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VALORIZATION OF STEEL FURNACE SLAG FOR CONSTRUCTION APPLICATIONS: TECHNICAL CHALLENGES AND OPPORTUNITIES

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Abstract

Steel furnace slags is a strategically important secondary resource for sustainable building materials, but its efficient utilization requires a clear understanding of its highly variable behaviour. Previous studies indicate that slag-derived composites often exhibit reduced workability due to particle size and shape, high water demand, and the slow reactivity of certain silicate phases. Dimensional stability remains a critical issue, as several types of steel slag from furnaces contain phases predisposed to delayed expansion, mainly related to the mineralogical composition of the particles. Furthermore, the presence of heavy metals requires detailed characterization, representing a critical factor in assessing the safety of using steel furnace slag in construction composites. In addition to these generalized mechanisms, an important regional challenge is the utilization of the large quantities of steel furnace slag accumulated in Romania from decades of steel production. These materials remain in landfills without being given a new cycle of use, despite their potential for integration into cement-based composites and civil infrastructure. This article examines the main technical limitations associated with the use of steel furnace slag, while highlighting possible characterization strategies and processing methods that can enable the safe and efficient use of existing steel furnace slag resources in Romania.

Key words*: circular economy, secondary raw materials, steel furnace slag valorization.*

INTRODUCTION

The construction industry faces intensifying pressure to mitigate its environmental impact through optimized utilization of secondary raw materials and systematic reduction of industrial waste (Müller et al., 2014; European Commission, 2015; Ghisellini et al., 2016). Within this framework, steel slag has garnered substantial attention due to its abundance and prospective applications in cementitious composites and civil infrastructure (Shi & Qian, 2000; Motz & Geiseler, 2001; Brand & Fanijo, 2020). As a by-product of steel manufacturing processes, steel slag represents both an environmental challenge and an opportunity for the development of more sustainable building materials (Mousavinejad & GilKalaye, 2024).

Global steel production generates each year very large volumes of steel slag, amounting to hundreds of millions of tons worldwide, and although partial reuse is achieved in certain regions, a significant portion of this material remains landfilled due to technical, environmental, and regulatory constraints (World Steel Association; Motz & Geiseler, 2001).

The literature consistently highlights the need for systematic characterization, controlled processing, and appropriate qualification for specific applications to enable the safe and efficient reuse of steel slag in construction materials (Shi & Qian, 2000; Provis & Van Deventer, 2009; Brand & Fanijo, 2020). However, the main obstacles to large-scale recycling include the pronounced variability between different types of slag (electric arc furnace slag, EAF; basic oxygen furnace slag, BOF; ladle metallurgy furnace slag, LMF; argon oxygen decarburization slag, AOD), the risk of delayed volumetric expansion associated with free CaO and MgO or other mineralogical

mechanisms, reduced workability in fresh composites, and concerns about heavy metal content and mobility (Shi & Qian, 2000; Deja, 2000; Santamaría et al., 2018; Brand & Fanijo, 2020).

In Romania, decades of steel production have resulted in the accumulation of substantial quantities of steel slag, which remain largely underutilized or landfilled in industrial waste dumps (Figure 1) (Baera et al., 2024; 2026). Research and exploitation strategies in the Romanian context, the term steel furnace slag (SFS) is particularly suitable, as most slag deposits come from primary steel production processes, mainly from basic oxygen furnaces (BOF) and electric arc furnaces (EAF) (Figure 1). The term SFS proves particularly apt for Romanian research and exploitation strategies, reflecting the predominance of furnace-derived deposits.

The principal national impediment remains the absence of comprehensive slag inventories and standardized qualification frameworks, severely constraining construction sector integration (Kurecki et al., 2024). Addressing this issue requires coordinated strategies focused on rapid characterization protocols, pilot-scale valorisation projects, and targeted pre-treatment methods, such as aging or carbonation, to mitigate expansion risks and environmental issues, while allowing the use of locally available secondary raw materials in civil infrastructure projects (Santamaría et al., 2018; Shi & Qian, 2000; Deja, 2000; Provis & Van Deventer, 2009; Brand & Fanijo, 2020;).

Despite these prospects, SFS deployment remains circumscribed by pronounced physicochemical and mineralogical variability arising from disparate steelmaking parameters, feedstock compositions, and cooling regimes materials (Shi & Qian, 2000; Motz & Geiseler, 2001; Brand & Fanijo, 2020).

Poor workability consistently manifests when SFS substitutes natural aggregates, attributable to angular morphology, rough surface texture, and elevated water absorption that exacerbate mixture friction and water demand (Yildirim & Prezzi, 2011; Ouda & Abdel-Gawwad, 2017; Loureiro et al., 2022). Parallel fresh-state concerns, dimensional stability constitutes a major technical challenge. Certain furnace slag typologies harbor reactive mineral phases capable of protracted hydration, inducing delayed volumetric expansion that compromises long-term durability (Santamaría et al., 2018; Adegoloye et al., 2016).

Environmental safety further requires consideration: the metallurgical provenance introduces trace metallic elements with exposure-dependent mobility, necessitating rigorous physicochemical characterization and leaching assessment (Alizadeh et al., 2003; Liu et al., 2016).

Regardless of these technical constraints, the substantial volumes of steel slag generated globally over decades of steel production constitute a valuable secondary resource. Extensive research validates its viability across diverse applications: concrete, mortar, asphalt mixtures, and specialized uses (Maslehuddin et al., 2013; Loureiro et al., 2022). Nevertheless, significant underutilization persists, underscoring the critical need for integrated approaches that synergize material characterization, performance validation, and tailored processing methodologies to enable safe, efficient valorisation (Fuente-Alonso et al., 2017; Loureiro et al., 2022). In this context, this article examines the main technical challenges associated with the use of steel slag in construction applications and discusses potential pathways for its safe and efficient use.

This review systematically outlines the principal technical challenges impeding steel slag deployment in construction while elucidating viable mitigation pathways for its effective utilization.

Despite inherent technical complexities necessitating rigorous evaluation, steel furnace slag remains a high-potential waste-by-product. Its recovery offers strategic opportunities to address environmental liabilities while advancing Circular Economy principles within the construction sector.



Figure 1. EAF landfill resulting from long-term steel production in Romania: a) the EAF landfill on the site; b-c) Location on the map of the Terova (near Resita, Caras-Severin County) EAF slag landfill (Baera et al., 2024)

MATERIALS AND METHODS

Review methodology

The present study was developed as a literature-based review focused on the main technical challenges and valorisation opportunities associated with the use of steel furnace slag (SFS) in construction applications. The paper was also supported by the research activities carried out within the research program PN 23 35 04 01 of Nucleu Programme of the National Research Development and Innovation Plan 2022-2027, "ECODIGICONS", supported by the Ministry of Research, Innovation and Digitalization. Baera et al. (2024), focused on the sustainable integration of secondary raw materials into construction materials and infrastructure applications.

The analysis was carried out by examining scientific publications addressing the physical, chemical, mineralogical, and environmental behaviour of steel furnace slag, together with its integration into cement-based materials and civil infrastructure systems. In parallel, selected observations obtained during the preliminary investigations performed within the research program PN 23 35 04 01 were considered as practical examples supporting the discussion regarding the behaviour of SFS-containing cementitious composites.

The literature selection process focused primarily on studies investigating the influence of SFS on fresh-state properties, dimensional stability, long-term durability, and leaching behaviour. Particular attention was also given to research discussing characterization methods, processing approaches, and potential mitigation strategies intended to improve the safe and efficient utilization of SFS in construction materials.

The reviewed information was collected from scientific journal articles, conference papers, technical reports, and relevant research studies published in recent decades. The analysis included studies related to different types of steel furnace slag, particularly electric arc furnace (EAF) slag and basic oxygen furnace (BOF) slag, due to their relevance for construction applications and their significant accumulation in industrial waste deposits.

The collected literature was subsequently organized according to the main technical aspects influencing the practical utilization of SFS, including chemical and mineralogical characteristics, fresh-state behaviour, dimensional stability, environmental assessment, and

potential valorisation pathways in construction and environmental applications.

Characterization and general properties of steel furnace slag

Steel furnace slag (SFS) forms during primary steelmaking processes (Figure 2), predominantly via basic oxygen furnaces (BOF) and electric arc furnaces (EAF), through high-temperature interactions among molten steel, fluxing agents, and furnace refractories (Figure 3).

As Brand & Fanijo (2020) emphasize, SFS exhibits pronounced compositional variability stemming from disparate steelmaking methodologies, raw material inputs, operational parameters, and cooling regimes, a characteristic profoundly influencing its performance within cementitious composites and necessitating rigorous consideration.

During steelmaking, fluxes including limestone ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$) facilitate impurity removal from molten steel, yielding slag enriched with calcium oxides (CaO), magnesium oxides (MgO), iron oxides (Fe), and silicates (SiO_2) (Yildirim & Prezzi, 2011; Brand & Fanijo, 2020).

BOF slags are generally characterized by high CaO contents and a strongly basic nature, whereas EAF slags tend to exhibit greater compositional diversity due to the heterogeneous nature of scrap feedstock. According to Brand and Fanijo, (2020), these differences in formation conditions result in distinct slag types with varying chemical, mineralogical, and physical characteristics.

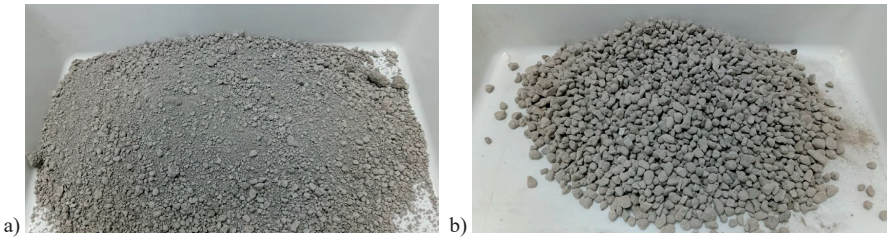


Figure 2. Representative electric arc furnace (EAF) slag: a) 0-4 mm fraction; b) 4-8 mm fraction

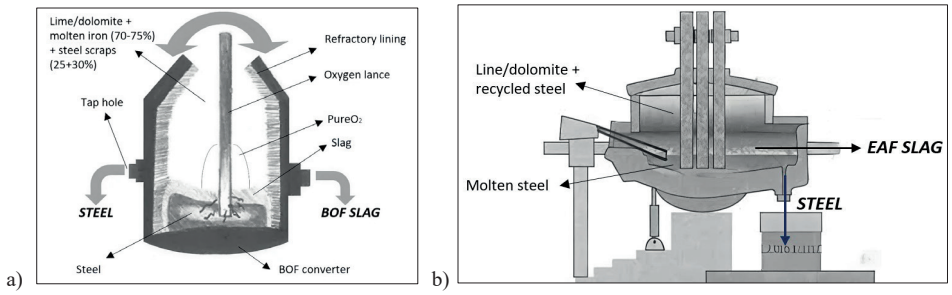


Figure 3. Schematic representation of: a) BOF process (Linz and Donawitz process); b) EAF steelmaking (Yldirim and Prezzi, 2011)

Chemical composition and mineralogical features

Steel furnace slag (SFS) typically comprises CaO, SiO_2, FeO/Fe_2O_3, and MgO as predominant constituents, with Al_2O_3 and other oxides present in smaller proportions (Yildirim & Prezzi, 2011; Brand & Fanijo, 2020). However, both Brand & Fanijo, (2020) and Yildirim & Prezzi (2011) report that the relative proportions of these oxides can vary significantly not only between BOF and EAF slags but also between different batches produced within the same steel plant.

From a mineralogical perspective, SFS consists of a complex assemblage of crystalline and amorphous phases, including dicalcium silicate (C_2S), wüstite (FeO), periclase (MgO), merwinite ($Ca_3MgSi_2O_8$), and calcium ferrites (e.g., C_2F). The presence of free CaO and free MgO is particularly important, as these phases

are associated with delayed hydration reactions and volumetric instability when exposed to moisture (Yildirim & Prezzi, 2011; Brand & Fanijo, 2020).

Microstructural characteristics and phase heterogenity

At the microscale, steel furnace slag particles frequently exhibit heterogeneous internal structures, characterized by differences between particle surfaces and cores. This phase heterogeneity originates from non-equilibrium cooling and localized chemical segregation during solidification, leading to the coexistence of phases with different reactivity within the same particle. Such internal heterogeneity has been shown to influence the interaction between slag particles and cementitious matrices, particularly at the interfacial transition zone, thereby affecting mechanical performance and long-term durability (Yildirim & Prezzi, 2011; Brand & Fanijo, 2020).

Variability and implications for construction applications

The combined chemical, mineralogical, and microstructural variability of steel furnace slag represents a major challenge for its standardized use in construction materials. As emphasized in the literature, differences in slag characteristics can lead to inconsistent workability, mechanical properties, and dimensional stability of SFS-containing composites if appropriate characterization is not performed. Consequently, the effective valorization of steel furnace slag requires thorough preliminary assessment, including chemical composition, mineralogical phase analysis, and microstructural evaluation, to ensure predictable performance in construction applications (Yildirim & Prezzi, 2011; Brand & Fanijo, 2020). The essential steps involved in the initial characterization of steel furnace slag are outlined below:

- *X-ray Fluorescence (XRF) analysis* used for the chemical evaluation of mineral wastes is a non-destructive analytical technique employed to identify and quantify the chemical elements present in solid materials;
- *X-ray Diffraction (XRD) analysis* is an instrumental analytical technique used for the identification and quantification of crystalline phases in mineral material;
- *Fourier Transform Infrared (FTIR) Spectroscopy* is an instrumental analytical technique used to identify functional groups and chemical bonds in the analysed materials by examining the absorption of infrared radiation by their molecular structure.
- *Thermogravimetric Analysis (TGA) and Differential Thermal Analysis (DTA)* comprise a set of thermoanalytical techniques used to evaluate the thermal behavior, chemical stability, and physicochemical transformations of materials.
- *Visual Analysis and Microscopy* represent a set of morphological and microstructural investigation methods used for the observation, description, and interpretation of the physical, structural, and mineralogical characteristics of the analysed materials. The method includes macroscopic (visual) and microscopic examinations (optical microscopy and scanning electron microscopy - SEM, optionally coupled with energy-dispersive spectroscopy, EDS) and is applied for the characterization of mineral wastes.

Figure 4 summarizes the key steps required to achieve an initial characterization of any steel furnace slag.

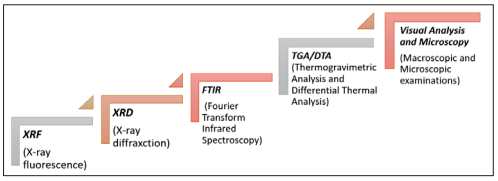


Figure 4. Schematic overview of the initial characterization steps for SFS slag

Following the initial characterization of the steel furnace slag type, the main issues to be addressed include reduced workability, dimensional stability, and concerns related to heavy metal content.

Experimental Observations Regarding Fresh-State Properties

Workability is widely regarded as one of the main challenges associated with incorporating steel furnace slag (SFS) into cement-based composites. As summarized by Brand and Fanijo (2020) mixtures containing SFS

generally exhibit reduced workability compared to reference mixtures with natural aggregates, usually manifested by lower slump values and increased mixture stiffness. However, the magnitude of this reduction depends largely on the type of slag, particle size distribution, and specific physical characteristics.

The angular morphology of steel slag particles is a major factor contributing to reduced workability. Unlike natural aggregates, SFS particles are characterized by irregular shapes and sharp edges, which increase internal friction and restrict particle mobility in the fresh state. Steel slag particles typically have rough and porous surfaces, which leads to higher water absorption compared to conventional aggregates (Yildirim & Prezzi, 2011; Brand & Fanijo, 2020). As a result, part of the mixing water is absorbed by the slag particles, leading to an increased water demand to achieve comparable workability.

In order to examine this aspect, two representative examples were considered.

The first example is based on previously published research that examined the incorporation of electric arc furnace (EAF) slag as a partial replacement for natural fine aggregates in cement-based materials (Darwis et al., 2024), while the second example consists of preliminary observations obtained as part of the program PN 23 35 04 01 of Nucleu Programme. The mixtures studied within the program PN 23 35 04 01 included different levels of replacement of natural fine aggregates with EAF slag. The evaluation focused on the behaviour of the cementitious mixtures in the fresh state, particularly on consistency and workability. The experimental determinations were performed in accordance with the applicable testing procedures for fresh mortars, in accordance with EN 1015-3.

Dimensional Stability and Expansion Mechanisms

In addition to issues related to fresh workability, the incorporation of steel furnace slag (SFS) into cement-based composites presents significant challenges related to dimensional stability. Unlike conventional natural aggregates, SFS can exhibit delayed volumetric changes when exposed to moisture, which can compromise the long-term performance and durability of cementitious materials (Brand & Fanijo, 2020). These effects are particularly critical in applications where dimensional stability is essential, such as structural concrete and infrastructure elements.

The dimensional instability of EAF is primarily associated with its complex chemical and mineralogical composition, which is significantly influenced by steel manufacturing conditions and cooling patterns (Yildirim & Prezzi, 2011; Brand & Fanijo, 2020). The presence of reactive oxide phases, combined with the heterogeneous distribution of mineral constituents in slag particles, can lead to time-dependent expansion when SFS is incorporated into cementitious systems and exposed to water (Brand & Fanijo, 2020). Unlike fresh workability issues, which are immediately observable, volumetric instability can develop gradually, often after placement, making it more difficult to detect and remediate.

Among the factors contributing to volumetric instability, the presence of free calcium oxide (free CaO) and free magnesium oxide (free MgO) plays a dominant role. Free CaO reacts relatively quickly with water to form calcium hydroxide, accompanied by a significant increase in volume. In contrast, free MgO hydrates much more slowly, leading to delayed expansion that can be observed over long periods of time. The degree of expansion depends not only on the total content of these oxides, but also on the size of the crystals, the degree of encapsulation in other phases, and accessibility to moisture (Yildirim & Prezzi, 2011; Santamaría et al., 2018; Brand & Fanijo, 2020).

The mineralogical heterogeneity of SFS further complicates its dimensional behaviour. As a result, different regions within the same particle may react differently to hydration processes, leading to localized expansion and the development of internal stresses. This heterogeneous behavior can contribute to the formation of microcracks and negatively affect the surrounding cement matrix. When EAF is used as a component in cementitious composites, dimensional instability can lead to internal stresses, microcracks, and, in severe cases, visible cracks or loss of durability (Santamaría et al., 2018; Brand & Fanijo, 2020). These effects are particularly relevant when SFS

is used as a replacement for aggregates, where volumetric changes directly influence the composite matrix.

Leaching Behaviour of Steel Furnace Slag and SFS Cement-Based Composites

The environmental evaluation of steel furnace slag (SFS) begins with the assessment of its leaching behavior in the raw materials. For granular materials such as steel slag, the EN 12457 is commonly applied, involving batch extraction under a defined liquid-to-solid ratio and controlled agitation conditions. This procedure enables the quantification of potentially hazardous elements released into an aqueous medium over a fixed period of contact.

Gomes & Pinto (2006) investigated the leaching behaviour of industrial steelmaking slags through laboratory extraction tests aimed at evaluating the mobility of heavy metals. In the experimental approach, slag samples were subjected to controlled leaching conditions, and the concentrations of dissolved elements were subsequently determined through chemical analysis of the leachate. Gomes & Pinto (2006) focused on elements such as Pb, Cd, Cr, and Zn, demonstrating that the release of these metals depends on physicochemical parameters including pH and slag composition. The results indicated that, although certain slags exhibited limited metal mobility under neutral conditions, measurable concentrations could be detected under specific environmental scenarios, emphasizing the importance of systematic leaching testing prior to reuse.

Similarly, investigations conducted under variable acidic and alkaline environments, as reported in the study available through Dhoble & Ahmed (2018), applied controlled leaching protocols over extended exposure periods (up to 50 days). The methodology involved immersing slag samples in aqueous solutions with adjusted pH values, followed by periodic sampling and chemical quantification of elements such as Cr, Fe, Ni, Zn, and As. The findings highlighted that metal release behaviour is strongly influenced by environmental conditions, particularly acidity, and that prolonged exposure may alter the mobility patterns of certain elements.

These experimental approaches confirm that the leaching potential of SFS must be evaluated through standardized or controlled laboratory procedures, rather than inferred solely from bulk chemical composition.

When SFS is incorporated into cement-based composites, the assessment framework shifts from granular waste characterization to evaluation of monolithic construction products. In the European context, the release of dangerous substances from solid construction materials is commonly assessed according to CEN/TS 16637-2, known as the Dynamic Surface Leaching Test (DSLT).

Unlike batch tests applied to granular materials, DSLT evaluates the time-dependent release of substances from the exposed surface of a monolithic specimen. The test involves repeated contact between the concrete sample and deionized water over predefined intervals, with periodic renewal of the leaching solution and subsequent chemical analysis of the eluate. This methodology allows the assessment of cumulative release and diffusion-controlled mechanisms over time.

In cementitious systems containing SFS, the alkaline matrix may contribute to partial immobilization of heavy metals through physical encapsulation and chemical stabilization. However, long-term exposure to water, environmental carbonation, or surface degradation may influence the release dynamics. Therefore, even if preliminary EN 12457 tests on the raw SFS indicate acceptable leaching levels, complementary assessment on the final cement-based composite remains essential to ensure environmental compliance throughout its service life.

The differentiation between leaching behaviour of the raw SFS and that of the final concrete product is therefore critical for a comprehensive environmental evaluation strategy.

Assessment of Potential Valorisation Opportunities for Steel Furnace Slag

The identification of potential valorisation opportunities for steel furnace slag (SFS) was conducted through a systematic review of the scientific literature addressing its applications in construction materials and environmental technologies. The analysis focused on studies investigating the use of SFS in cement-based materials, road infrastructure, and environmental remediation systems.

One of the most extensively investigated valorisation pathways for SFS is integration into

cement-based materials. Numerous studies report the successful use of SFS as a partial replacement for natural aggregates in concrete and mortar mixtures, contributing to improved mechanical performance and enhanced durability of cementitious composites (Chatzopoulos et al., 2021; Ren & Li, 2023; Mitwally et al., 2024; Ibrahim et al., 2025; Khan et al., 2025). The angular particle morphology and high density of steel slag aggregates may improve the mechanical interlocking within the cement matrix, leading to increased compressive strength and improved resistance to mechanical loading. Beyond its use as aggregate, SFS has also been investigated as a potential substitute for cement components in mortar and concrete mixtures. In such applications, finely processed SFS may partially replace clinker-based materials, contributing to the reduction of cement consumption and associated CO_2 emissions (Cai et al., 2024; Zhou et al., 2025).

Another important opportunity of valorisation pathway involves the use of SFS in road infrastructure applications. Due to its high hardness, abrasion resistance, and favorable mechanical properties, SFS have been widely investigated for use in asphalt mixtures, base layers, and other pavement structures (Hainin et al., 2015; Dayioğlu et al., 2023; Patel et al., 2023). These properties contribute to improved load-bearing capacity, enhanced skid resistance, and increased durability of pavement systems compared to conventional granular aggregates. In addition to asphalt mixtures and road base layers, SFS has also been explored for the production of paving elements such as concrete paving blocks used in urban infrastructure. The high density and mechanical stability of SFS aggregates make them suitable for prefabricated pavement elements where resistance to wear and mechanical stress is required (Pasetto et al., 2023; Sun et al., 2025).

In addition to construction applications, SFS has also been explored for environmental remediation purposes, particularly in water treatment systems. Due to its mineralogical composition and alkaline nature, SFS can act as an effective adsorbent for removing pollutants from aqueous solutions. Experimental studies demonstrate that SFS can adsorb heavy metal ions and other contaminants from water, highlighting their potential application as filtration media in water purification systems (Song et al., 2014; Plaza et al., 2021; Maarup et al., 2023). Overall, the literature indicates that steel furnace slag represents a versatile secondary resource with multiple valorisation opportunities across construction and environmental applications (Figure 5).



Figure 5. Main valorisation pathways of steel furnace slag in construction and environmental applications (AI-generated image)

RESULTS AND DISCUSSIONS

Effects of SFS on Fresh-State Properties

The influence of steel furnace slag (SFS) on the fresh-state behaviour of cementitious composites was evaluated through two representative examples.

The first example refers to investigations performed within the framework of the PN 23 35 04 01 research programme and reported by

Baera et al. (2024). The study evaluated the partial replacement of natural fine aggregate with electric arc furnace (EAF) slag originating from western Romania at substitution levels of 25% and 50%. The results demonstrated a consistent reduction in fresh-state workability for mixtures containing EAF slag compared to the reference compositions. Furthermore, the decrease in consistency became more pronounced as the replacement level increased, indicating a direct relationship between slag content and workability loss.

The second example conducted by Darwis et al. (2024), steel slag was used as a substitute for fine aggregate (sand) in concrete mixtures at replacement levels ranging from 0% to 100%. The results indicate a clear reduction in workability with increasing steel slag content. The reference mixture exhibited the highest slump value, while progressively lower slump values were recorded as the proportion of steel slag increased. Overall, the slump decreased from values of approximately 84 mm for the reference composition to around 60-70 mm at high substitution levels (80% and 100%), highlighting the adverse effect of steel slag incorporation on fresh-state workability due to its higher water absorption and irregular particle morphology.

The results indicate that fresh-state performance is strongly influenced by the characteristics of the slag used and the degree of replacement adopted. The consistent behavior observed in cement-based mixtures underscores the importance of specific material evaluation when blast furnace steel slag is considered as an alternative component in cementitious composites.

The patterns observed are consistent with those reported in the literature and support the hypothesis that the physical characteristics of SFS play a significant role in determining the workability of cement-based mixtures.

Dimensional Stability and Expansion Mechanisms

Based on studies Baera et al. (2024), Baera et al. (2026) and Darwis et al. (2024), cementitious composites containing steel furnace slag substitutions demand increased monitoring attention, as insufficient assessment may result in adverse long-term performance. Although no immediate dimensional instability was detected during the early stages, the behaviour of the investigated mixtures indicates that the incorporation of SFS requires careful evaluation in relation to potential time-dependent volumetric changes.

The results suggest that the risk of delayed expansion is closely related to the intrinsic characteristics of the SFS rather than to the cementitious compositions itself. In this context, the presence of reactive oxide phases and the heterogeneous internal structure of SFS particles, as described previously, may contribute to localized expansion and internal stress development when favourable conditions are present. These effects are not necessarily evident at early ages, emphasizing the importance of correlating experimental observations with material characterization data. Any volumetric changes occurring within the SFS particles may directly affect the surrounding cement matrix, potentially leading to microcracking and reduced durability over time. The results underline that dimensional stability should not be assessed exclusively based on short-term performance, but rather in relation to the long-term behaviour expected under service conditions.

Overall, the findings confirm that the dimensional stability of SFS-containing composites is strongly dependent on slag-specific properties, reinforcing the need for a material-oriented evaluation approach prior to practical application.

Mitigation Strategies in Case of Elevated Leaching

In cases where leaching tests indicate elevated concentrations of hazardous elements, several mitigation strategies may be considered to reduce metal mobility prior to or after incorporation into cement-based compositions. Experimental investigations on SFS have shown that the release of heavy metals is strongly influenced by physicochemical parameters, particularly pH and environmental exposure conditions (Gomes & Pinto, 2006). Adjusting these parameters through controlled aging or conditioning treatments may therefore contribute to lowering metal solubility.

Furthermore, studies performed under variable acidic and alkaline conditions demonstrate that

prolonged exposure and pH variation significantly affect the mobility of elements such as Cr, Fe, Ni, Zn, and As (Dhoble & Ahmed, 2018). These findings suggest that pre-treatment approaches aimed at stabilizing reactive phases, reducing surface reactivity, or promoting the formation of less soluble compounds may enhance environmental compatibility.

In addition, incorporation of SFS into cementitious matrices may contribute to partial immobilization through physical encapsulation and chemical stabilization mechanisms, particularly under highly alkaline conditions (Gomes & Pinto, 2006). Consequently, appropriate material conditioning combined with optimized mix design may represent effective pathways to mitigate excessive leaching where initial tests indicate environmental risk.

CONCLUSIONS

This study highlights the importance of a comprehensive and specific approach to the material in terms of utilizing steel furnace slag (SFS) in cement-based composites. The conclusions highlight that the successful integration of SFS largely depends on the initial thorough characterization of the raw material, as steel furnace slag cannot be considered a uniform or inherently stable constituent.

The preliminary characterization stage is essential in identifying the key physical, chemical, and mineralogical characteristics of SFS and establishing correlations between these characteristics and the most critical challenges associated with its use. In particular, reduced workability, dimensional instability, and the presence of heavy metals have been identified as the main issues requiring careful evaluation. These challenges are closely related to the specific properties of the SFS, such as particle morphology, mineralogical heterogeneity, reactive oxide phases, and chemical composition.

Among these aspects, dimensional stability is a major concern due to the potential for delayed expansion effects. Therefore, the potential for delayed expansion highlights the need for comprehensive characterization, including mineralogical evaluation and expansion-related testing, prior to the practical application of SFS in construction materials. At the same time, workability effects and environmental considerations further reinforce the need to correlate material characterization results with performance indicators in the short and long term.

The assessment of leaching behaviour represents a critical component in the environmental evaluation of steel furnace slag (SFS) and its cement-based compositions. While preliminary testing on raw materials of SFS provides essential information regarding the intrinsic mobility of potentially hazardous elements, the behaviour of the final cementitious composite may differ substantially due to encapsulation and chemical stabilization mechanisms. A comprehensive evaluation strategy must therefore integrate both stages of assessment, ensuring that material conditioning, mix design, and long-term exposure conditions are collectively considered. Such an approach supports the responsible valorisation of SFS while maintaining environmental safety and regulatory compliance.

The results also demonstrate that short-term observations are not sufficient to fully assess the behaviour of SFS-containing composites. Long-term monitoring and performance evaluation are essential to capture time-dependent processes and to support the development of appropriate mitigation strategies. Addressing these challenges requires not only systematic testing, but also the identification and optimization of potential solutions, such as adjusting the composition design, material processing methods, or conditioning treatments.

Despite the challenges identified, SFS remains a material with significant potential for recovery. When properly characterized and controlled, SFS offers important opportunities for sustainable resource use, contributing to waste reduction, conservation of natural aggregates, and implementation of circular economy principles in the construction sector.

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