# A Comprehensive Review of Sustainable Concrete Development with High Industrial Waste Content

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**Abstract -** *The construction industry is increasingly pressured to implement sustainable practices and lessen its environmental footprint. A crucial element of this initiative is re-evaluating the use of industrial waste materials, such as copper slag, steel slag, and iron slag, as substitutes for natural aggregates in concrete production. This comprehensive review paper delves into the intricate realm of sustainable concrete development, where the incorporation of substantial volumes of industrial waste materials has emerged as a prominent and environmentally-conscious solution. Within this context, the paper meticulously explores the properties of sustainable concrete, with a specific emphasis on employing waste materials to substitute for either fine or coarse natural aggregates. It delves deeply into the essential characteristics of these waste materials, rigorously assessing their appropriateness for concrete applications and their environmental impact.*

*Furthermore, the paper conducts a thorough performance evaluation of such sustainable concrete, scrutinizing aspects like compressive strength, flexural strength, durability, and resistance to various environmental factors. By considering the environmental benefits and performing a life cycle assessment, this review paper elucidates the overarching advantages of sustainable concrete development that incorporates a high content of industrial waste materials. In conclusion, this review consolidates findings from extensive literature, emphasizing the crucial role industrial waste materials can play in promoting sustainable concrete and reducing the construction industry's environmental footprint. It serves as an invaluable resource for researchers, engineers, and practitioners dedicated to advancing and implementing sustainable construction practices.*

***Key Words***: Sustainable Concrete, Industrial Waste, High Industrial Waste, construstion industry, flexural Strength.

## 1.INTRODUCTION

The construction sector is under increasing pressure to adopt sustainable practices and minimize its environmental impact. A crucial aspect of this endeavour involves reconsidering the utilization of industrial by-products, such as copper slag, steel slag, and iron slag, as substitutes for natural aggregates in concrete production. This extensive review paper delves into the intricate domain of sustainable concrete development, highlighting the prominent role of incorporating significant amounts of industrial by-products as an environmentally-conscious solution.

The paper meticulously examines the properties of sustainable concrete, focusing specifically on the use of waste materials to replace fine or coarse natural aggregates. It thoroughly assesses the essential characteristics of these by-products, evaluating their suitability for concrete applications and their environmental implications. Additionally, the paper conducts a comprehensive performance analysis of such sustainable concrete, scrutinizing factors such as compressive strength, flexural strength, durability, and resistance to various environmental stressors.

By analysing the environmental benefits and conducting a life cycle assessment, this review paper elucidates the overarching advantages of sustainable concrete development incorporating a high proportion of industrial by-products. In conclusion, this review compiles insights from various sources, highlighting the crucial role these by-products can play in promoting sustainable concrete practices and reducing the construction industry's environmental footprint. It acts as a valuable resource for researchers, engineers, and professionals dedicated to supporting and implementing sustainable construction methodologies.

In steel production, the generation of solid waste and carbon dioxide emissions is substantial, with around 1 ton of solid waste and 1.85 tons of carbon dioxide emitted per metric ton of steel produced (Association, 2021). In 2020, global crude steel production reached 1.878 billion tons, with the United States contributing 72.7 million tons, making it the fourth-largest producer worldwide (Association, 2021). Similarly, ferronickel production significantly contributes to carbon dioxide emissions, producing approximately 12 tons of carbon dioxide per ton of ferronickel (Ma et al., 2019).

The cement industry is another major emitter of carbon dioxide, contributing approximately 7-8% of total global emissions (Andrew, 2018). Carbon dioxide emissions in cement production arise from fossil fuel combustion and limestone calcination, with each kilogram of limestone producing 0.44 kilograms of carbon dioxide during the calcination process (Worrell et al., 2001).

To tackle these environmental challenges, researchers are investigating various strategies aimed at reducing carbon dioxide emissions and repurposing industrial waste materials. Utilizing materials such as steel slag, ferronickel slag, and copper slag in construction applications presents a promising approach to decrease cement usage and mitigate emissions. However, it's crucial to consider both the environmental impact and microstructure of these waste materials to ensure their suitability for construction applications.

By exploring the potential of utilizing these waste materials in construction, this review paper aims to contribute to efforts to reduce industrial emissions and promote sustainable construction practices.

## 2. INDUSTRIAL WASTE MATERIALS IN SUSTAINABLE CONCRETE

### Types of Industrial Waste Materials

### 2.1. Steel Slags

Steel slags are typically produced through three primary methods of steel production: Basic Oxygen Furnace (BOF), Electric Arc Furnace (EAF), and Ladle Furnace (LD) (Yildirim and Prezzi, 2011). In the BOF and EAF processes, steel slags are generated during the initial stages of steelmaking, while the LD process produces steel slags during the final refining stage (Rieger et al., 2021).

In the BOF process, steel scraps are melted in a basic oxygen furnace, where high-pressure oxygen is injected to reduce the carbon content and refine the steel (Yildirim and Prezzi, 2011). Similarly, in the EAF process, electric arcs heat recycled steel scrap to produce molten steel. In both processes, the resulting molten steel is separated from the steel slag, which is then cooled to form basic oxygen furnace slag.

Similarly, in the EAF process, steel scraps are melted using graphite electrodes, and refining operations involve the use of ferroalloys (Lehmann and Nadif, 2011). Calcium oxide (CaO) is added to the furnace, and oxygen is injected to oxidize impurities, resulting in the formation of slags that float on the liquid metal (Yildirim and Prezzi, 2011). The molten steel is subsequently extracted, and the steel slags undergo processing according to established standards.

### 2.2.Ferronickel Slags

Ferronickel slag is a by-product of ferronickel smelting in electric furnaces, where calcine is melted at high temperatures (Diaz et al., 1988). During the smelting process, a bottom layer of molten ferronickel forms, topped by a layer of ferronickel slag, along with off-gases containing carbon dioxide and nitrogen (Moats and Davenport, 2014). Ferronickel is primarily used in the production of stainless steel and high-temperature steel, with slag generated in the final refining phase of the metallurgical operation (Crundwell et al., 2011).

Stainless steel slag has potential applications in construction materials, such as enhancing compressive and flexural strength when used as a partial replacement for conventional aggregates (Rosales et al., 2017). However, it is essential to consider the environmental and economic impacts of incorporating stainless steel slag into construction materials (Di Maria et al., 2018; Salman et al., 2016).

### 2.3. Copper Slags

Copper production involves ore refining through pyrometallurgical or hydrometallurgical processes, resulting in the generation of copper slags and tailings (ICMM, 2019; EPA, 1990). In the pyrometallurgical process, copper-rich froth is formed during flotation, and any remaining materials are drained and stockpiled as waste tailings. Subsequently, copper matte is smelted, producing sulfuric acid and slag. Some sites conduct further processing to reclaim residual copper or iron, leading to the formation of copper slag tailings (Phiri et al., 2022).

In a hydrometallurgical method, the ore is leached with diluted sulfuric acid to produce a copper sulphate solution, which is further processed to obtain pure copper (EPA, 1990; Sinclair and Thompson, 2015). The tailings generated in both processes contain various chemical constituents and are subject to regulatory oversight to manage their environmental and health impacts (Cacciuttolo and Atencio, 2022; Pehoiu et al., 2019).

The structure and properties of copper slag depend on the cooling process. Rapid cooling results in a glassy state that is suitable for pozzolanic properties, while slow cooling leads to a crystalline state (Phiri et al., 2021; Potysz et al., 2016). Copper slag differs from steel and iron slag due to its higher iron oxide concentration.

## 3. CHARACTERISTICS AND PROPERTIES

Inorganic binders encompass materials such as cement and industrial by-products, including steel slag, ferronickel slag, copper slag, and tailings. Their suitability is often assessed based on their reactivity. Steel slag primarily comprises CaO, while ferronickel slag and copper slag are rich in $SiO_2$. Steel slag shares chemical similarities with Portland cement, whereas ferronickel slag and copper slag typically exhibit pozzolanic properties.

**Table-1:** Chemical components of BOF, EAF, and LF steel slags.

| Authors | | Components by wt % | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $Al_2O_3$ | CaO | FeO/ $Fe_2O_3$ | $K_2O$ | MgO | MnO | $Na_2O$ | $SO_3$ | $SiO_2$ | $TiO_2$ |
| BOF | (Wang et al., 2013) | 5.37 | 38.62 | 25.40 | – | 7.68 | 1.94 | – | 0.18 | 15.45 | – |
| | (Kang et al., 2019) | 2.7 | 40 | 33 | – | 2.3 | 4.1 | – | – | 14 | 0.49 |
| | (Zhang et al., 2019) | 3.03 | 43.99 | 19.3 | 0.32 | 4.12 | 2.24 | 0.35 | 0.44 | 12.86 | 1.23 |
| | (Mahieux et al., 2009) | 2 | 47.5 | 22.6 | 0.1 | 6.3 | 1.9 | 0.2 | 0.2 | 11.8 | 0.5 |
| | (Shen et al., 2009) | 0.98 | 39.3 | 38.06 | – | 8.56 | 4.24 | – | – | 7.75 | 0.94 |
| | (Carvalho et al., 2017) | 1.01 | 45.11 | 29.55 | – | 6.13 | 4.39 | 0.23 | 0.14 | 11.33 | 0.45 |
| EAF | (Rooholamini et al., 2019) | 4.88 | 33.27 | 25.93 | 0.59 | 4.25 | – | 0.45 | 2.25 | 19.5 | 1.11 |
| | (Oluwasola et al., 2015) | 4 | 55.2 | 16.8 | 0.16 | 3.06 | 2.59 | 0.75 | 0.85 | 10.9 | – |
| | (Pattanaik et al., 2021) | 12 | 30.7 | 31.05 | 0.08 | 7.72 | 0.48 | 0.09 | – | 12.77 | – |
| | (Roslan et al., 2020) | 4.84 | 16.9 | 43.4 | – | 1.86 | 2.66 | 0.15 | – | 26.4 | – |
| | (Masoudi et al., 2017) | 4.15 | 39.43 | 25.28 | 0.28 | 5.72 | – | – | 0.56 | 17.32 | – |
| | (Zhang et al., 2019) | 4.25 | 37.96 | 28.21 | 0.09 | 3.40 | 3.56 | 0.2 | 0.69 | 15.5 | 0.81 |
| LF | (Adolfsson et al., 2011) | 32.5 | 40 | 4.8 | 0.1 | 5.9 | 8.1 | 0 | – | 5 | 0.6 |
| | (Shi, 2002) | 4.3 – 5.2 | 55.9 – 57.0 | 1.0 – 1.6 | – | 3.2 – 4.2 | 0.5 – 1.0 | – | 1.7 –2.4 | 26.4 - 26.9 | 0.3 |
| | (Nguyen et al., 2018) | 28.3 | 46.3 | 5 | - | 7.4 | - | - | 0.5 | 8.6 | - |
| | (Seti´en et al., 2009) | 4.3 - 18.6 | 50.5 - 57.5 | 1.6 - 3.3 | 0.012 -0.02 | 7.5 - 11.9 | 0.36 - 0.52 | 0.03 – 0.065 | - | 12.6 - 19.8 | 0.18 - 0.89 |
| | (Mahoutian et al., 2014) | 16.55 - 23.17 | 57.55 - 65.23 | 0.79 - 3.55 | – | 3.96 - 5.04 | - | 0.08 - 1.16 | - | 6.21 - 12.35 | - |

Table 1 provides an overview of the chemical compositions of BOF, EAF, and LF slags, while Fig. 2(a) presents a Bar Chart illustrating the chemical compositions of steel slag. These slags typically exhibit high levels of calcium oxide and silicon dioxide, although variations in chemical composition arise depending on the production method. Comparing the heavy metal concentrations across BOF, EAF, and LF, we observe distinct differences. The BOF slag shows higher concentrations of chromium and lead compared to EAF and LF slags. In contrast, the EAF slag has a relatively lower concentration of these metals, but it shows higher copper content. The LF slag, while generally lower in metal concentrations, also contributes to the overall understanding of the variation in slag composition from different furnace types. These variations highlight the need for tailored approaches in handling and utilizing each type of slag to mitigate environmental impacts effectively.

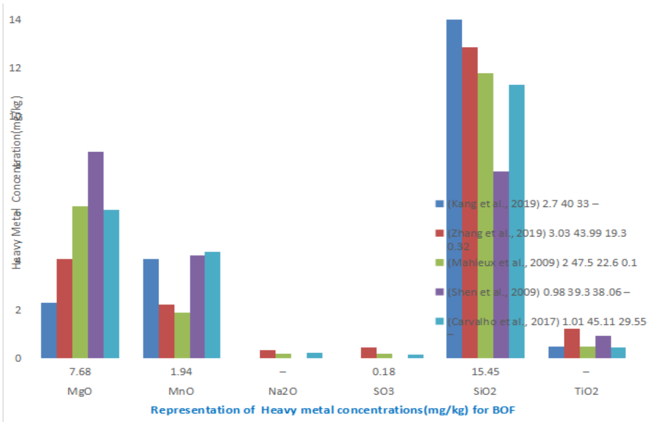


**Figure-1:** Bar Chart:Steel slag.

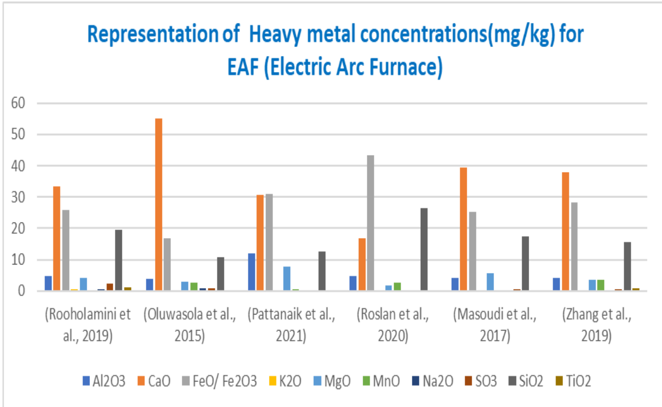


**Figure-2:** Bar Chart:Ferronickel slag.

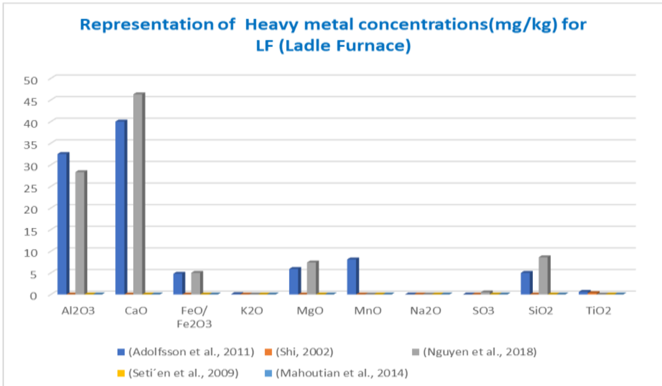


**Figure-3:** Bar Chart: Copper slag.

The chemical makeup of EAF slags can vary due to the use of steel scraps as raw materials, which impacts the composition of the resulting slags. LF slags, on the other hand, typically contain lower amounts of iron oxide (usually less than or equal to 5%) compared to BOF and EAF slags, while maintaining relatively high levels of calcium oxide and silicon dioxide.

**Table-2:** Chemical components of ferronickel slag.

| Authors | | Components by wt % | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $Al_2O_3$ | CaO | FeO / $Fe_2O_3$ | $K_2O$ | MgO | MnO | $Na_2O$ | $SO_3$ | $SiO_2$ | $TiO_2$ |
| Ferronickel slag | (Katsiotis et al., 2015), (Lemonis et al., 2015) | 5.98 | 4.12 | 2.75 | 40 | 0.4 | 7.8 | 0.52 | 0.09 | 0.64 | 41 |
| | (Saha and Sarker, 2017b), (Rahman et al., 2017) | 2.67 | 0.42 | 1.08 | 12 | - | 32 | - | 0.11 | - | 53 |
| | (Li et al., 2019) | 6.56 | 11.49 | - | 13 | 0.2 | 16 | - | 0.8 | 0.52 | 48 |
| | (Cao et al., 2020) | 5.91 | 8.93 | 1.14 | 9.7 | - | 24 | 0.45 | - | - | 45 |
| | (Wang et al., 2018) | 26.3 | 25.19 | 2.3 | 1.6 | - | 8.9 | 2.25 | - | 0.9 | 30 |
| | (Nuruzzaman et al., 2022) | 2.98 | 0.5 | - | 12 | 0 | 31 | - | 0.09 | - | 52 |
| | (Chen et al., 2020) | 17.5 | 32.15 | - | 2.7 | 0.4 | 9.6 | - | 0.39 | 2.24 | 25 |

Additionally, slags derived from stainless steel by-products tend to have lower iron oxide but

Higher Silicon Dioxide content compared to those from carbon steel (Adegoloye et al., 2016).

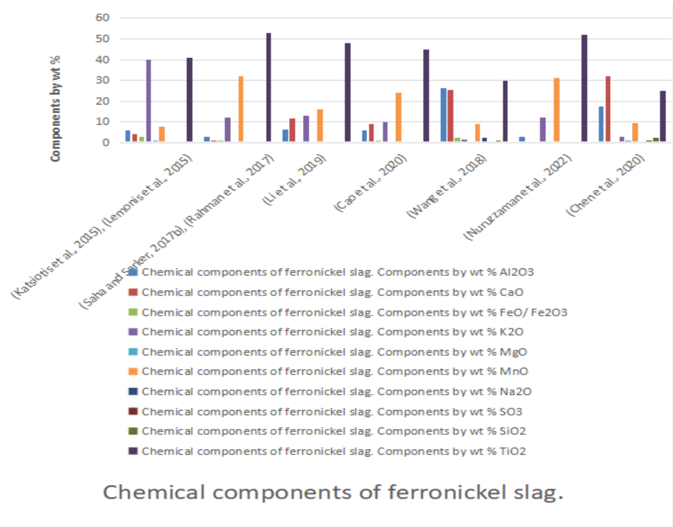


**Figure-4:** Chemical components of ferronickel slag.

Table 2 outlines the compositions of ferronickel slags, accompanied by a Bar Chart illustrating their chemical compositions in Fig. 2(b). Ferronickel slag primarily comprises iron, magnesium, and silicon, with silicon being the most abundant among these components. Due to its high silicon dioxide content and low calcium oxide content, ferronickel slag exhibits pozzolanic characteristics rather than hydraulic ones.

This makes it suitable for use as a clinker replacement in blended cement, with its pozzolanic activity contributing to the formation of secondary calcium silicate hydrate (C-S-H) gel, thereby enhancing late-age strength development. Incorporating ferronickel slag as supplementary cementitious material can reduce the Ca/Si ratio of the C-S-H gel and enhance the polymerization of the silicate chains (Huang et al., 2017). Occasionally, ferronickel slag may contain high levels of magnesium, such as forsterite and ferroan, which do not affect the expansion of the mix (Rahman et al., 2017). According to Australian Standard 3582.2, the maximum allowable content of MgO in supplementary cementitious materials should be less than 15% (Standard, 2016).

Copper slag exhibits high iron content and low calcium content, as evidenced by various studies (Al-Jabri et al., 2009; De Schepper et al., 2015; Edwin et al., 2016; Marghussian and Maghsoodipoor, 1999; Sarfo et al., 2017; Sun et al., 2022). As shown in Table 3 and the ternary diagrams depicting the chemical compositions of copper slag in Fig. 2(c), crystalline silica ($SiO_2$) constitutes the main component by weight, ranging from 40% to 75%.

**Table-3:** Chemical components of copper slags and copper tailing.

| Authors | | Components by wt % | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $Al_2O_3$ | CaO | FeO/ $Fe_2O_3$ | $K_2O$ | MgO | MnO | $Na_2O$ | $SO_3$ | $SiO_2$ | $TiO_2$ |
| copper slags | (DeSchepper et al., 2015) | 5.92 | 7.09 | 45.45 | 0.19 | 0.81 | 0.74 | 0.8 | 0.4 | 25.87 | 0.31 |
| | (Al-Jabri et al., 2009) | 2.79 | 6.06 | 53.45 | 0.61 | 1.56 | 0.06 | 0.28 | 1.9 | 33.05 | 0 |
| | (Sarfo et al., 2017) | 3.01 | 2.76 | 53.64 | 1.21 | 0.53 | - | 1.43 | - | 28.07 | - |
| | (Sun et al., 2022) | 3.5 | 4 | 43.03 | - | 1.39 | - | - | - | 33.4 | - |
| | (Edwin et al., 2016) | 5.9 | 7.1 | 45.5 | 0.2 | 0.8 | 0.7 | 0.8 | 0.4 | 25.9 | 0.3 |
| | (Lowinska-Kluge et al., 2011) | 14.89 | 25.29 | 7.88 | 3.08 | 7.9 | - | 0.87 | - | 39.85 | - |
| | (Marghussian and Maghsoodipoor, 1999) | 3.78 | 5.24 | 44.78 | 2.03 | 1.16 | - | 0.3 | 1.1 | 40.97 | 0.58 |
| | (Filipovi´c et al., 2021) | 3.53 | 20.06 | 29.99 | 0.43 | 0.5 | 0.04 | 0.15 | 1.2 | 42.06 | 0.28 |
| | (Park et al., 2022) | - | 10.2 - 10.6 | 28.1 - 28.6 | - | 14.6 - 16.6 | - | 0.9 | - | 45 - 45.1 | - |
| copper tailing | (Liu et al., 2022) | 22.556 | 0.537 | 1.485 | 1.97 | - | 0.01 | - | 9.8 | 63.32 | 0.17 |
| | (Ghazi et al., 2022) | 17.03 | 2.9 | 3.86 | 2.63 | 1.53 | 0.04 | 0.6 | 4.5 | 60.9 | 0.4 |
| | (A. Nikvar-Hassani et al., 2022) | 24.6 | 0.18 | 4.35 | 5.38 | 1.48 | - | - | 1.2 | 61.2 | 0.83 |
| | (Lori et al., 2021) | 12.05 | 0.66 | 6.97 | 3.39 | 1.82 | - | 0.64 | 7 | 55.67 | - |
| | (Ince et al., 2021) | 6.97 | 16.3 | 47.7 | 0.79 | 2.11 | 0.65 | 0.62 | 1.1 | 20.5 | - |
| | (Ahmari and Zhang, 2012) | 7.08 | 7.52 | 4.33 | 3.26 | 4.06 | - | 0.9 | 1.7 | 64.8 | - |
| | (Oluwasola et al., 2015) | 15.4 | 12.48 | 19 | 1.24 | 0.87 | 0.87 | 0.46 | 2.5 | 44.1 | - |

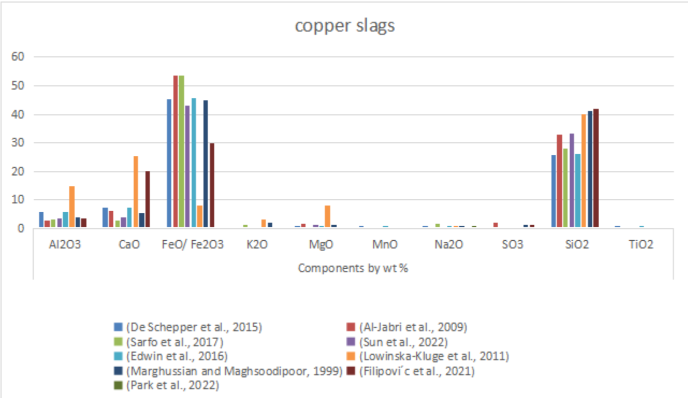


**Figure-5:** Copper Slags.

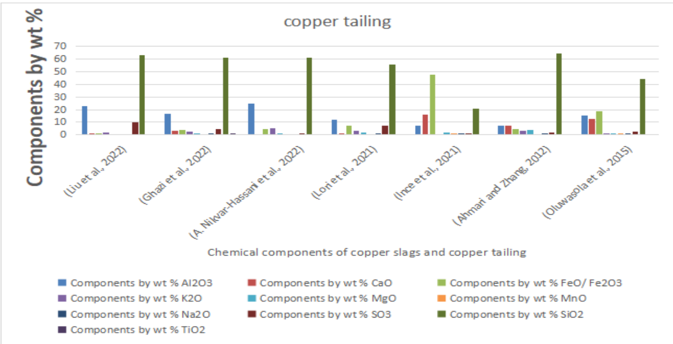


**Figure-6:** Copper tailing.

Secondary components such as $Al_2O_3$ and CaO typically account for 10% to 20% of the weight, while metal oxide content ranges from 0% to 20%. Sulphates and alkali metals like lithium and sodium are present in percentages ranging from 0% to 5%. The primary health concern associated with these materials arises from trace elements, including copper, arsenic, thorium, uranium, lead, and cadmium, each generally present in amounts less than 1% (EPA, 2023b). However, due to the scale of waste, these toxic elements can accumulate to hazardous levels. The significant presence of crystalline silica and heavy metals increases the risk of cancer after prolonged exposure and inhalation of dust (Horwell and Baxter, 2006).

## 4.MICROSTRUCTURE AND PERFORMANCE ANALYSIS

In materials science, understanding the structure of materials is crucial for assessing their performance, particularly for potential use in construction materials. Therefore, analyzing the microstructure of a material is essential. Researchers often utilize scanning electron microscopy (SEM) to examine the material's microstructure (Aljerf, 2015). Furthermore, the distribution of porosity is evaluated using mercury intrusion porosimetry (MIP).

All slags intended for use in cement production must comply with the specifications outlined in ASTM C989 (C989/C989M-18a, 2018). This standard establishes the criteria necessary to meet minimum requirements for concrete or mortar containing slag. These specifications are applicable when utilizing Portland cement. According to the standard, slag cement must have sulphide and sulphur levels below 2.5%, with particle sizes such that less than 20% is retained on a 45-micron sieve. Additionally, it mandates an air content of less than 12% and requires a Slag Activity Index of 95% at 28 days.

The Slag Cement Association (SCA) maintains a database of slag cement producers and provides various case studies, including one focusing on the Southern Beltway, a limited-access road in Canonsburg, PA, USA. This project covered a nineteen-mile stretch with a budget of $180 million. The mix design utilized a 40% slag cement replacement rate and a water-cement ratio of 0.42. This mixture design achieved a 28-day compressive strength of 6700 psi (Association, 2022).

### 4.1.Steel Slag

When observing the microstructure of unaged steel slag at the SEM level, it is noted that the surface appears rough with numerous pores, some of which are filled with crystalline material (Li et al., 2022). This observation aligns with findings from mercury intrusion porosimetry (MIP), which indicate that mortar-slag mixes exhibit a higher pore distribution compared to mortar without slag after 28 days (Hadj-sadok et al., 2011). Moreover, as mortars age during curing, the pore distribution tends to decrease, although the decrease is not significant. This increased porosity in steel slag allows it to absorb more binder and water when used as pavement material (J. Liu et al., 2020; Ren et al., 2021).

The presence of pores in steel slag results in a higher water absorption rate, ranging from 0.9% to 2.5%, compared to basalt and granite, which absorb only 0.4% to 0.7% and 0.5% to 1.1%, respectively (Kumar and Varma, 2021). This increased water absorption is attributed to the larger surface area of steel slag compared to smoother aggregates of similar volume. While this larger surface area can enhance the bond between binder and aggregate, it may have adverse effects on the strength and rigidity of the resulting concrete.

However, the crystalline nature of steel slag makes it stable and inert in concrete, which makes it a suitable replacement for natural fine aggregate. Studies have shown that incorporating steel slag as a replacement for natural sand can improve the compressive strength of mortar samples due to dense particle packing and higher intrinsic hardness (Rashad et al., 2016; Tiwari et al., 2016). Steel slag typically shares a similar or higher specific gravity as natural sand, and its increased porosity results in higher water absorption as the proportion of steel slag in the mix increases.

In general, substituting coarse aggregate with coarse steel slag enhances various mechanical properties such as compressive strength, tensile strength, durability in chloride-exposed environments, and the elastic modulus of a mix (Faleschini et al., 2015). Utilizing steel slag as an aggregate leads to higher compressive strength, tensile strength, and modulus of elasticity compared to aggregates like calcareous, dolomitic, and quartzite limestone (Beshr et al., 2003). Research has demonstrated that incorporating 50% or more steel slag aggregate, instead of natural aggregates, improves concrete durability and physical properties (Maslehuddin et al., 2003). Further studies support these findings, indicating that replacing 75% of natural aggregate with steel slag aggregate enhances the mechanical properties of the mix, with optimal strength achieved at a blend of 70% steel slag and 30% natural aggregate, balancing strength and cost-effectively (Asi et al., 2007; Behiry, 2013).

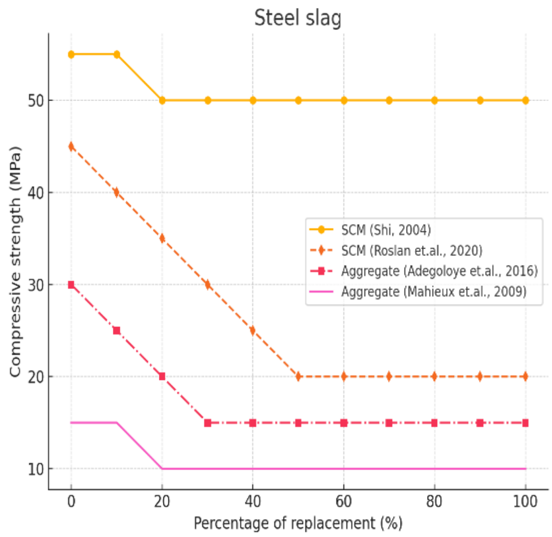


**Figure-7:** Slag Steel.

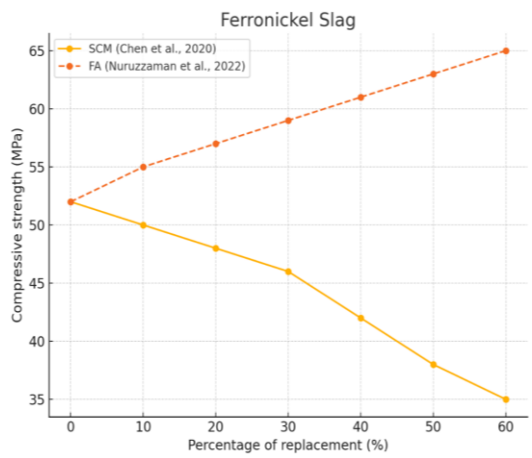


**Figure-8:** Ferronickel Slag.

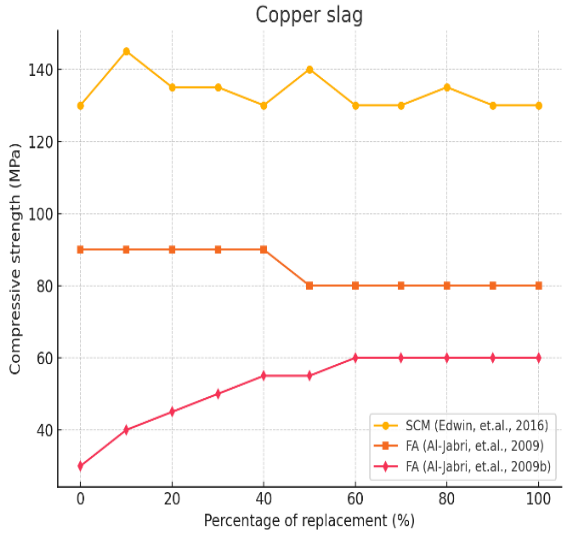


**Figure-9:** Copper Slag.

Compressive strength of materials replaced by: Fig 7, Steel slag; Fig 8 Ferronickel Slag; Fig 9 Copper slag.

In magnesium phosphate cement applications, the addition of 5% and 10 % of steel slag by weight can increase compressive strength after aging for 3 to 60 days (Ruan et al., 2022). Additionally, mechanical characteristics and durability improve with increasing quantities of steel slag in flexible pavement applications (Behiry, 2013). Studies also indicate that pavements incorporating steel slag exhibit outstanding performance in terms of skid resistance, moisture damage, rutting, and fatigue (Kumar and Varma, 2021). Figure 3(a) illustrates the compressive strength of concrete at 28 days with a specific water-binder ratio when steel slag is included as supplementary cementitious material and aggregate.

Research findings on the advantages of carbonation curing vary widely (Dongxue et al., 1997; Kang et al., 2020). Some studies indicate that with a constant water-binder ratio, increasing the proportion of steel slag results in higher permeability to chloride ions, reduced compressive strength, and notably diminished carbonation resistance at 28 days (Dongxue et al., 1997; Wang et al., 2013). Conversely, other studies suggest that the carbonation process benefits construction materials incorporating steel slag by enhancing low cementitious activity, reducing heavy metal leaching, and mitigating volume instability caused by expansive compounds such as CaO/MgO (Song et al., 2021; Wang et al., 2023).

Accelerated carbonation may offer environmental advantages; research indicates that 1 kg of steel slag can absorb 0.25 kg of $CO_2$ (Huijgen et al., 2005).

According to Table 1, both Basic Oxygen Furnace (BOF) and Electric Arc Furnace (EAF) steel slags often exhibit high FeO content. This high FeO content, combined with the highly crystalline nature of the slag, enhances its stability but can lead to chemical inactivity during the hydration process (Muhmood et al., 2009). Consequently, steel slags are commonly used as aggregate after activation. To increase the reactivity of steel slag, it can be utilized as a supplementary cementitious material by undergoing a grinding process. Grinding the slag increases its specific surface area by creating surface defects and transforming its crystalline structure into an amorphous one. An example of ground steel slag retaining an amorphous nature is Ground Granulated Blast Furnace Slag (GGBFS).

Research suggests that the steel slag content in a mix should not exceed 50% of the total dry weight (J. Liu et al., 2020; Qasrawi et al., 2009). However, it's important to note that the high porosity of steel slag may result in low freezing resistance of the mix (Manso et al., 2006). Additionally, studies have shown that incorporating Electric Arc Furnace (EAF) slag in mortar can diminish its strength by reducing the bond quality between the cement paste and aggregates. This reduction is attributed to the high iron oxide content and crystallinity of the slag, which induce chemical inactivity during the hydration process (Rooholamini et al., 2019).

### 4.2.Ferronickel slag

Ferronickel slag performs similarly to natural aggregates in high-strength concrete. Replacing 50% of the aggregate with ferronickel slag enhances compressive strength and modulus of elasticity, increasing from 28 to 32 GPa. A 27% replacement also boosts sulphate resistance by up to 22%. However, a 50% replacement reduces abrasion resistance and strength against chloride ion attack, although it still outperforms concrete without ferronickel slag.

Fig 8 illustrates the 28-day compressive strength of concrete with a specific water-binder ratio and ferronickel slag as supplementary cementitious material and fine aggregate. Table 4 compares the 7-day compressive strength of mortar containing ferronickel slag with that containing Electric Arc Furnace (EAF) slag.

**Table-4:** Comparison of compressive strength of concrete with ferronickel slag and electric-arc furnace slag.

| **Comparison of compressive strength of concrete with ferronickel slag and electric-arc furnace slag.** | | | |
|---|---|---|---|
| Aggregates | Control (Mpa) | Replacement (MPa) | |
| | | 50% | 100% |
| Ferronickel slag (Saha and Sarker, 2017a) | 32.5 | 47.5 | 33.75 |
| Electric-arc-furnace slag (Rooholamini et al., 2019) | 28.18 | 22.27 | 12.27 |

Ferronickel slag mortar tends to exhibit higher compressive strength than EAF slag mortar. Incorporating 50% ferronickel slag content into mortar improves compressive strength at 7 days and all curing ages, while 50% EAF slag in mortar can lower compressive strength at 7 days (Saha and Sarker, 2017a; Rooholamini et al., 2019).

In self-compacting concrete, higher levels of ferronickel slag (30% to 50%) increase compressive strength (Nuruzzaman et al., 2022) and improve chloride and corrosion resistance (Chen et al., 2020). Additionally, copper slags enhance workability in high-performance concrete as their proportion increases (Al-Jabri et al., 2009; Edwin et al., 2016).

Ferronickel slag can replace natural fine aggregate partially due to its larger particle size compared to natural sand. Its amorphous silica content makes it reactive, leading to significant volume expansion when it reacts with free alkali in cement (Saha and Sarker, 2016). This expansion issue can be managed by using supplementary cementitious materials such as fly ash to replace a portion of the cement (Saha et al., 2018).

Ferronickel slag is ideal for mortar due to its dense particle packing and lower fineness modulus. However, its higher iron oxide content presents challenges in grinding it to an optimal particle size for maximizing strength, which can increase costs due to requiring larger grinding equipment (Saha and Sarker, 2016). Additionally, significant magnesium oxide content may delay complete hydration, extending the curing period to several years.

Irjet Template sample paragraph .Define abbreviations and acronyms the first time they are used in the text, even after they have been defined in the abstract. Abbreviations such as IEEE, SI, MKS, CGS, sc, dc, and rms do not have to be defined. Do not use abbreviations in the title or heads unless they are unavoidable.

## 5. ENVIRONMENTAL IMPACT AND SUSTAINABILITY

### 5.1.Steel Slag

When incorporating industrial by-products such as steel slags, it's critical to assess their environmental impact, especially regarding potential heavy metal content. These slags can leach heavy metals when exposed to rainwater, posing risks of soil and groundwater contamination in construction applications (Aljerf, 2018a).

The Toxicity Characteristic Leaching Procedure (TCLP), established by the US EPA, is widely used to assess heavy metal leaching from materials (EPA, 2009). Before adopting by-products for long-term use, conducting tests like TCLP is crucial. In steel slag asphalt concrete mixes, the TCLP test is employed to detect the presence of eight heavy metals.

(Hasita et al., 2021). Additionally, tests are performed to assess different steel slags produced via blast furnaces (BF), basic oxygen furnaces (BOF), and electric arc furnaces (EAF) (Proctor et al., 2000). Summary findings from various studies are presented in Table 5.

Based on the established criteria, heavy metals in pavement mixed with steel slag are below EPA limits, suggesting they are suitable for use in public areas. The TCLP method with an acetic acid solution (pH 4) was used for the leaching test (Proctor et al., 2000). However, EPA standards recommend further testing at different pH levels (3, 5.5, and 7–8) for comprehensive assessment (EPA, 2009).

The primary issue with the chemical makeup of raw steel slag is the risk of heavy metal leaching into groundwater. Once dissolved, these metals can spread through water pathways, posing a contamination risk to the local environment if not controlled. The TCLP test is typically employed to assess this risk. Additionally, air pollution may occur during both the production and utilization of slag.

According to an EPA report, the water-cooling process during slag production releases between 34 and 52 mg of particulates per liter of quench water used (Annamraju et al., 1984). Regulations by state environmental agencies address concerns about off-gassing of hydrogen sulfide and sulfur dioxide. Using steel slag instead of gravel on dirt roads raises dust exposure concerns due to heavy traffic and wind, potentially dispersing the material locally (Kacer et al., 2023).

## 5.2.Ferronickel Slag

It's similar to steel slags used in construction, ferronickel slags may also risk contaminating soil and groundwater due to their heavy metal content, potentially leading to leaching (Xi et al., 2018). Raw ferronickel slag contains higher chromium levels compared to Portland cement, and chromium can leach under highly alkaline conditions (Kim et al., 2019).

Research findings indicate that substituting ferronickel slag with 5%, 10%, and 30% replacements does not lead to leaching of chromium or other heavy metals (Kim et al., 2019). The study used Toxicity Characteristic Leaching Procedure (TCLP) tests recommended by the US EPA to assess concentrations of $Cr^{6+}$, Pb, Cu, As, Cd, and Hg.

Another study found that heavy metal concentrations in concrete specimens using ferronickel slag as a replacement for fine aggregates consistently remained below allowable limits set by the US EPA and UK Environment Agency (Saha and Sarker, 2017b). The study conducted leaching tests following the NEN 7345 standard from the Netherlands Standardization Institute.

Concrete specimens were made, cured for 28 days, and then immersed in purified water for an additional 64 days, with dissolved heavy metals measured at the end of the process (Katsiotis et al., 2015). These tests confirm the environmental safety of using ferronickel slag in construction.

Saha and Sarker (2017b) reported in Tables 5 and 6 that leached heavy metal concentrations were well below hazardous waste and drinking water limits, indicating minimal leaching.

However, Katsiotis et al. (2015) found higher levels of chromium and lead in their specimens, exceeding drinking water standards, indicating the need for careful consideration before applying these materials. It's important to note that heavy metal content can vary based on the manufacturing process.

As per the US EPA and UK Environment Agency standards, ferronickel slag can be used if it stays below specified limits. Another test, replacing 20% of ferronickel slag and using the NEN 7375 monolithic leaching method, showed heavy metal concentrations below regulatory thresholds (Salman et al., 2016).

Therefore, ferronickel slag remains viable within hazardous limits. Overall, its use as a binder or aggregate demonstrates minimal heavy metal leaching and negligible environmental impact (Saha et al., 2018).

## 5.3.Copper SlagTop of Form

Tailing ponds pose a significant risk of hazardous waste to the environment, primarily through soil leaching and, occasionally, structural failures in the containment dams if not effectively managed (Komljenovic et al., 2020). Research has observed elevated levels of heavy metals in farmlands near copper tailing ponds (Xiao et al., 2022). Health risks associated with these metals can be assessed using guidelines such as the Technical Guidelines for Risk Assessment of Contaminated Sites and US EPA guidelines (EPA, 1990). These assessments provide indices indicating both carcinogenic and non-carcinogenic hazards in the tested soil samples (Teng et al., 2015).

The extensive surface area of loose tailing waste promotes leaching of hazardous materials by solvents (Pehoiu et al., 2019). To mitigate this, tailings are stored in large open-air ponds lined with impermeable barriers, preventing interaction with underlying soil and contaminated water. Keeping the waste submerged underwater helps prevent the dispersion of contaminated dust by wind. Mines often use a series of ponds arranged along slopes to facilitate downhill water flow (Cacciuttolo and Atencio, 2022). Operators manage water levels by adjusting fluid flow between ponds to prevent overflow or dam breaches that could lead to surrounding areas being flooded with mining waste.

Unlike tailings, copper slag is economically viable as a blasting aggregate or in concrete production as a pozzolanic material (Phiri et al., 2021). However, it poses health risks such as long-term exposure to dust inhalation and the leaching of heavy metals into the environment (Mugford et al., 2017).

Regulatory bodies such as the United States Occupational Safety and Health Administration (OSHA) offer tables of personal exposure limits to guide manufacturers in maintaining safe levels of chemical components present in slag (Administration, 2021). Customizing these limits is crucial due to variations in slag's chemical composition across different sites.

Leaching or weathering of copper slag and tailings can release toxic metals into the local environment around mining operations, posing significant pollution risks (Punia, 2021). These risks escalate when stockpiles are exposed without proper pollution mitigation measures. To meet increasing metal demands, there is a growing trend to extract usable metals from slag materials for use as additives in concrete (Marin et al., 2022; Phiri et al., 2022).

Using copper slags and tailings in concrete shows potential for sequestering harmful metals, as the cement matrix can contain any leached metals within the composite (Ahmari and Zhang, 2012; Ghazi et al., 2022; Gorai and Jana, 2003; Ince et al., 2021; Wang et al., 2020).

Leaching tests for copper slag and copper tailings were carried out following the US EPA's Toxicity Characteristic Leaching Procedure (TCLP), detailed in Table 5. While heavy metal levels in copper slag remained below US EPA thresholds (EPA, 2009), leaching from copper tailings exceeded these safe limits.

The small particle size of copper tailings allows for increased dust generation and provides a large surface area for metals to leach out when exposed to water. Storing large quantities of copper tailings poses significant and long-term environmental risks, as well as higher costs.

## 6.CONCLUSION

This study provides a comprehensive review of steel slag, ferronickel slag, copper slag, and copper tailings, examining their chemical composition, performance, and environmental aspects. These materials demonstrate potential as partial substitutes for cement and fine aggregates in concrete, enhancing mechanical strength while effectively trapping heavy metals within the composite.

Reactivity is crucial for utilizing waste materials effectively. Ferronickel slag, copper slag, and copper tailings have high $SiO_2$ content, facilitating a pozzolanic reaction with cement to form a secondary calcium silicate hydrate. Steel slag, dominated by CaO, closely resembles Portland cement in composition. All four waste materials examined can replace cement, though those with high crystallinity may require grinding to transition into an amorphous phase.

Additionally, these inert waste materials can substitute for both fine and coarse aggregates. Incorporating them at specified levels has been found to enhance mechanical strength and durability in concrete applications.

Construction materials containing various types of steel slags (BF, BOF, and EAF), ferronickel slag, or copper slag have been found environmentally safe in leaching tests, with leached toxic elements below US EPA limits. However, leaching from copper tailings has exceeded safe limits, emphasizing the need for careful material management.

To mitigate environmental and health impacts, tailings are stored in large open-air ponds. Studying the degradation of these wastes can identify suitable legacy storage sites for material extraction. Many mining or refining wastes are highly toxic and pose storage challenges without clear economic uses. Hence, research should prioritize characterizing and utilizing these wastes to reduce their environmental and economic burdens.

Future research could focus on how weathering and degradation affect the pozzolanic activity of slag and mill tails stored long-term. Additionally, conducting a comprehensive life cycle assessment (LCA) to compare greenhouse gas emissions from the four waste products studied would provide valuable insights into their environmental impact and support informed decision-making on their utilization.

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