Review Article

Advances in Understanding the Alkali-Activated Metallurgical Slag

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Received 14 April 2021; Accepted 8 May 2021; Published 25 May 2021

Academic Editor: Tingting Zhang

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This paper summarized and reviewed the mechanism and macro-performance of alkali-activated metallurgical slag, including steel slag, copper slag, ferronickel slag, and lead-zinc slag. Better activated method and alkali-activator are still needed to be developed to improve the performance of the metallurgical slag with low reactivity. Besides, the chemical components’ variation of these metallurgical slags from different regions will lead to unpredictable performance, which needs further study.

1. Introduction

It is widely accepted that alkali-activated material (AAM) is a potential alternative for ordinary Portland cement (OPC) [1]. These materials are commonly generated by aluminosilicate precursor, which can be obtained from solid industrial waste, such as granulated blast furnace slag (GBFS), fly ash, mineral processing tailings [2], catalyst residues, waste glass, waste ceramic, coal bottom ash [3], rice husk ash [4], palm oil fuel ash, etc. [5]. In 2016, approximately 1.45 Gt CO2, which is about 8% of CO2 total emissions from human activities, was released from the cement industry [6]. About 50%–60% CO2 emission of cement industry comes from the calcination of limestone. Therefore, the replacement of OPC by AAM is recognized as one potential way to reduce carbon emission [7]. Life-cycle analysis (LCA) of alkali-activated materials has been thoroughly discussed by Habert. According to the statistics of different studies, LCA of AAM reduces approximately 40%–80% CO2 emissions compared to an OPC baseline [1]. Need to add that the baselines of OPC are specified inconsistently among various reports because the mix design, local conditions (such as transport distances and cost of electricity generation) as well as industry and environmental policy significantly affect the baseline [1].

Compared to OPC, AAM could have superior properties through reasonable design. Better acids and sulfate resistance [8], higher strength [9], and higher temperature resistance [10] were reported in AAM. These advantages of AAM are mainly achieved by the presence of aluminosilicate gel such as hydrated calcium aluminosilicate gel (C-A-S-H) and hydrated sodium aluminosilicate gel (N-A-S-H). These two kinds of aluminosilicate gel are different from the main product, namely, C-S-H in cement. A highly crosslinked silicon structure of Q3 and Q4 with less bound water was found in aluminosilicate gel due to the substitution of aluminum for silicon [11], which contributed to the better properties of AAM. Furthermore, AAM shows a better performance in alkali-aggregated reactions (AAR) compared to OPC [12].

According to the different precursors activated, AAM is commonly divided into two different binder systems [5]. The primary type of alkali-activated binder is high-calcium alkali-activated binder mainly derived from alkali-activated blast furnace slag (AAS) [13]. The secondary-type binder system is the so-called “geopolymer” mainly derived from alkali-activated fly ash (AAF). The former system is dominated by C-A-S-H products with a tobermorite-like structure (mainly Q2 with smaller parts of Q1 and Q3) [14]. The main product in geopolymer is N-A-S-H with a zeolitic-like
structure (mainly Q4 with few Q3) [12]. Blast furnace slag is more reactive than fly ash, as a higher pH and temperature is needed to activate the fly ash [5]. This means AAS has a wider range of activators compared to AAF, such as sodium carbonate and sodium sulfate. Besides the different gels in these two systems, a wide range of secondary phases such as hydrotalcite and AFm-like crystal were observed in AAS [15].

Recently, various metallurgical slags are generated in the production of metal processing, such as steel slag, copper slag, ferronickel slag, and lead-zinc slag. Steel slag is a solid waste generated during the conversion of iron into steel, which is about 15% of the crude steel output [16, 17]. Copper slag is an industrial by-product produced by the copper-making process, whose yield is 2–3 times that of copper output [18, 19]. Ferronickel slag as an industrial waste comes from the process of nickel-iron alloy production [20, 21]. Approximately 12–14 tons of ferronickel slag per ton of nickel is produced [22, 23]. The main solid waste generated during lead and zinc production is lead-zinc slag. According to statistics, the extraction cost per 100 tons of lead and zinc is 71 tons of lead slag and 96 tons of zinc slag [24, 25]. It is estimated that the annual production of steel slag, copper slag, ferronickel slag, and lead-zinc slag each year worldwide is 200 million tons, 70 million tons, 150 million tons, and 25 million tons, respectively [17, 23]. Although the yield of these slags is high, the utilization rate is low. For example, until now, the steelmaking industry produced nearly 1.2 billion tons of steel slag in China, and only less than 30% slag is recycled and applied in some low-value-added fields [26, 27]. Most of metallurgical slags are stockpiled in an open field. Dealing with a large amount of industrial waste is a severe challenge to global environmental governance. The best way to solve this problem is to transform metallurgical slags into new materials with high added value, which will also bring huge economic benefits to the society.

Most metallurgical slags are used as potential alternative materials in civil engineering. They are usually used as aggregates or fillers in place of other conventional sand and stone materials due to their low activity [28, 29]. Powdered slag has higher market value as compared to granuluseslag for construction. A possible application for those solid wastes is to produce alkali-activated materials because they are high-quality aluminosilicate resources. With the further implementation of the concept of sustainable development, the research on cement with less clinker and no clinker has been paid more attention. Alkali-activated material as a kind of inorganic polymer material has great potential and is expected to be an alternative to cement and concrete. Meanwhile, in recent decades, with the development of mine cemented backfill technology in underground mine backfill, more and more mines use cementitious materials and alternative binders to replace conventional hydraulic backfilling at home and abroad [30]. Compared to building materials, the quantity of mine backfill material is large and the strength requirement is easily met. When alkali-activated materials are used to replace other conventional materials for mine backfill, it helps to effectively deal with the solid wastes, substantially preserve natural resources and energy, and create the conditions for reducing potentially harmful waste disposal costs. Hence, it indicates that alkali-activated material is suitable for mine backfill.

Within this context, the purpose of this paper is to review steel slag, copper slag, ferronickel slag, and lead-zinc slag as a precursor in alkali-activated material. The challenges and opportunities of using slags in alkali-activated material are also discussed.

2. Alkali-Activated Steel Slag Material

2.1. Physical Properties and Chemical Composition. The type of modern steel determines the elimination of different impurities in the steelmaking process. In terms of carbon steel, it can be produced in a ladle furnace (LF), an electric arc furnace, and a basic oxygen furnace (BOF) in different countries [30–32]. Thus, depending on the type of furnace, steel slag can be broadly classified into three categories, i.e., BOF steel slag, EAF steel slag, and LF steel slag [33]. As for steel slag in alkali-activated material, it usually refers to BOF steel slag, which is also called converter steel slag [34]. Today, in China and the United States, BOF steel slag makes up approximately 70% and 40% of steelmaking, respectively [35, 36]. BOF steel slag is rock-like and dark. The density is 3–3.6 kg/m³, which is higher than the natural aggregate [37]. The water absorption rate of steel slag is 0.4%–3.5% [38, 39]. BOF steel slag is very hard and not easy to be ground due to its high Fe content, so BOF steel slag and its products have good abrasion resistance [37, 38].

Different chemical compositions are heavily affected by steel slag type. BOF slag has more FeO than EAF steel slag and less SiO₂ than LF steel slag [35, 37]. The main chemical compositions of BOF steel slag are presented in Figure 1. In general, BOF steel slag primarily consists of 35%–50% CaO, 15%–35% Fe₂O₃, 10%–20% SiO₂, 2%–10% MgO, 0%–5% MnO, 1%–7% Al₂O₃, 1%–3% P₂O₅, and 0%–2% TiO₂. It is worth noting that there is a great difference in Fe₂O₃ content. High Fe₂O₃ content in steel slag plays an important role in grinding and application quality of steel slag. However, with the improvement of magnetic separation technology of BOF slag, the Fe₂O₃ content in BOF slag has been effectively reduced [26, 37]. The chemical composition analysis on newly produced slag has showed that the total amount of Fe₂O₃ is less than 20%.

Steelmaking slag is usually air-cooled to ambient conditions, and so BOF steel slag is highly crystallized [38, 39]. Those oxides in BOF steel slag form different mineralogical compositions. Essential mineral phases in BOF steel slag are tricalcium silicate (C₃S), dicalcium silicate (C₂S), CaO-FeO-MnO-MgO solid solution (RO phase), dicalcium ferrite (C₂F), tetracalcium aluminoferrite (C₄AF), merwinite (C₆Mg₆Si₄O₁₆), lime (free CaO), and periclase (free MgO) [16, 26, 37, 40]. The Fe mainly exists in forms such as RO phase, C₄aF, and C₆F, and these phases have no sufficient reactivity. During cooling, C₃S undergoes polymorphic transformations, where β-C₃S transforms γ-C₃S at approximately 500°C, resulting in volumetric expansion of 12% [37–39]. A small amount of C₂S and β-C₃S with dense structure and large crystal size have low reactivity, while...
The hydration sensitivity and even mechanical behavior of the material to activation depends on several factors, such as the phase compositions and fineness of the precursor, the curing conditions and alkaline conditions containing initial alkalinity, and the type and concentration of activator used [37]. Wang et al. [44] changed the pH value of NaOH solution in NaOH-activated steel slag and studied effects on kinds and morphologies of hydration products. They found that although increasing the initial alkalinity could promote the early hydration of active components like C$_2$S, C$_3$S, and C$_{12}$A$_7$, it had little effect on their late-age hydration degree [44].

The alkaline activator has a very important function. According to research findings, compared to sodium sulfate, sodium hydroxide, and sodium carbonate as activators, liquid sodium silicate (water glass) could activate steel slag more efficiently and is an appropriate activator for alkali-activated steel slag materials [34, 37, 45, 46]. Sun et al. [47] had investigated the hydration properties and microstructure characteristics of alkali-activated steel slag binder [47]. According to their findings, both hydration processes and products between water glass-activated steel slag and Portland cement were similar: (i) five hydration stages including the rapid exothermic stage, the dormant stage, the acceleration stage, the deceleration stage, and the steady stage and (ii) C-(A)-S-H gel and crystalline Ca(OH)$_2$ as the main hydration products [47]. The increasing of the moduli of water glass solution from 0.5 to 2.0 lead to the finer pore structure and higher mechanical strength [48]. Meanwhile, additional silicate had a retarding effect on the development of hydration process and the formation of hydration products [48]. However, increasing modulus had a negligible impact on the type of products of alkali-activated steel slag [48]. In addition, they also conducted detailed comparisons between the alkali-activated steel slag binder and Portland cement with the same water/binder ratio of 0.45 due to similar reaction conditions [47]. They found that alkali-activated steel slag has a faster reaction, fewer hydration products, poorer crystallization of Ca(OH)$_2$, a lower Ca/Si ratio, and a similar Al/Si ratio of gels than Portland cement [47]. Meanwhile, in terms of microstructure, alkali-activated steel slag hardened paste had more pores and looser microstructure causing long-term adverse impact on strength development [47].

Liu et al. [49] investigated the early age evolution including microstructure and reaction degree of alkali-activated steel slag from multiple perspectives under high curing temperature. They used ground steel slag with a specific surface area of 440 m$^2$/kg, SiO$_2$/Na$_2$O molar ratio equal to 2.42 in the activator, and curing temperature of 60°C [49]. The most important conclusion is that they demonstrated the type of gel product [49]. According to their findings, the nano-C-S-H and nano-C-A-S-H gel first condensed due to the dissolution Si and Al phases, and then the formation of C-A-S-H gel was continuously conducted at longer curing time because Si-O-Si bond translated into Si-O-Al [49]. Kang et al. [50] synthesized a novel CeO$_2$-loaded porous NaOH-activated steel slag-silica fume catalyst for photocatalytic water-splitting of hydrogen production, and they found that three-dimensional polymeric structure C-S-H gel (Ca$_{1.5}$SiO$_{3.5}$·xH$_2$O) was the main phase in the alkali-activated steel-slag-based material.
compressive strength by 40% [51]. So steel slag as a solo precursor is not an ideal material for the production of alkali-activated materials. In most studies on alkali-activated steel slag materials, better cementitious property is achieved by blending with other materials like GBFS, fly ash, and metakaolin.

When blended with blast furnace slag, alkali-activated GBFS-steel slag material shows significant cementitious slag properties in the presence of alkaline activator. You et al. [52] systematically studied the effect of steel slag on properties of alkali-activated GBFS material at room temperature. The Na₂O content was 4% by total weight of precursors and the modulus of water glass was 1.5 in all the alkali-activated mortars [52]. The content of steel slag was 50% by mass in the precursor [52]. Hydration process, strength, autogenous and drying shrinkages, pore structure, water absorption, and chloride ion penetration resistance of mortars were investigated [52]. They found that adding steel slag could decrease the hydration heat but prolong the setting time and improve workability [52]. Furthermore, incorporating steel slag could increase water absorption, reduce autogenous and drying shrinkage, and chloride ion penetration resistance [52]. The reason was that the replacement of steel slag could significantly increase the total porosity of the matrix due to its lower activity and the consequent less products [52]. You et al. [53] also investigated corrosion behavior of low-carbon steel reinforcement in alkali-activated GBFS and alkali-activated GBFS-steel slag under simulated marine environment. They found that the corrosion products were hematite and goethite [53]. The addition of steel slag had a beneficial influence on corrosion resistance due to improved interface transition zone between reinforcements and mortars [53].

Several studies have been undertaken to understand the investigation effects of steel slag on hydration properties of alkali-activated fly ash materials. Song et al. [54] used steel slag with various replacement levels (0, 10%, 20%, 30%, 40% and 50% by mass) to replace fly ash for alkali-activated binary composite material. They evaluated the influence of steel slag on setting times, flowability, viscosity, strength, absorptivity, and microstructural properties at standard curing conditions [54]. Adding steel slag obviously increased the setting times and flowability but decreased the viscosity [54]. The optimum content of steel slag was found to be 20% due to the negligible 28-day compressive strength loss and best flexural strength, elasticity modulus, and absorptivity [54]. The reason for the development of the strength was the formation and coexistence of C-S-H gel and C-A-S-H gel exhibiting better bonding [54]. Guo and Yang [55] synthesized engineered cementitious composite by using fly ash-steel slag activated by water glass with the modulus of 1.5 and polyvinyl alcohol fibers. They also thought C-S-H gel and N-A-S-H gel as self-healing products had a positive effect on self-healing property [55]. However, Nikljos et al. [56] had different conclusions about the type of reaction product and the development of compressive strength due to high curing temperature of 65°C at the early age. They thought that the main products were N-(C)-A-S-H gel along with N-A-S-H gel [56]. They found that steel slag up to 30% in the range of 0%–40% positively affects the strength evolution [56]. The 28-day compressive strength of alkali-activated fly ash mortar containing 30% steel slag exceed 35 MPa, and the study by Guo X had come to the same conclusions [56–58]. Nikljos et al. [56] also evaluated the thermal resistance of alkali-activated fly ash-steel slag materials. They found that steel slag had a negative effect on the thermal resistance, i.e., the mechanical and dimensional stability was above 600°C [56].

Bai et al. [59] and Furlani et al. [60] investigated the content and fineness of steel slag as a precursor on the properties of alkali-activated metakaolin material. In the study by Bai et al. [59], they set two curing conditions (exposed curing at room temperature, sealed curing, and moist curing) and four substitution rates (0, 10%, 20%, and 40%). Mechanical properties, acid and alkali erosion endurance, and microstructure were investigated [59]. They found that adding 10% steel slag could ensure the optimum properties and moist curing was the best curing method [59]. The highest compressive strength and bending strength could reach 70 MPa and 8 MPa, respectively [59]. Moreover, microstructure was enhanced due to beneficial physical and chemical reactions between the active components of steel slag and metakaolin [59]. According to the research of Furlani et al. [60], two steel slag maximum particle sizes (250 μm and 125 μm) were used to replace metakaolin (0%, 20%, 40%, 60%, 80%, and 100% by mass). They found that finer steel slag could play a better role, and 40% steel slag was the best dosage [60]. They thought that the increase of compressive strength was attributed to the formation of stronger mechanical bonds replacing part of the original N-A-S-H gel [60].

Besides the binary systems above, steel slag is commonly mixed with slag to form ternary and other composite systems. It is also expected to be an effective way to use steel slag. In alkali-activated fly ash-GBFS-steel slag ternary system by Song et al. [61], water glass with a modulus of 1.6 was used as activator, and composite additive of GBFS-steel slag varied from 10% to 50%. The optimum content of GBFS-steel slag was found to be 40% [61]. The setting time, initial flow, and early and later compressive strength of paste increased due to the presence of steel slag [61]. In addition, the brittleness decreased by adding steel slag [61]. More gel products formed by hydration of GBFS-steel slag refined the pore structure, which was the main reason for the improvement of strength [61]. In alkali-activated ultrafine palm oil fuel ash-steel slag composite system, Yusuf at al. [62] evaluated the contributions of steel slag on compressive strength and shrinkage of pastes and mortars. The dosage of steel slag varied from 0% to 80% for pastes and 0% to 60% for mortars [62]. They found that steel slags reduced shrinkage by refining pores, eliminating micro-cracks, and increasing the density and strength of microstructure [62].

3. Alkali-Activated Copper Slag

3.1. Properties of Copper Slag. Copper slag (CS) is a by-product generated from the refining of copper. About 2.2 tons of copper slag will be produced for each ton of copper
produced [63], and about 40 million tons of CS are produced annually in the world [64]. Depending on different cooling processes, CS can be divided into two different groups, namely, granulated water-cooled slag and air-cooled slag [64]. Granulated CS (GCS) contains an amorphous phase, which mainly consists of iron oxides, silicon dioxide, and calcium oxide [65]. Air-cooled slag with a slower cooling process mainly contains crystalline phases, which consist of similar chemical components [66]. Figure 2 shows the typical XRD patterns of GCS and air-cooled CS. Table 1 shows the chemical composition and mineral composition of copper slag cooled with different processes in other studies. Mineral composition of granulated water-cooled CS and air-cooled CS usually contains same mineral components, namely, magnetite (Fe₃O₄) and fayalite (Fe₂SiO₄) [67]. Figure 3 shows the statistical chemical content of copper slag from other studies.

The common utilization options of copper are recovering of the metal and producing value-added products, such as abrasive and cutting tools, tiles, glass, road-base construction, pavement, as well as cement and concrete [74]. Due to the amorphous nature of Granulated CS, the hydration properties of GCS are more active compared to air-cooled CS [73], which means granulated CS is more suitable for supplementary cementitious materials, while air-cooled CS is more suitable to be used as aggregate in concrete [75, 76].

Using granulated CS as supplementary cementitious material involves an optimal dosage of 5%-15% [77]; a higher dosage of GCS decreases the strength of the cementitious material [78]. Thus, this utilization method is not enough for utilizing GCS. Alkali-activated CS has been investigated by some researchers. CS can be used as a filling material activated by sodium hydroxide [70]. About 20–30 MPa compressive strength of the binder of alkali-activated CS was achieved [79–81], which shows that alkali-activated granulated CS is a potential environment-friendly material for replacing cement.

3.2. Mechanism of Alkali-Activated Copper Slag. The mechanism of alkali-activated granulated copper slag is different when different activators are used [82]. Compressive strength result shows that the activation effect of sodium silica (SS) is better than sodium hydroxide (SH) [82], as the binder compressive strength of sodium silica is 5–6 times higher than that of sodium hydroxide.

The mineralogical characterization of alkali-activated CS with XRD shows that different products were formed when different activators were used. In SS-activated GCS, a weak peak, which represents the poor crystallinity of C-S-H, was formed. In SH-activated GCS, a sharp peak occurs at the similar position of weak peak in SS, which represents the plombierite (tobermorite 14 Å) [82].

The reaction products in the pastes of CS activated with SS are mostly amorphous C–S–H gels with higher degrees of polymerization, which bond the matrix together with fewer pores. However, the products formed in the pastes of CS activated with SH contain some highly crystalline plombierite, and the matrix is loose and porous [82]. Besides, quantitative XRD shows that the original crystal in GCS, especially the fayatite and monticellite, are reduced in SS-activated GCS. This can be interpreted as the original crystal in GCS dissolved and participated in the formation of product [82]. The reaction degree of alkali-activated CS of different activators is consistent with the compressive strength and XRD result. CS reaction degree of SH and SS are 37.8% and 47.8%, respectively.

The different mechanisms of SH and SS were determined by pH and [SiO₄]⁴⁻ concentrations. CS surface will dissolve with the attack of OH⁻, Ca²⁺ and [SiO₄]³⁻ were dissolved into the solution to form the product. Compared to SH, although the pH of SS is lower, more [SiO₄]⁴⁻, which dissolved slower than Ca²⁺, is provided in SS. This can be explained that although the initial reaction rate of SS is slower than SH, the total heat release of SS is higher than SH [73]. The precipitation of the product might also be hindered when OH⁻ is excessive [82].

3.3. Performance of Alkali-Activated Copper Slag. Alkali-activated GCS has the potential to be used as a construction material. The compressive strength of GCS varies when different activators are used. SS is more effective than SH, and a higher modulus of SS increases the compressive strength of alkali-activated CS mortar [75]. Twenty-eight-day compressive strength of alkali-activated CS can reach 20 MPa, and the strength can still develop before 90 days [73].

SH is not a suitable activator for GCS, and 28-day compressive strength of SH-activated GCS is lower than 5 MPa [73, 82]. The strength development of later stage (90 days) is not developed [73]. This might due to the products of SH-activated CS containing highly crystalline plombierite, which is small in specific surface area and thus loosens the matrix [82].

Shrinkage of alkali-activated CS was also investigated [81]; drying shrinkage of alkali-activated CS is higher than Portland cement due to refined pore structures of alkali-activated CS. Increasing of both alkali content and modulus will increase the shrinkage of alkali-activated CS. The porosity result shows that the increasing of alkali dosage refines the pore structure [81]. Similar with Portland cement, shrinkage was smaller after 14 days. Therefore, it is suggested that a lower alkali content and modulus is more effective for controlling the shrinkage of alkali-activated CS.

4. Alkali-Activated Ferronickel Slag

4.1. Raw Material Properties of Ferronickel Slag. Ferronickel slag is an industrial waste obtained from ferronickel alloy production. The ferronickel industry uses two main smelting technologies: the electric furnace method and the blast furnace method. The electric furnace method is currently the main method of ferronickel alloy production, while the blast furnace method is only used in parts of eastern China. According to the differences of raw material and manufacturing technology, ferronickel slag can be
Figure 2: XRD patterns of the copper slag samples. (a) Air-cooled samples. (b) Water-cooled samples [67].

Table 1: Chemical composition of copper slag (M = magnetite, F = fayalite, H = hematite, D: diopside, C: clinoferosilite).

| Material | Fe_2O_3 | SiO_2 | CaO  | Al_2O_3 | MgO  | Cooling process | Mineral composition | Ref. |
|----------|---------|-------|------|---------|------|----------------|---------------------|------|
| 1        | 59.78   | 25.18 | 3.75 | 3.51    | 0.69 | Air-cooled     | M, F, D             | [67] |
| 2        | 59.94   | 21.68 | 1.76 | 2.83    | 1.13 | Air-cooled     | F, H                | [68] |
| 3        | 44.21   | 35.29 | 1.82 | 2.7     | 1.14 | Water-cooled   | M, F                | [67] |
| 4        | 47.01   | 33.4  | 4.0  | 3.5     | 1.39 | Water-cooled   | F, H                | [69] |
| 5        | 30.48   | 39.14 | 13.41| 7.76    | 2.09 | —              | M, F, C, D          | [66] |
| 6        | 53.11   | 28.70 | 3.87 | 5.8     | 1.56 | —              | F                   | [70] |
| 7        | 65.27   | 27    | 2    | 3       | 0.29 | —              | —                   | [71] |
| 8        | 57.8    | 30.53 | 1.6  | 2.8     | 1.49 | —              | —                   | [72] |
| 9        | 49.6    | 34.17 | 4.29 | 4.67    | 0.71 | Air-cooled     | M, F                | [73] |
| 10       | 44.05   | 34.74 | 2.66 | 10.52   | 1.03 | Water-cooled   | M, F                | [73] |

Figure 3: Statistical chart of content of copper slag.
categorized as electric furnace ferronickel slag (EFFS) and blast furnace ferronickel slag (BFFS) with different chemical and mineralogical compositions. In addition, the cooling method of the molten slag has an important influence on its composition. The chemical compositions of ferronickel slag obtained from different sources are presented in Table 2. In general, BFFS is composed of SiO₂, Al₂O₃, and CaO, as BFFS has a large amount of amorphous phase [83, 84]. EFFS is mainly composed of SiO₂, MgO, and Fe₂O₃, and its mineral composition is mainly composed of crystalline phases, such as enstatite, forsterite, and diopside. EFFS can be divided into air-cooled slag and water-cooled slag depending on different cooling methods. Generally, EFFS generated from laterite ore contains a high FeO/Fe₂O₃ and low MgO, whereas that from garnierite ore contains low Fe₂O₃ and high MgO [85–89]. The chemical composition of air-cooled EFFS differs only relatively little from that of water-cooled EFFS. However, the glassy phase content of water-cooled EFFS is higher than that of air-cooled EFFS. It can be seen that the nature of ferronickel slag depends on its source and treatment process.

4.2. Reaction Mechanism of Alkali-Activated Ferronickel Slag. The reaction process of alkali-activated ferronickel slag is similar to that of alkali-activated slag/fly ash. The reaction of alkali-activated BFFS can be simplified as in Figure 4. After the addition of the activator solution, the structure of the BFFS is first attacked by the alkaline solution; then, BFFS is subsequently depolymerized to low polymer or silicate and aluminate tetrahedral units. Finally, the depolymerized substances polymerize to form the crystalline product strätlingite and amorphous product C-A-S-H, which is responsible for the high strength of alkali-activated BFFS [83]. BFFS tends to form strätlingite rather than hydrotalcite, mainly because of the high aluminum content of BFFS and the small amount of magnesium dissolved, which is mainly present in the form of spinel and forsterite with a stable structure, and hardly reacts in alkaline solutions. The Ca/Si and Al/Si ratios of C-A-S-H are 0.64 and 0.57–1.44, respectively. The difference in composition between EFFF and BFFS results in the generation of different hydration products. Hydroxysodalite was found in the reaction products of alkali-activated low-calcium and low-magnesium EFFS with kaolinite that exhibited higher strength [89]. Maragkos et al. [88] found that increasing the OH⁻ concentration could enhance the dissolution of silicon and aluminum in EFFS. And high SiO₂/Na₂O ratio can promote the condensation reaction. The presence of alkali metal cations plays a catalytic role and has an important influence on gel hardening and crystallization. Compared to NaOH, KOH provides more inorganic polymer precursors, as the larger K⁺ size contributes to the formation of larger silicate oligomers, to which Al(OH)₃ tends to bind; thus, better solidification and higher compressive strength are obtained [95]. The main product of alkali-activated high-Mg EFFS/fly ash is N-A-M-S-H, where the magnesium dissolved in EFFS participates in the reaction and is incorporated into the N-A-S-H molecular structure [99, 100]. There are three typical phases identified in water-quenched high Mg EFFS, namely, FNS I, II, and III phases, which are Mg-Si phase, Si-Ca-Al phase, and Gr-Fe phase, respectively [94]. The FNS I phase (Mg-Si phase) is more prone to dissolve and preferentially participate in the reaction process than the other two phases. The dissolved Mg from FNS is mainly involved in the formation of hydrotalcite and N-M-S-H gels. The heavy metals in ferronickel slag mainly include Mn, Cr, and Ni. Wang et al. [83] reported that the alkali-activated matrix has a good stabilization effect on heavy metals, which greatly reduces the risk of heavy metals leaching. Cao et al. [94] found that Cr exists in EFFS in the form of Gr-Fe phase, which remains stable under the activation of alkali. Cr could not be detected during the leaching process. According to Komnitsas et al. [101], alkali-activated EFFS encapsulated the heavy metals such as Pb, Cr, and Ni. Therefore, heavy metals could not leach out from the concrete and maintained the structural integrity. In summary, alkali-activated ferronickel slag is an environmentally friendly material, and there is no problem of heavy metal leaching.

4.3. Properties of Alkali-Activated Ferronickel Slag. Wang et al. [83] found that alkali-activated BFFS showed comparable compressive strength and lower 7-day autogenous shrinkage to the alkali-activated slag. And BFFS activated by Ms = 0.5 waterglass obtained the highest compressive strength (70 MPa) at 90 days. Xu et al. [92] investigated the type and content of solid activators on the compressive strength of alkali-activated BFFS. The results showed that alkali-activated BFFS with Na₂SiO₃/Na₂CO₃ activators have a denser microstructure, lower porosity, and smaller pore size than alkali-activated BFFS with Na₂SiO₃ or NaOH activators. The compressive strength of the Na₂SiO₃/Na₂CO₃ sample can reach 96 MPa when the Na₂O content is 0.107 mol. It had been shown that low-calcium EFFS can also be used to prepare alkali-activated materials with superior properties. According to Maragkos et al. [88], the properties of alkali-activated EFFS depend on the solid to liquid ratio (S/L). The optimum quantities of S/L and NaOH concentrations were 5.6 g/mL and 7 M, respectively. Under optimum conditions, the alkali-activated EFFS exhibited a very high compressive strength of 118 MPa and a very low water absorption of about 0.8%. Komnitsas et al. [89] investigated the performance of sodium-silicate-activated EFFS/kaolin-based materials. They found that only aging period had a very significant effect on the final compressive strength while heating time and the temperature had a negligible effect on strength development. The alkali-activated samples showed excellent resistance to freeze-thaw cycles. However, the strength declined in acidic environment due to the formation of halite, magnesium calcite, calcite, aragonite, and akermanite on the surface of the immersed samples. Sakka et al. [87] evaluated the effect of fire exposure on the alkali-activated EFFS materials. The results showed that these samples had a low thermal conductivity and high fire resistance like commercial fire-resisting materials. It is even possible to prepare alkali-activated ferronickel slag concrete, which belongs to the category of ultrahigh performance concrete, with a
strength of up to 120 MPa. Komnitas et al. [101] reported that NO$_3^-$ or SO$_2^{4-}$ ions reduced the strength of alkali-activated EFFS due to the fact that they consumed most of the available moles of alkali activators, hindering the polymerization reaction and therefore producing a limited number of gels.

According to the literature, it was found that an EFFS with a high MgO content is not very well utilized due to the low reactivity and high magnesium oxide content, which may lead to bulk stability problems [8]. Cao et al. [102] used EFFS with high MgO content as a partial replacement for blast furnace slag to prepare alkali-activated cements (AACs). The results showed that the incorporation of less than 40% FNS has no significant effect on the setting time; however, the incorporation of 60% FNS will not only prolong the setting time but also reduce the compressive strength. For Na$_2$SiO$_3$-activated AACs, increasing EFFS content in the mixture will lead to the increase of autogenous shrinkage, drying shrinkage, and total porosity. For NaOH-activated AACs, the autogenous shrinkage and drying shrinkage are decreased with the addition of EFFS, while the total porosity is increased. Kuri et al. [103] reported that EFFS replacing part of the fly ash reduced workability and shortened setting time but increased compressive strength, with 75% EFFS being the optimum content. They found that Mg was involved in the formation of N-M-A-S-H and therefore did not cause bulk stability problems, whereas Komnitas et al. [89, 95] argued that magnesium acted as chemically inert in alkali-activated EFFS materials. It also depends on the source of the FNS. It is closely related to the source of ferronickel slag. Yan et al. [100] further suggested that EFFS can improve the thermal stability of alkali-activated materials by replacing some of the fly ash, and can effectively reduce the shrinkage of alkali-activated materials below 600°C.

5. Alkali-Activated Lead-Zinc Slag

5.1. Characterization of Lead-Zinc Slag. Lead-zinc slag is a by-product of the lead and zinc production industry, generated from the ores during smelting [104, 105]. It is reported that the production of 1t of lead and zinc discharges 7,100 kg and 9,600 kg slag [24], respectively. These lead-zinc slags are generally landfilled, not only occupying large areas of arable land but also polluting the environment due to the leaching of heavy metals and the radiation of nuclides.

The chemical composition of lead-zinc slag changes depending on the ores, the fluxes, the smelting process, and

| Material | SiO$_2$ | Al$_2$O$_3$ | FeO | Fe$_2$O$_3$ | MgO | CaO | MnO | Gr$_2$O$_3$ | NiO | Types of ores source | Ref. |
|----------|--------|------------|-----|------------|-----|-----|-----|-------------|-----|----------------------|------|
| BFFS     | 29.95  | 26.31      | 1.55| 8.93       | 25.19| 2.25| 2.3 | 0.01        |     | China                | [83] |
| BFFS     | 33.15  | 21.94      | 2.15| 12.54      | 22.5 | 3.36| 2.08| 0.02        |     | China                | [84] |
| BFFS     | 37.2   | 21.37      | 1.72| 10.53      | 24.82|     |     |             |     | China                | [90] |
| BFFS     | 36.7   | 18.11      | 1.83| 11.63      | 28.77|     |     |             |     | China                | [91] |
| BFFS     | 22.26  | 18.97      | 2.87| 7.81       | 33.9 | 2.87|     |             |     | China                | [92] |
| EFFS-W   | 46.1   | 4.46       | 12.25| 27.12      | 6.75 | 0.79| 1.5 | 0.19        |     | China                | [84] |
| EFFS-W   | 50.48  | 3.08       | 10.37| 32.61      | 1.01 | 0.62| 1.37| 0.06        |     | China                | [84] |
| EFFS-W   | 44.9   | 4.94       | 14.36| 23.29      | 8.24 | 0.98| 2.47| 0.13        |     | China                | [84] |
| EFFS-W   | 47.61  | 6.56       | 13.24| 15.94      | 11.49| 0.7 |     |             |     | China                | [93] |
| EFFS-W   | 45.23  | 5.91       | 9.74 | 24.17      | 8.93 |     | 1.14| 0.29        |     | China                | [94] |
| EFFS-W   | 53.1   | 2.4        | 11.3 | 32.3       | 0.23 |     |     |             |     | Soci’et’e Le Nickel (SLN), New Caledonia | [23] |
| EFFS-W   | 41.14  | 13.79      | 34.74| 3.59       | 0.71 |     | 5.4 | 0.14        |     | Laterites LARCO, Greece | [87] |
| EFFS-W   | 40.29  | 10.11      | 37.69| 5.43       | 3.65 |     | 2.58| 0.09        |     | Laterites LARCO, Greece | [88] |
| EFFS-W   | 32.74  | 8.32       | 38.8 | 0.76       | 2.76 | 3.73| 3.07| 0.1         |     | Laterites LARCO, Greece | [89] |
| EFFS-W   | 32.74  | 8.32       | 43.83| 2.76       | 3.73 |     | 3.07|             |     | Laterites LARCO, Greece | [95] |
| EFFS-W   | 51.93  | 2.92       | 12.98| 30.87      | 0.5  |     |     |             |     | Garnierite ore, New Caledonia | [85] |
| EFFS-W   | 52.52  | 2.33       | 10.8 | 33.16      | 0.27 |     |     |             |     | Garnierite ore, New Caledonia | [96] |
| EFFS-W   | 53.29  | 2.67       | 11.9 | 31.6       | 0.42 |     | 1.08| 0.1         |     | Garnierite ore, New Caledonia | [86] |
| EFFS-W   | 52.27  | 6.19       | 4.2  | 26.93      | 8.77 |     | 0.04|             |     | China                | [96] |
| EFFS-W   | 58.1   | 2.29       | 11.1 | 26.5       | 0.29 |     |     |             |     | SNNC, South Korea      | [97] |
| EFFS-A   | 62.8   | 1.95       | 7.13 | 24.7       | 2.07 |     |     |             |     | SNNC, South Korea      | [97] |
| EFFS-A   | 51.23  | 3.66       | 8.06 | 31.91      | 1.32 |     |     |             |     | China                | [98] |

EFFS-A: air-cooled EFFS slag; EFFS-W: water-cooled EFFS slag.
the impurities in the coke and the iron. The chemical compositions of lead-zinc slag from different research papers [24, 104–123] are summarized in Table 3. It could be found in Table 3 that the major composition of lead-zinc slag is FeOx, SiO2, CaO, Al2O3, and ZnO. As shown in Figure 5, the major constituents of the lead-zinc slag, in decreasing order of wt%, were the following: FeOx (34%, ranging from 27% to 37%), SiO2 (28%, ranging from 21% to 33%), CaO (17%, ranging from 14% to 23%), ZnO (8%, ranging from 3% to 10%), and Al2O3 (5%, ranging from 2% to 8%). Figure 5 also shows that the contents of the major compositions of lead-zinc slag are significantly different from various areas and the smelting factory. Some heavy and toxic elements, such as Pb, Zn, Cd, Cr, Mn, Cu, etc., could be found in lead-zinc slag, which limits its utilization due to the large leaching risk. The density of lead-zinc slag ranges from 3.6 g/cm3 to 3.9 g/cm3 [105, 118, 124], which is larger than that of traditional aluminosilicate waste due to high iron oxide content.

The phase composition of lead-zinc slag greatly changes depending on the ores, the fluxes, the smelting process, and the cooling method. The lead-zinc slag was reported to be mostly composed of an iron-silica-lime glass matrix and the content of the glass phase in lead-zinc slag is generally larger than 80% [24, 115, 117]. The kinds of the crystal phases in lead-zinc slag are also dependent on the ores and fluxes. Figure 6 provides an example of the XRD pattern of lead-zinc slag, which proves that most components are amorphous. As shown in Figure 6, the crystal phases in lead-zinc slag are ZnS, FeS, FeO, Fe3O4, and Pb metal, which is consistent with the results reported by Weeks [105]. Xia et al.
Figure 6: XRD pattern of lead-zinc slag.

Figure 7: XRD of lead-zinc slag with high percentage of crystal phases. (a) Lead-zinc slag from Belgium [120]. (b) Lead-zinc slag from Brazil [110].
reported that the small amount of crystal phases is ringwoodite and Fe metal. Spinel [24, 104, 107, 110, 112, 125, 126], calcium iron silicate [117], magnesioferrite [117], fayalite [125], Olivine [104, 110], kirschsteinite [125], hedenbergite [104, 125], willemite [110, 112], melilite [1, 8, 10, 22], and franklinite [126] were also found in lead-zinc slag from various areas. Due to the difference in smelting processes, two kinds of lead-zinc slag were reported to be composed mainly of crystal phases and their XRD patterns are provided in Figure 7.

5.2. Reaction Mechanism of the Alkali-Activated Lead-Zinc Slag. Similar to the blast furnace slag [127], fly ash [128], and rice husk ash [129], most of the lead-zinc slag is composed by amorphous aluminosilicate phases. So the reaction process of alkali-activated lead-zinc slag is similar to the traditional alkali-activated materials: dissolution and dispersion of raw materials, rearrangement and exchange of dissolved species, gelation and solidification, and continuous gel evolution toward crystallization [130, 131].

The leaching risk of the heavy metals in lead-zinc slag is the key factor that limits its application as construction materials. Alkali-activated material is an effective system for the solidification of heavy metals. But, high Si content and low Al content in lead-zinc slag make it difficult to form a rigid Al-Si network structure [117]. The lack of \( \text{AlO}_4^- \) unit tends to decrease the capacity of alkali-activated materials for element immobilization since the heavy metals mainly bonded with alumina tetrahedron [132]. So, some studies were conducted by mixing the lead-zinc slag with fly ash and alkalis to form a geopolymer [113, 117, 119]. The morphology of the fly ash-zinc slag composite geopolymer was reported by Nath [117]. It was found that the reaction products were refined with the increasing of the zinc slag content (see Figure 8). Zhang [24] has also studied the self-cementation of lead-zinc slag through alkali-activated materials and found that the solidification efficiency was larger than 90% for most of the heavy metals. The physical encapsulation was found to be the main mechanism of the solidification of the heavy metals in alkali-activated materials.

5.3. Properties of the Alkali-Activated Lead-Zinc Slag Material. The performance of the alkali-activated materials containing lead-zinc slag is also dependent on the properties of the raw materials. Xia et al. [122] found that the compressive strength of hardened alkali-activated materials decreases with the increasing of the lead-zinc slag content. It means that lead-zinc slag has a negative effect on the performance of the alkali-activated materials. It was supposed that the
high iron content in lead-zinc slag tend to be oxidized and the oxidation might increase the porosity and volume of solidified body, which ultimately resulted in decrease of compressive strength. But, Nath [117] found that the relatively high CaO content in lead-zinc slag results in the formation of Ca-rich dense gel and the development of compact microstructure. The 28-day compressive strength of alkali-activated zinc slag even reached 71 MPa. And the highest compressive strength even reaches 96 MPa. It means that the dispersion of the chemical composition of raw materials significantly affects the mechanical performance of the alkali-activated lead-zinc slag.

6. Conclusion and Outlook

The main mineral phases in steel slag are tricalcium silicate, dicalcium silicate, RO phase, tetracalcium aluminoferrite, etc. The phase composition of steel slag is similar to that of cement and thus steel slag has the potential cementitious property. But, the low activity of steel slag is the biggest obstacle and challenge to the proper utilization of alkali-activated steel slag materials. Moreover, there is great uncertainty about the hydration mechanism of the steel slag as a solo precursor.

Copper slag is mainly composed of crystal phases, i.e., magnetite (Fe₃O₄) and fayalite (Fe₅SiO₄). The utilization of copper slag as an alkali-activated material depends on the cooling process of the copper slag. Granulated water-cooled copper slag with a relatively higher amorphous phase is more suitable for alkali activation. In terms of activator, sodium hydroxide is less effective than water glass due to the formation of the high crystallized product. Although many studies have evaluated the mechanical properties of alkali-activated copper slag, heavy metal leaching assessment should be considered in the future study as copper usually contains heavy metals.

BFFS has good reactivity due to the large amount of amorphous phase; therefore, alkali-activated BFFS has superior mechanical properties. The reaction products are strätlingite and C-A-S-H. The reactivity of EFFS is closely related to its source and treatment process. EFFS generated from laterite ore contains a low MgO, whereas that from garnierite ore contains a high MgO. The amorphous phase content of EFFS with low Mg content is high, while the amorphous phase content of EFFS with high Mg content is low, and there are a large number of Mg-containing crystals for the main mineral phases in EFFS, namely, forsterite (Mg₂SiO₄), enstatite (MgSiO₃), and clinoenstatite (MgSiO₃).

Data Availability

Previously reported data were used to support this study. These prior studies are cited at relevant places within the text as references.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

The authors are grateful for the financial support from the National Natural Science Foundation of China (Grant No. 52008229).

References

[1] J. L. Provis, “Alkali-activated materials,” Cement and Concrete Research, vol. 114, pp. 40–48, 2018.
[2] J. Ye, W. Zhang, and D. Shi, “Performance evolutions of tailing-slag-based geopolymer under severe conditions,” Journal of Sustainable Cement-Based Materials, vol. 4, no. 2, pp. 101–115, 2015.
[3] R. Siddique, “Design and development of self-compacting concrete made with coal bottom ash,” Journal of Sustainable Cement-Based Materials, vol. 4, no. 3-4, pp. 225–237, 2015.
[4] S. K. Das, J. Mishra, S. M. Mustakim, A. Adesina, C. R. Kaze, and D. Das, “Sustainable utilization of ultrafine rice husk ash in alkali activated concrete: characterization and performance evaluation,” Journal of Sustainable Cement-Based Materials, pp. 1–19, 2021.
[5] J. L. Provis, “Geopolymers and other alkali activated materials: why, how, and what?,” Materials and Structures, vol. 47, no. 1-2, pp. 11–25, 2014.
[6] R. M. Andrew, “Global CO₂ emissions from Cement Production (1928–2017),” Earth System Science Data, vol. 10, pp. 2213–2239, 2018.
[7] E. Gartner and H. Hirao, “A review of alternative approaches to the reduction of CO₂ emissions associated with the
manufacture of the binder phase in concrete,” *Cement and Concrete Research*, vol. 78, pp. 126–142, 2015.

[8] T. A. Aiken, W. Sha, J. Kwasny, and M. N. Soutsos, “Resistance of geopolymer and Portland cement based systems to silage effluent attack,” *Cement and Concrete Research*, vol. 92, pp. 56–65, 2017.

[9] M. Albitar, M. S. Mohamed Ali, P. Visintin, and M. Drechsler, “Durability evaluation of geopolymer and conventional concretes,” *Construction and Building Materials*, vol. 136, pp. 374–385, 2017.

[10] A. M. M. A. Bakri, H. Kamarudin, M. Binhussain, I. K. Nizar, A. R. Rafiza, and Y. Zarina, “Comparison of geopolymer fly ash and ordinary portland cement to the strength of concrete,” *Advanced Science Letters*, vol. 19, no. 12, pp. 3592–3595, 2013.

[11] P. K. Sarker and S. McBeath, “Fire endurance of steel reinforced fly ash geopolymer concrete elements,” *Construction and Building Materials*, vol. 90, pp. 91–98, 2015.

[12] P. Duxson, J. L. Provis, G. C. Lukey, F. Separovic, and P. K. Sarker, “Fire endurance of steel reinforced fly ash geopolymer concrete elements,” *Construction and Building Materials*, vol. 90, pp. 91–98, 2015.

[13] N. R. Rakhimova and R. Z. Rakhimov, “A review on alkali-activated slag cements incorporated with supplementary materials,” *Journal of Sustainable Cement-Based Materials*, vol. 3, no. 1, pp. 61–74, 2014.

[14] I. G. Richardson, A. R. Brough, G. W. Groves, and C. M. Dobson, “The characterization of hardened alkali-activated blast-furnace slag pastes and the nature of the calcium silicate hydrate (C-S-H) phase,” *Cement and Concrete Research*, vol. 24, no. 5, pp. 813–829, 1994.

[15] M. Ben Haha, G. Le Saout, F. Winnefeld, and B. Lothenbach, “Influence of activator type on hydration kinetics, hydrate assemblage and microstructural development of alkali activated blast-furnace slags,” *Cement and Concrete Research*, vol. 41, no. 3, pp. 301–310, 2011.

[16] I. Yüksel, “A review of steel slag usage in construction industry for sustainable development,” *Environment, Development and Sustainability*, vol. 19, no. 2, pp. 369–384, 2017.

[17] S. Zhuang and Q. Wang, “Inhibition mechanisms of steel slag on the early-age hydration of cement,” *Cement and Concrete Research*, vol. 140, Article ID 106283, 2021.

[18] J. Labaj, L. Blacha, M. Jodkowski, A. Smalczer, M. Fröhlichová, and R. Findorak, “The use of waste, fine-grained carbonate material in the process of copper slag reduction,” *Journal of Cleaner Production*, vol. 288, 2021.

[19] Z. Zulhan and N. Agustina, “A novel utilization of ferro-nickel slag as a source of magnesium metal and ferroalloy production,” *Journal of Cleaner Production*, vol. 292, Article ID 125307, 2021.

[20] J. Sun, Z. Wang, and Z. Chen, “Hydration mechanism of composite binders containing blast furnace ferronickel slag at different curing temperatures,” *Journal of Thermal Analysis and Calorimetry*, vol. 131, no. 3, pp. 2291–2301, 2018.

[21] J. Sun, J. Feng, and Z. Chen, “Effect of ferro-nickel slag as fine aggregate on properties of concrete,” *Construction and Building Materials*, vol. 206, pp. 201–209, 2019.

[22] A. K. Saha, M. N. N. Khan, and P. K. Sarker, “Value added utilization of by-product electric furnace ferro-nickel slag as construction materials: a review,” *Resources, Conservation and Recycling*, vol. 134, pp. 10–24, 2018.

[23] Q. D. Nguyen, A. Castel, T. Kim, and M. S. H. Khan, “Performance of fly ash concrete with ferro-nickel slag fine aggregate against alkali-silica reaction and chloride diffusion,” *Cement and Concrete Research*, vol. 139, Article ID 106265, 2021.

[24] P. Zhang, F. Muhammad, L. Yu et al., “Self-cementation solidification of heavy metals in lead-zinc smelting slag through alkali-activated materials,” *Construction and Building Materials*, vol. 249, Article ID 118756, 2020.

[25] M. Alwaeli, “Investigation of gamma radiation shielding and compressive strength properties of concrete containing scale and granulated lead-zinc slag wastes,” *Journal of Cleaner Production*, vol. 166, pp. 157–162, 2017.

[26] Y. Jiang, T.-C. Ling, C. Shi, and S.-Y. Pan, “Characteristics of steel slags and their use in cement and concrete-A review,” *Resources, Conservation and Recycling*, vol. 136, pp. 187–197, 2018.

[27] X. Wang, X. Li, X. Yan, C. Tu, and Z. Yu, “Environmental risks for application of iron and steel slags in soils in China: a review,” *Pedosphere*, vol. 31, no. 1, pp. 28–42, 2021.

[28] S. N. Chinnu, S. N. Minnu, A. Bahrudeen, and R. Senthilkumar, “Recycling of industrial and agricultural wastes as alternative coarse aggregates: a step towards cleaner production of concrete,” *Construction and Building Materials*, vol. 287, Article ID 123056, 2021.

[29] Q. Dong, G. Wang, X. Chen, J. Tan, and X. Gu, “Recycling of steel slag aggregate in portland cement concrete: an overview,” *Journal of Cleaner Production*, vol. 282, Article ID 124447, 2021.

[30] D. Q. Deng, L. Liu, Z. L. Yao, K. I.-I. L. Song, and D. Z. Lao, “A practice of ultra-fine tailings disposal as filling material in a gold mine,” *Journal of Environmental Management*, vol. 196, pp. 100–109, 2017.

[31] B. Li, Y. Wang, L. Yang, and Y. Zhang, “Sulfate resistance and hydration products of steam cured steel slag blended cement mortar under dry-wet cycle,” *Journal of Sustainable Cement-Based Materials*, vol. 8, no. 6, pp. 353–366, 2019.

[32] C. A. C. Balaguera and M. A. G. Botero, “Multiphase phosphate cements from steel slags,” *Journal of Sustainable Cement-Based Materials*, pp. 1–20, 2020.

[33] M. Salman, Ö. Cizer, Y. Pontikes et al., “Cementitious binders from activated stainless steel refining slag and the effect of alkali solutions,” *Journal of Hazardous Materials*, vol. 286, pp. 211–219, 2015.

[34] C. Shi and S. Hu, “Cementitious properties of ladle slag fines under autoclave curing conditions,” *Cement and Concrete Research*, vol. 33, no. 11, pp. 1851–1856, 2003.

[35] C. Thomas, J. Rosales, J. A. Polanco, and F. Agrela, *Steel Slags*, pp. 169–190, Elsevier Ltd, Amsterdam, Netherlands, 2019.

[36] M. Češnovar, K. Traven, B. Horvat, and V. Ducman, “The potential of ladle slag and electric arc furnace slag use in synthesizing alkali activated materials, the influence of curing on mechanical properties,” *Materials (Basel)*, vol. 12, 2019.

[37] V. A. Nunes and P. H. R. Borges, “Recent advances in the reuse of steel slags and future perspectives as binder and aggregate for alkali-activated materials,” *Construction and Building Materials*, vol. 281, Article ID 122605, 2021.

[38] A. M. Kaja, K. Schollbach, S. Melzer, S. R. van der Laan, H. J. H. Brouwers, and Q. Yu, “Hydration of potassium citrate-activated BOF slag,” *Cement and Concrete Research*, vol. 140, Article ID 106291, 2021.

[39] T. He, Z. Li, S. Zhao, Z. Zhao, and X. Zhao, “Effect of reductive component-conditioning materials on the composition, structure, and properties of reconstructed BOF slag,” *Construction and Building Materials*, vol. 255, Article ID 119269, 2020.
Advances in Civil Engineering

[40] G. C. Wang, “Slag use as an aggregate in concrete and cement-based materials,” in The Utilization of Slag in Civil Infrastructure Construction, pp. 239–274, Elsevier Ltd, Amsterdam, Netherlands, 2016.

[41] J. Feng and J. Sun, “A comparison of the 10-year properties of converter steel slag activated by high temperature and an alkaline activator,” Construction and Building Materials, vol. 234, Article ID 116948, 2020.

[42] P. S. Humbert and J. Castro-Gomes, “CO2 activated steel slag-based materials: a review,” Journal of Cleaner Production, vol. 208, pp. 448–457, 2019.

[43] Q. Wang, D. Wang, and S. Zhuang, “Soundness of steel slag with different free CaO and MgO contents,” Construction and Building Materials, vol. 151, pp. 138–146, 2017.

[44] Q. Wang, J. Yang, and P. Yan, “Influence of initial alkalinity on the hydration of steel slag,” Science China Technological Sciences, vol. 55, no. 12, pp. 3378–3387, 2012.

[45] C. Shi, “Characteristics and cemenitious properties of ladle slag fines from steel production,” Cement and Concrete Research, vol. 32, no. 3, pp. 459–462, 2002.

[46] W. Ni, E. Wang, J. Li, and H. Sun, “Cementing properties of steel slag activated by sodium silicates and sodium hydroxide,” Journal of University of Science and Technology Beijing Mineral Metallurgy Material, vol. 12, pp. 464–468, 2005.

[47] J. Sun, Z. Zhang, S. Zhuang, and W. He, “Hydration properties and microstructure characteristics of alkali-activated steel slag,” Construction and Building Materials, vol. 241, Article ID 118141, 2020.

[48] J. Sun and Z. Chen, “Effect of silicate modulus of water glass on the hydration of alkali-activated converter steel slag,” Journal of Thermal Analysis and Calorimetry, vol. 138, no. 1, pp. 47–56, 2019.

[49] Z. Liu, D.-W. Zhang, L. Li, J.-X. Wang, N.-N. Shao, and D.-M. Wang, “Microstructure and phase evolution of alkali-activated steel slag during early age,” Construction and Building Materials, vol. 204, pp. 158–165, 2019.

[50] L. Kang, Y. J. Zhang, L. Zhang, and K. Zhang, “Preparation, characterization and photocatalytic activity of novel CeO2 loaded porous alkali-activated steel slag-based binding material,” International Journal of Hydrogen Energy, vol. 42, no. 27, pp. 17341–17349, 2017.

[51] Y. Zhou, J. Sun, and Y. Liao, “Influence of ground granulated blast furnace slag on the early hydration and microstructure of alkali-activated converter steel slag binder,” in Journal of Thermal Analysis and CalorimetrySpringer, Berlin, Germany, 2020.

[52] N. You, B. Li, R. Cao, J. Shi, C. Chen, and Y. Zhang, “The influence of steel slag and ferronickel slag on the properties of alkali-activated slag mortar,” Construction and Building Materials, vol. 227, Article ID 116614, 2019.

[53] N. You, J. Shi, and Y. Zhang, “Corrosion behaviour of low-carbon steel reinforcement in alkali-activated slag-steel slag and Portland cement-based mortars under simulated marine environment,” Corrosion Science, vol. 175, Article ID 108874, 2020.

[54] W. Song, Z. Zhu, Y. Peng et al., “Effect of steel slag on fresh, hardened and microstructural properties of high-calcium fly ash based geopolymers at standard curing condition,” Construction and Building Materials, vol. 229, Article ID 116933, 2019.

[55] X. Guo and J. Yang, “Intrinsic properties and micro-crack characteristics of ultra-high toughness fly ash/steel slag based geopolymer,” Construction and Building Materials, vol. 230, Article ID 116965, 2020.

[56] I. Niklič, S. Markovič, I. Janković-Častvan et al., “Modification of mechanical and thermal properties of fly ash-based geopolymer by the incorporation of steel slag,” Materials Letters, vol. 176, pp. 301–305, 2016.

[57] X. Guo and G. Xiong, “Resistance of fiber-reinforced fly ash-steel slag based geopolymer mortar to sulfate attack and drying-wetting cycles,” Construction and Building Materials, vol. 269, Article ID 121326, 2021.

[58] X. Guo and X. Pan, “Mechanical properties and mechanisms of fiber reinforced fly ash-steel slag based geopolymer mortar,” Construction and Building Materials, vol. 179, pp. 633–641, 2018.

[59] T. Bai, Z.-G. Song, Y.-G. Wu, X.-D. Hu, and H. Bai, “Influence of steel slag on the mechanical properties and curing time of metakaolin geopolymer,” Ceramics International, vol. 44, no. 13, pp. 15706–15713, 2018.

[60] E. Furlani, S. Maschio, M. Magnan et al., “Synthesis and characterization of geopolymers containing blends of unprocessed steel slag and metakaolin: the role of slag particle size,” Ceramics International, vol. 44, no. 5, pp. 5226–5232, 2018.

[61] W. Song, Z. Zhu, S. Pu et al., “Efficient use of steel slag in alkali-activated fly ash-steel slag-ground granulated blast furnace slag ternary blends,” Construction and Building Materials, vol. 259, Article ID 119814, 2020.

[62] M. O. Yusuf, M. A. Megat Johari, Z. A. Ahmad, and M. Maslehuddin, “Shrinkage and strength of alkali activated ground steel slag/ultratine palm oil fuel ash pastes and mortars,” Materials & Design, vol. 63, pp. 710–718, 2014.

[63] B. Gorai and R. K. Jana, “Characteristics and utilisation of copper slag-a review,” Resources, Conservation and Recycling, vol. 39, no. 4, pp. 299–313, 2003.

[64] R. K. Dhir, J. de Brito, R. Mangabhai, and C. Q. Lye, Sustainable Construction Materials: Copper Slag. Woodhead Publishing, Cambridge, UK, 2017.

[65] J. Alp, H. Deveci, and H. Sün, “Utilization of flotation wastes of copper slag as raw material in cement production,” Journal of Hazardous Materials, vol. 159, no. 2-3, pp. 390–395, 2008.

[66] A. Nazer, J. Paya, M. V. Borrachero, and J. Monzó, “Use of ancient copper slags in Portland cement and alkali activated cement matrices,” Journal of Environmental Management, vol. 167, pp. 115–123, 2016.

[67] D. Wang, Q. Wang, and Z. Huang, “Reuse of copper slag as a supplementary cemenitious material: reactivity and safety,” Resources, Conservation and Recycling, vol. 162, Article ID 105037, 2020.

[68] B. Traynor, C. Mulcahy, H. Uvegi, T. Aytas, N. Chanut, and E. A. Olivetti, “Dissolution of olivines from steel and copper slags in basic solution,” Cement and Concrete Research, vol. 133, Article ID 106065, 2020.

[69] Y. Feng, Q. Yang, Q. Chen et al., “Characterization and evaluation of the pozzolanic activity of granulated copper slag modified with CaO,” Journal of Cleaner Production, vol. 232, pp. 1112–1120, 2019.

[70] W. Lan, A. Wu, and P. Yu, “Development of a new controlled low strength filling material from the activation of copper slag: influencing factors and mechanism analysis,” Journal of Cleaner Production, vol. 246, Article ID 119060, 2020.

[71] P. R. Prem, M. Verma, and P. S. Ambily, “Sustainable cleaner production of concrete with high volume copper slag,” Journal of Cleaner Production, vol. 193, pp. 43–58, 2018.
R. Sharma and R. A. Khan, "Influence of copper slag and metakaolin on the durability of self-compacting concrete," Journal of Cleaner Production, vol. 171, pp. 1171–1186, 2018.

J. Liu and R. Guo, "Hydration properties of alkali-activated quick cooled copper slag and slow cooled copper slag," Journal of Thermal Analysis and Calorimetry, vol. 139, no. 6, pp. 3383–3394, 2020.

C. Shi, C. Meyer, and A. Behnood, "Utilization of copper slag in cement and concrete," Resources, Conservation and Recycling, vol. 52, no. 10, pp. 1115–1120, 2008.

W. Wu, W. Zhang, and G. Ma, "Mechanical properties of copper slag reinforced concrete under dynamic compression," Construction and Building Materials, vol. 24, no. 6, pp. 910–917, 2010.

B. M. Mithun and M. C. Narasimhan, "Performance of alkali activated slag concrete mixes incorporating copper slag as fine aggregate," Journal of Cleaner Production, vol. 112, pp. 837–844, 2016.

W. A. Moura, J. P. Gonçalves, and M. B. L. Lima, "Copper slag waste as a supplementary cementing material to concrete," Journal of Materials Science, vol. 42, no. 7, pp. 2226–2230, 2007.

K. S. Al-Jabri, R. A. Taha, A. Al-Hashmi, and A. S. Al-Harthi, "Effect of copper slag and cement by-pass dust addition on mechanical properties of concrete," Construction and Building Materials, vol. 20, no. 5, pp. 322–331, 2006.

J. Singh and S. Singh, "Development of alkali-activated cementitious material using copper slag," Construction and Building Materials, vol. 211, pp. 73–79, 2019.

J. Singh and S. P. Singh, "Synthesis of alkali-activated binder at ambient temperature using copper slag as precursor," Materials Letters, vol. 262, Article ID 127169, 2020.

J. Singh and S. P. Singh, "Evaluating the alkali-silica reaction in alkali-activated copper slag mortars," Construction and Building Materials, vol. 253, Article ID 119189, 2020.

Z. Yan, Z. Sun, J. Yang, H. Yang, Y. Ji, and K. Hu, "Mechanical performance and reaction mechanism of copper slag activated with sodium silicate or sodium hydroxide," Construction and Building Materials, vol. 266, Article ID 120900, 2021.

D. Wang, Q. Wang, S. Zhuang, and J. Yang, "Evaluation of alkali-activated blast furnace ferronickel slag as a cementitious material: reaction mechanism, engineering properties and leaching behaviors," Construction and Building Materials, vol. 188, pp. 860–873, 2018.

Y. Huang, Q. Wang, and M. Shi, "Characteristics and reactivity of ferronickel slag powder," Construction and Building Materials, vol. 156, pp. 773–789, 2017.

M. Nuruazzaman, J. O. Camargo Casimiro, and P. K. Sarker, "Fresh and hardened properties of high strength self-compacting concrete using by-product ferronickel slag fine aggregate," Journal of Building Engineering, vol. 32, Article ID 101686, 2020.

A. K. Saha and P. K. Sarker, "Sustainable use of ferronickel slag fine aggregate and fly ash in structural concrete: mechanical properties and leaching study," Journal of Cleaner Production, vol. 162, pp. 438–448, 2017.

K. Sakkas, P. Nomikos, A. Sofianos, and D. Panias, "Utilisation of FeNi-Slag for the production of inorganic polymeric materials for construction or for passive fire protection," Waste and Biomass Valorization, vol. 5, no. 3, pp. 403–410, 2014.

I. Maragkos, I. P. Giannopoulou, and D. Panias, "Synthesis of ferronickel slag-based geopolymers," Minerals Engineering, vol. 22, no. 2, pp. 196–203, 2009.

K. Komnitsas, D. Zaharakis, and V. Perdikatsis, "Geopolymerisation of low calcium ferronickel slags," Journal of Materials Science, vol. 42, no. 9, pp. 3073–3082, 2007.

A. Qi, X. Liu, Z. Wang, and Z. Chen, "Mechanical properties of the concrete containing ferronickel slag and blast furnace slag powder," Construction and Building Materials, vol. 231, Article ID 117120, 2020.

Q. Liu, S. Chen, W. Lin, A. Qi, and Z. Chen, "Experimental behaviors of prefabricated members made of ferronickel slag concrete," Construction and Building Materials, vol. 261, Article ID 120519, 2020.

L. Xu, X. Wang, C. Guan, W. Wu, and L. Zhang, "The effect of activators on the mechanical properties and microstructure of alkali-activated nickel slag," Advances in Civil Engineering, vol. 2020, Article ID 1764108, 17 pages, 2020.

B. Li, B. Huo, R. Cao, S. Wang, and Y. Zhang, "Sulfate resistance of steam cured ferronickel slag blended cement mortar," Cement and Concrete Composites, vol. 96, pp. 204–211, 2019.

R. Cao, Z. Jia, Z. Zhang, Y. Zhang, and N. Banthia, "Leaching kinetics and reactivity evaluation of ferronickel slag in alkaline conditions," Cement and Concrete Research, vol. 137, Article ID 106202, 2020.

K. Komnitsas, D. Zaharakis, and V. Perdikatsis, "Effect of synthesis parameters on the compressive strength of low-calcium ferronickel slag inorganic polymers," Journal of Hazardous Materials, vol. 161, no. 2-3, pp. 760–768, 2009.

T. Yang, X. Yao, and Z. Zhang, "Geopolymer prepared with high-magnesium nickel slag: characterization of properties and microstructure," Construction and Building Materials, vol. 59, pp. 188–194, 2014.

Y. C. Choi and S. Choi, "Alkali-silica reactivity of cementitious materials using ferro-nickel slag fine aggregates produced in different cooling conditions," Construction and Building Materials, vol. 99, pp. 279–287, 2015.

M. Zhai, H. Zhu, G. Liang et al., "Enhancing the recyclability of air-cooled high-magnesium ferronickel slag in cement-based materials: a study of assessing soundness through modifying method," Construction and Building Materials, vol. 261, Article ID 120523, 2020.

J. C. Kuri, M. N. N. Khan, and P. K. Sarker, "Workability, strength and microstructural properties of ground ferronickel slag blended fly ash geopolymer mortar," Journal of Sustainable Cement-Based Materials, pp. 1–18, 2020.

T. Yang, Q. Wu, H. Zhu, and Z. Zhang, "Geopolymer with improved thermal stability by incorporating high-magnesium nickel slag," Construction and Building Materials, vol. 155, pp. 475–484, 2017.

K. Komnitsas, D. Zaharakis, and G. Bartzas, "Effect of sulphate and nitrate anions on heavy metal immobilisation in ferronickel slag geopolymers," Applied Clay Science, vol. 73, pp. 103–109, 2013.

R. Cao, B. Li, N. You, Y. Zhang, and Z. Zhang, "Properties of alkali-activated ground granulated blast furnace slag blended with ferronickel slag," Construction and Building Materials, vol. 192, pp. 123–132, 2018.

J. C. Kuri, M. N. N. Khan, and P. K. Sarker, "Fresh and hardened properties of geopolymer binder using ground high magnesium ferronickel slag with fly ash," Construction and Building Materials, vol. 272, Article ID 121877, 2021.
[104] V. Ettler and Z. Johan, “12 years of leaching of contaminants from Pb smelter slags: geochemical/mineralogical controls and slag recycling potential,” Applied Geochemistry, vol. 40, pp. 97–103, 2014.

[105] C. Weeks, R. J. Hand, and J. H. Sharp, “Retardation of cement hydration caused by heavy metals present in ISF slag used as aggregate,” Cement and Concrete Composites, vol. 30, no. 10, pp. 970–978, 2008.

[106] V. Ettler, M. Komáreková, J. Jehlička et al., “Leaching of lead metallurgical slag in citric solutions: implications for disposal and weathering in soil environments,” Chemosphere, vol. 57, no. 7, pp. 567–577, 2004.

[107] N. Seignez, A. Gauthier, D. Bulteel et al., “Effect of Pb-rich and Fe-rich entities during alteration of a partially vitrified metallurgical waste,” Journal of Hazardous Materials, vol. 149, no. 2, pp. 418–431, 2007.

[108] N. Seignez, A. Gauthier, D. Bulteel, D. Damidot, and J.-L. Potdevin, “Leaching of lead metallurgical slags and pollutant mobility far from equilibrium conditions,” Applied Geochemistry, vol. 23, no. 12, pp. 3699–3711, 2008.

[109] V. Ettler, Z. Johan, B. Kříbek, O. Šebek, and M. Mihaljević, “Mineralogy and environmental stability of slags from the Tsumeb smelter, Namibia,” Applied Geochemistry, vol. 24, no. 1, pp. 1–15, 2009.

[110] L. R. P. De Andrade Lima and L. A. Bernardzé, “Characterization of the lead smelter slag in santo amaro, bahia, Brazil,” Journal of Hazardous Materials, vol. 189, no. 3, pp. 692–699, 2011.

[111] L. R. P. de Andrade Lima and L. A. Bernardzé, “Evaluation of the chemical stability of a landfilled primary lead smelting slag,” Environmental Earth Sciences, vol. 68, no. 4, pp. 1033–1040, 2013.

[112] N.-H. Yin, Y. Siwry, F. Guyot, P. N. L. Lens, and E. D. van Hullebusch, “Evaluation on chemical stability of lead blast furnace (LBF) and imperial smelting furnace (ISF) slags,” Journal of Environmental Management, vol. 180, pp. 310–323, 2016.

[113] S. Onisei, Y. Pontikes, T. Van Gerven et al., “Synthesis of inorganic polymers using fly ash and primary lead slag,” Journal of Hazardous Materials, vol. 205-206, pp. 101–110, 2012.

[114] T. C. Alex, A. M. Kalinkin, S. K. Nath et al., “Utilization of zinc slag through geopolymerization: influence of milling atmosphere,” International Journal of Mineral Processing, vol. 123, pp. 102–107, 2013.

[115] C. Atzeni, L. Massidda, and U. Sanna, “Use of granulated slag from lead and zinc processing in concrete technology,” Cement and Concrete Research, vol. 26, no. 9, pp. 1381–1388, 1996.

[116] S. H. G. Mosavinezhad and S. E. Nabavi, “Effect of 30% ground granulated blast furnace, lead and zinc slags as sand replacements on the strength of concrete,” KSCE Journal of Civil Engineering, vol. 16, pp. 989–993, 2012.

[117] S. K. Nath, “Fly ash and zinc slag blended geopolymer: immobilization of hazardous materials and development of paving blocks,” Journal of Hazardous Materials, vol. 387, Article ID 121673, 2020.

[118] R. Barna, P. Moszkowicz, and C. Gervais, “Leaching assessment of road materials containing primary lead and zinc slags,” Waste Management, vol. 24, no. 9, pp. 945–955, 2004.

[119] M. Albitar, M. S. Mohamed Ali, P. Visintin, and M. Drechsler, “Effect of granulated lead smelter slag on strength of fly ash-based geopolymer concrete,” Construction and Building Materials, vol. 83, pp. 128–135, 2015.

[120] N. Saikia, G. Cornelis, G. Mertens et al., “Assessment of Pb-slag, MSWI bottom ash and boiler and fly ash for using as a fine aggregate in cement mortar,” Journal of Hazardous Materials, vol. 154, no. 1-3, pp. 766–777, 2008.

[121] J. Touray, “Primary phases and natural weathering of old lead–zinc,” The Canadian Mineralogist, vol. 39, pp. 873–888, 2001.

[122] M. Xia, F. Muhammad, L. Zeng et al., “Solidification/stabilization of lead-zinc smelting slag in composite based geopolymer,” Journal of Cleaner Production, vol. 209, pp. 1206–1215, 2019.

[123] B. Tripathi and S. Chaudhary, “Performance based evaluation of ISF slag as a substitute of natural sand in concrete,” Journal of Cleaner Production, vol. 112, pp. 672–683, 2016.

[124] M. Alwaeli, “Application of granulated lead-zinc slag in concrete as an opportunity to save natural resources,” Radiation Physics and Chemistry, vol. 83, pp. 54–60, 2013.

[125] V. Ettler, O. Legendre, F. Bodenak, and J.-C. Touray, “Primary phases and natural weathering OF old lead zinc pyrometallurgical slag from pribram, Czech Republic,” The Canadian Mineralogist, vol. 39, no. 3, pp. 873–888, 2001.

[126] N. Seignez, D. Bulteel, D. Damidot, A. Gauthier, and J. L. Potdevin, “Weathering of metallurgical slag heaps: multi-experimental approach of the chemical behaviours of lead and zinc,” Waste Management and the Environment III, vol. 92, pp. 31–40, 2006.

[127] M. Palacios, Y. F. Houst, P. Bowen, and F. Puertas, “Adsorption of superplasticizer admixtures on alkali-activated slag pastes,” Cement and Concrete Research, vol. 39, no. 8, pp. 670–677, 2009.

[128] G. Xu and X. Shi, “Characteristics and applications of fly ash as a sustainable construction material: a state-of-the-art review,” Resources, Conservation and Recycling, vol. 136, pp. 95–109, 2018.

[129] P. Sturm, G. J. G. Gluth, H. J. H. Brouwers, and H.-C. Kühne, “Synthesizing one-part geopolymers from rice husk ash,” Construction and Building Materials, vol. 124, pp. 961–966, 2016.

[130] M. C. G. Juenger, F. Winnefeld, J. L. Provis, and J. H. Ideker, “Advances in alternative cementitious binders,” Cement and Concrete Research, vol. 41. no. 12, pp. 1232–1243, 2011.

[131] S. Zhao, F. Muhammad, L. Yu et al., “Solildification/stabilization of municipal solid waste incineration fly ash using uncalcined coal gangue-based alkali-activated cementitious materials,” Environmental Science and Pollution Research, vol. 26, no. 25, pp. 25609–25620, 2019.

[132] C. Fernández-Pereira, Y. Luna-Galiano, M. Pérez-Clemente et al., “Immobilization of heavy metals (Cd, Ni or Pb) using aluminia geopolymer,” Materials Letters, vol. 227, pp. 184–186, 2018.