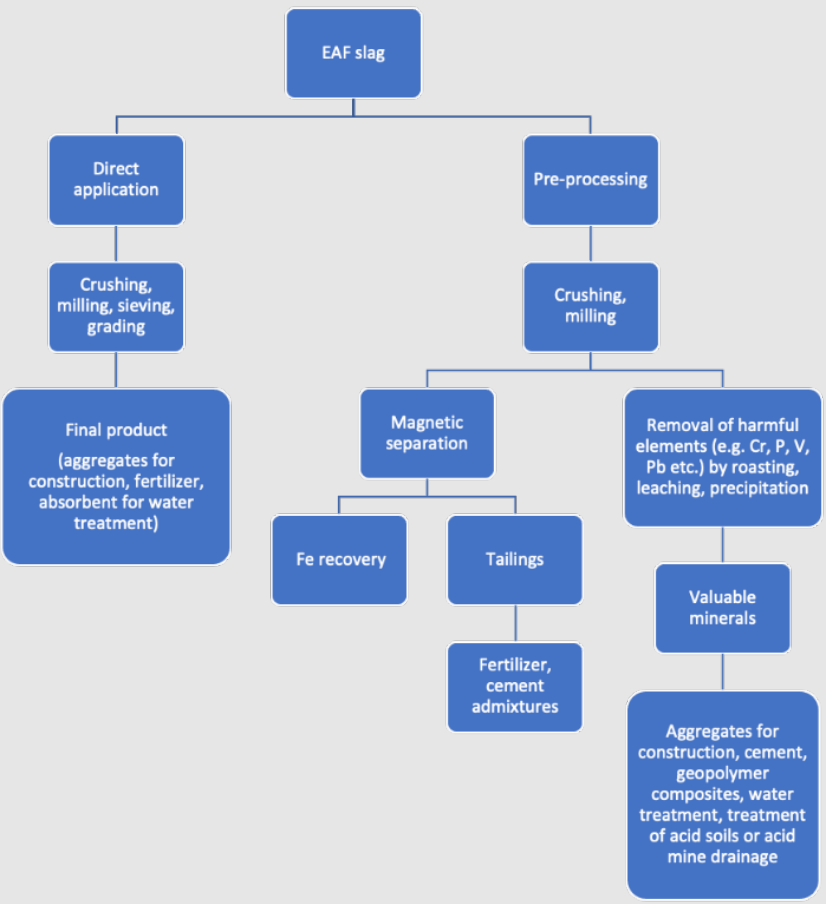


Figure 4. Possible ways of EAF slag recycling and its further uses.

6.1. Physical (Mechanical) Processes

After the slag has been produced during the manufacturing of steel, the slag is required to undergo different physical processes to adjust its technical properties for a specific application. These physical processes include weathering, crushing, and sizing.

6.1.1. *Crushing and Screening*[80]

Crushing and screening are fundamental steps in processing EAF slag. The slag is crushed to break it down into smaller particles, facilitating handling and further processing. Subsequently, screening separates different-sized particles, ensuring uniformity for various applications, such as

aggregate production for construction purposes. Different concretes and bituminous mixtures made with EAF slag as an aggregate have displayed promising physical and mechanical properties which have ensured greater reliability in their utilization.[81]

6.1.2. *Sizing and Classification*[13]

Sizing and classification are applied to sort the crushed slag particles into different size fractions. This process utilizes mesh screens or other classification techniques to achieve the desired particle size ranges, catering to specific downstream applications. In a State Highway Administration (SHA) research report, the optimum size for steel slag was a U.S. 3/8" (9.5 mm) sieve utilized for studying the impact on compaction characteristics when applied as an additive mixture in asphalt binder[82].

6.1.3. Magnetic separation

Magnetic separation is a key process in EAF slag recycling, aimed at recovering valuable metal components, particularly iron, entrapped in the slag. The use of powerful magnets attracts and separates magnetic particles from non-magnetic ones, resulting in a metal-rich fraction that can be further processed or reused. Recovering iron from the slag offers two significant advantages: substituting it for scrap iron in steelmaking reduces the demand for virgin raw materials, while the separated slag can be effectively utilized in construction materials or cement production. A study conducted by Menad et al.[83] analyzed generated EAF slag with Mössbauer spectroscopy, concluding that 58% of their slag composition consists of magnetic components.

Magnetic separation was completed by the Frantz separation technique which separates the magnetic phases from the non-magnetic phases into two different fractions by applying a magnetic field. After the separation of magnetic and non-magnetic fractions was completed, the samples were analyzed by XRD where wüstite (FeO) was found to be greater in the non-magnetic fraction.

Different magnetic machines that are used to separate metallic iron and iron minerals from steel slag include cross-belt magnetic separators, drum magnetic separators, and magnetic pulley separators.[84] An example of a system where multiple steps of crushing, vibrating, and magnetic separating enable a stepwise flow of steel slag can be seen in **Figure 5**. Eventually the slag is

broken down to a specific particle size where the metallic iron and oxides concentrate are able to be separated.

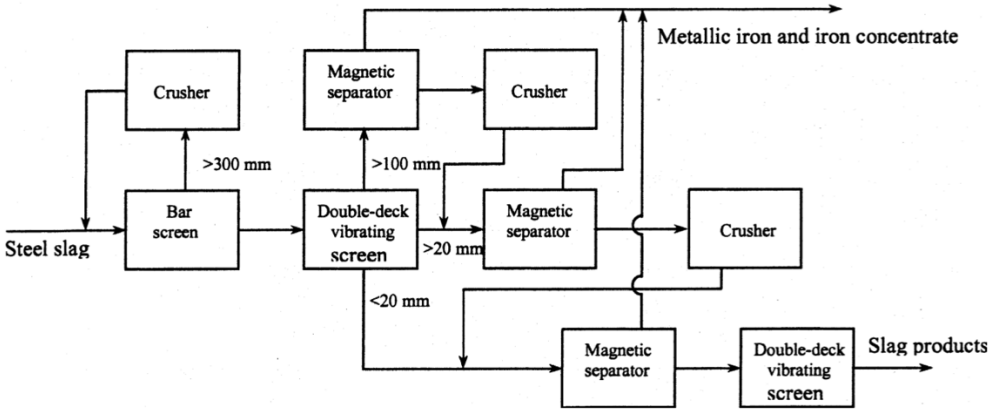


Figure 5. Slag processing flow chart. Reproduced with permission.[85] Copyright 2003, Elsevier Science Ltd.

6.2. Chemical Processes

The chemical process for recycling Electric Arc Furnace (EAF) slag follows a systematic approach to recover valuable metals and minerals. Initially, the collected slag undergoes conditioning through crushing, which enhances its processability by reducing particle size and increasing reactivity. Next, the conditioned slag is subjected to leaching, where a chemical solution, such as an acid or a base, selectively dissolves the valuable metals and minerals from the slag matrix. The choice of leaching agent is tailored to the specific metals targeted for recovery. Following leaching, a selective precipitation step is employed to separate and recover specific metals as solid compounds by adjusting pH levels or using specific reagents. The precipitated solids are then separated from the leach solution through filtration or other techniques, ensuring the concentration of the targeted metals. The residual slag, now depleted of the valuable metals, undergoes further treatment to minimize environmental impact. This treatment may involve solidification, stabilization, or neutralization to render the residue inert and safe for disposal. The solid precipitates obtained from selective precipitation undergo additional processing, such as smelting or refining, to produce pure metals or metal alloys. The recovered metals find application in various industries, such as steel production, electronics, and construction.

A good review of relatively recent leaching studies on steelmaking slags is a reported by Menad et al.[86] Various metals have been successfully extracted on the lab scale test with basic and acidic leaching processes – **Table 2**.

In the steelmaking industry in V-bearing slags, stable low valence oxides in spinel form $(Fe,Mn)_x(V,Cr,Ti)_{3-x}O_4$ pose challenges for conventional leaching methods.[87] Therefore, roasting is applied to disrupt stable spinel and olivine, oxidizing vanadium ferrospinel into dissoluble vanadate. Subsequent leaching with acid, alkali, or water yields intermediate products like vanadic acid; further precipitation with ammonium sulfate forms ammonium metavanadate, which, upon calcination, produces high-purity V_2O_5 with up to 85% V extraction efficiency. Whereas Cr extraction efficiency is only about 5% in an industrial scale.[88]

Table 2. Studies on metals extraction from slags and oxides by leaching and roasting processes.

Metal	Leaching agent	Efficiency reported	Authors
Cr	NaOH and $NaNO_3$	89% Cr	Kim et al.[89]
Cr, V	Na_2SO_3	99.7% Cr, 99.6 V	Wang et al. [90]
Cr, V	Na_2CO_3 $(NH_4)_2SO_4$	99% Cr, 95% V	Wen et al. [91]
Cr, V	Calcification roasting		Jiang et al.[92]
Cr	NaOH	99.1% Cr	Ji et al.[88]
Cr, V	KOH, NaOH	95% V, 90 Cr	Wang et al.[93]
V	Na_2CO_3, $CaCO_3$	92.3% V	Zhang et al.[94]
V	Na_2CO_3	>80% V	Gao et al.[95]
Cr, V	Na_2CO_3 and NaOH	95.8% V, 97.6% Cr	Li et al.[96]
Mo, V	NaOH and/or $NaAlO_2$.	89% Mo, 85% V	Wiewiorowski et al.[97]
Mo, Al	NaOH	96% Mo, <99% Al	Huang et al.[98]
V, Cr, Al	bioleaching	8% V, 84% Cr, >99% Al	Gomes et al.[99]
V	$H_2C_2O_4$	86.8% V	Hu et al.[100]
V, Cr	MnO_2 and H_2SO_4	98.7% V, 99.4% Cr	Chen et al.[101]
V, Cr	H_2SO_4 and hydrolysis precipitation	86.5% V, 96.9% Cr	Wang et al.[102]
V	Cr_2O_3 and H_2SO_4	91% V	Zhang et al.[103]
Cr	CH_3COOH+HCl, Na_2EDTA+NH_2OH·HCl, HF+HNO_3+H_2O_2	65% Cr, >99% Mo, >99% V	Spanka et al. [104]
V	NaCl, H_2SO_4, Na_2CO_3	95% V	Nkosi et al.[105]
V, Cr, Mo	KOH, NaOH, K_2CO_3	62.5% V, 97.5 % Cr, 95.8% Mo	Menad et al.[86]
V, Cr, Mo	Salt roasting, KOH, NaOH-Na_2CO_3, KOH-Na_2CO_3,	62.5% V, 97.5 % Cr, 96.3% Mo	Menad et al.[83]

6.3. Thermal Processes

Thermal processes for EAF slag recycling encompass utilizing the slag as a raw material in metallurgical processes and subjecting it to thermal treatment for aggregate production. Scientifically, these methods offer sustainable solutions for waste management and resource conservation in the steel industry. Through controlled heating in specialized furnaces, metal recovery from EAF slag is achieved, separating valuable constituents such as iron, manganese, chromium, and nickel. The recovered metals can be refined for reuse in various metallurgical applications, contributing to resource efficiency. Additionally, the thermal treatment of EAF slag yields processed slag or synthetic slag, which serves as a fluxing agent in steelmaking, optimizing steel quality and composition. Moreover, the thermal transformation of EAF slag into aggregates via sintering or expansion techniques results in durable and granular materials suitable for construction purposes.[13]

For example, steelmaking slags can be processed with a very typical carbothermic reduction technique.[41] In this case, iron is extracted from EAF slag with the carbothermic reduction at 1500-1600 ^{0}C, while the other metals are extracted in another step with the acid backing process (heating to 100-500 ^{0}C). Kim et al.[41] was able to extract iron together with niobium, chromium, and manganese in metallic form (70% Fe, 17% Mn, 7% Cr, 0.2% Nb, and 5%C). Titanium, magnesium, and aluminum were extracted in the slag form. Acid baking and water leaching were used to achieve >85% leaching of Ti and ~100% leaching of magnesium and aluminum from the iron-depleted slag phase. Mensah and Das[106] also showed a successful carbothermic reduction of the metallic phase (close to pig iron composition) from the EAF slag. The extraction rate of iron was 84% and close to that value Ni, Co, and Mo. Some partial recovery of V, Cr, and Mn into metallic was also achieved.

Carbothermic reduction can assure the low cost of iron depletion. The remaining slag can be used as raw material for cement clinker. If two-stage processes are to be applied, the disadvantages of the scheme proposed are overall complicated technology involving acids handling, leachate processing, and CO_2 emissions from carbothermic reduction.

Alternatively, in order to minimize the CO_2 emissions from slag treatment, it can be iron-depleted with the use of hydrogen. It is well known, that FeO in the liquid slag can be rapidly reduced with the use of hydrogen.[107–110] For example, Htet et al.[111] were able to partially reduce iron from synthetic HIsarna slag (referring to slag from the HIsarna process developed by a group of European steel companies, with the support of the European Union in the ULCOS (Ultra-Low CO2 Steelmaking) project)[112] by blowing and purging with Ar-10%H_2 gas mix. Moreover, there are no principal restrictions to applying an even more efficient reduction method - H_2 plasma.

Another process that can be classified as thermal is oxidation and vaporization. Vanadium can be extracted in the form of V_2O_5 from the liquid slag by oxidation and vacuum treatment.[113,114] More than 77% of V_2O_5 was evaporated in the lab scale tests with relatively simple and not optimized treatment. In this conceptual design of industrial application, slag could be treated with oxygen/air blowing right after taping, before it gets solidified. Thus, energy and chemical consumptions are minimized.

7. Potential Adding Value of the EAF Slag

If the EAF slag is depleted in FeO content, it can be marketed close to or even similar to blast furnace slag for cement production, thus, increasing its value almost ten-fold – from today's 10 $/t to >100 $/t.

Another source of value comes from the return of iron back into the steelmaking loop. Under the assumption of average 30% FeO content in EAF slag, it would imply 230 kg Fe/t_{slag}. Value returning of this iron back to the EAF can be estimated based on the scrap or HBI price (iron sources for EAF steelmaking), to 200 $/t. Thus, the returning iron value is easily estimated as 40-50 $/$t_{slag}$.

If Cr_2O_3 is efficiently removed from the slag, it would add a value of ca 200 $/t of chromium oxide. This adds an almost negligible value of less than 1 $/t of slag. However, if Cr can be recovered in the metallic fraction - for example, as a part of Fe-Cr alloy its value significantly increases. The value of 1% Cr_2O_3 entrapped in slag, if it is recovered from the slag as a pure metallic Cr is $150 using this year's price of 22,500 $/t Cr_{met}.[115]

Even such a vague estimation suggests a significant potential to increase the value of EAF slag recycling from today's $10 to $200-300.

8. Conclusions

EAF slag maintains its classification as a non-hazardous material according to the EPA unless in the form of EAF slag dust. Current considerations for a reclassification of EAF slag as hazardous is ongoing with discussions between the EPA and National Academy of Sciences (NAS).[8] EAF slag from industrial plants in the U.S. have shown no evidence of harmful levels of hexavalent chromium which would be influential in the determination of the reclassification, based on the findings of this review. Among the main challenges of EAF slag application are high variations of slag composition and volume instability of slag during/after hydration.

Analysis of the U.S. recycling practices revealed two main features. Firstly, EAF slag is almost completely reused with only marginally small amounts of slag being landfilled. Secondly, slag is used mostly as a low value-added aggregate in various construction applications. Thus, a serious potential of unlocking additional value from EAF slag recycling still remains a challenge for the steelmaking industry. Besides the usage of slag as a clinker material for the cement industry, which by itself creates additional value and significant energy and emissions reduction, a review of modern technologies proposed for steelmaking slag recycling highlighted options for recovery of valuable metals such as Cr, V, Mo, Fe and others in different ways, such as leaching, reduction, oxidation.

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