USE OF ELECTRIC ARC FURNACE STEELMAKING SLAG IN ACCELERATED CARBONATION

UTILIZAÇÃO DE ESCÓRIA DE ACIARIA DE FORNO ELÉTRICO A ARCO NA CARBONATAÇÃO ACELERADA

UTILIZACIÓN DE ESCORIA DE ACERÍA DE HORNO ELÉCTRICO DE ARCO EN LA CARBONATACIÓN ACELERADA

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ABSTRACT
The valorization of industrial waste in the steel industry is of great interest within the circular economy model and in the development of strategies for carbon sequestration. Currently, due to sustainable policies, the number of industrial process plants in steel factories is increasing, where the steel production system using basic oxygen furnaces (BOF) is being replaced by electric arc furnaces (EAF). Compared to BOF, the EAF has the advantage of using a renewable energy source and recycling scrap for steel production, thus resulting in lower emissions of polluting gases. The EAF process generates byproducts, such as slag, with a chemical composition different from the residues of the BOF process, which limits its use in conventional applications in civil construction, such as infrastructure works or as an additive to cement. The accelerated carbonation process allows reactions between CO_2 and oxides present in EAF steel slag to occur in a shorter time within the reactor, with a significant increase in compressive strength and chemical stability of the samples when compared to the carbonation of the material under atmospheric conditions. This work aims to present a review of recent studies on the use of EAF slag and its application in the accelerated carbonation process as a means of valorizing this waste.

KEYWORDS
Accelerated carbonation; Electric arc furnace steel slag; Carbon sequestration.

RESUMO
A valorização de rejeitos industriais na indústria siderúrgica possui grande interesse no modelo de economia circular e também na idealização de estratégias para sequestro de carbono. Atualmente, em razão de políticas sustentáveis, cresce o número de plantas de processos industriais em fábricas de aço, onde há a troca do sistema de fabricação do aço via fornos de oxigênio básico (FOB) por fornos elétricos a arco (FEA). Em relação ao FOB, o FEA tem vantagem ao utilizar uma fonte de energia renovável e reaproveitar a sucata para a produção do aço, tendo, portanto, uma menor emissão de gases poluentes. O processo com FEA gera subprodutos, como a escória, com composição química diferente dos resíduos do processo FOB, que limitam seu emprego em usos convencionais na construção civil, como em obras de infraestrutura ou como adição ao cimento. O processo de carbonatação acelerada permite que as reações entre o CO2 e os óxidos presentes na escória de aciaria FEA ocorram em menor tempo no reator, com ganho expressivo na resistência à compressão e estabilidade química das amostras, quando comparado a carbonatação

http://dx.doi.org/10.29183/2447-3073.MIX2025.v11.n2.165-175
ISSN: 2447-0899 (IMPRESSA) | 2447-3073 (ONLINE)
Mix Sustentável | Florianópolis | v.11 | n.2 | p.165-175 | OUT. | 2025

do material em condições atmosféricas. Este trabalho busca apresentar uma revisão de trabalhos recentes para com o uso da escória FEA e seu aproveitamento no processo de carbonatação acelerada como valorização deste resíduo.

PALAVRAS-CHAVE
Carbonatação acelerada; Escória de aciaria de forno elétrico a arco; Sequestro de carbono.

RESUMEN
La valorización de residuos industriales en la industria siderúrgica despierta gran interés en el modelo de economía circular, así como en el desarrollo de estrategias para el secuestro de carbono. Actualmente, debido a políticas de sostenibilidad, ha aumentado el número de plantas de procesos industriales en fábricas de acero que sustituyen el sistema de fabricación basado en hornos de oxígeno básico (BOF, por sus siglas en inglés) por hornos eléctricos de arco (EAF). En comparación con el BOF, el EAF presenta la ventaja de utilizar una fuente de energía renovable y de reutilizar chatarra para la producción de acero, lo que conlleva una menor emisión de gases contaminantes. El proceso con EAF genera subproductos como la escoria, cuya composición química difiere de los residuos generados por el proceso BOF, lo cual limita su uso en aplicaciones convencionales de la construcción civil, como obras de infraestructura o adiciones al cemento. El proceso de carbonatación acelerada permite que las reacciones entre el CO_2 y los óxidos presentes en la escoria del EAF ocurran en menor tiempo dentro del reactor, proporcionando un aumento significativo en la resistencia a la compresión y en la estabilidad química de las muestras, en comparación con la carbonatación en condiciones atmosféricas. Este trabajo tiene como objetivo presentar una revisión de estudios recientes sobre el uso de la escoria del EAF y su aprovechamiento en el proceso de carbonatación acelerada como forma de valorización de este residuo.

PALABRAS CLAVE
Carbonatación acelerada; Escoria de acería de horno eléctrico de arco; Captura de carbono.

1. INTRODUCTION

The steel industry carries out processes that release large amounts of greenhouse gases (GHGs) and faces challenges regarding the proper disposal and use of waste generated during steel production (FLORÉN et al., 2019). In 2022, global steel production reached approximately 1834 million tons, and for every ton of steel produced, 1.91 tons of CO_2 are emitted (WSA, 2023). On the global stage, Brazil currently ranks 9th among the largest steel producers, with a production of 34.10 million tons in 2022, corresponding to 1.9% of global production (IAB, 2023).

According to Zeleke et al. (2018), steel production occurs through different processes, the main ones being: the Bessemer process, the open-hearth process, the electric arc furnace (EAF) process, and the Linz-Donawitz (LD) oxygen converter process, also known as the basic oxygen furnace (BOF), with the main solid co-products being slag (90% by mass), dust, and sludge (WSA, 2021). On average, the production of one ton of steel results in 200 kg of slag from electric arc furnaces (EAF) and 400 kg of slag from oxygen converter furnaces (BOF), including co-products such as dust, sludge, and other materials (WSA, 2021). Steel slag waste can be almost entirely utilized since, when removed from factory equipment, it has a potential utilization rate of over 80% for steel production slag and nearly 100% for pig iron production slag (WSA, 2021). The search for alternatives to use steel slag in product chains is also justified by its current destination within industrial yards, where unused steel slag is often buried or stored outdoors, occupying land and posing threats to the environment and health due to the heavy metals it contains (SONG et al., 2021).

The use of electric arc furnaces (EAF) is considered essential for reducing CO_2 emissions in the steel industry (MERKI; KRASSNIG, 2023). In recent times, the European Union's decarbonization programs have intensified, aiming to reduce the use of basic oxygen furnaces (BOF) in the sector by promoting their replacement with electric arc furnaces (EUROFER, 2023). In this context, the constant increase in steel production from scrap melting in electric arc furnaces (EAF) results in a large amount of EAF slag (MENAD et al., 2021).

However, the accelerated carbonation process can enable the reuse of slags in recurring applications in other industries. For the production of cementitious matrices with steel slag, accelerated carbonation improves the material's pore microstructure, enhancing its durability and strength (LIU et al., 2021; YI et al., 2021). Using steel slag as a raw material in the production of construction materials not only reduces the amount of waste generated but also lowers the environmental and economic costs associated with disposal (MOON, 2019; SRIVASTAVA, 2021).

When comparing EAF and BOF slags, Li, Zhong, and Ling (2022) observe that these slags may contain distinct minerals, which can affect carbonation efficiency and their properties. It is also noteworthy that steel slag is rich in calcium and silicon oxides, making it a suitable raw material for producing clinker-free materials (SRIVASTAVA et al., 2021).

1. 1. Chemical composition

The chemical composition of electric arc furnace (EAF) slag is strongly related to the characteristics of the recycled steel used (YILDIRIM and PREZZI, 2011). According to Jiang et al. (2018), since it is a byproduct of recycled steel scrap, the composition of EAF slag can exhibit a broader chemical variation compared to basic oxygen furnace (BOF) slag. Table 01 shows the chemical composition of EAF slag as reported by recent research.

https://doi.org/10.29183/2447-3073.MIX2025.v11.n2.165-175

1. 2. Production Process

The operation of a typical electric arc furnace relies on graphite electrodes to create an electric arc that melts the metal, while additional process steps, such as casting and rolling, are comparable to the blast furnace route (EUROFER, 2020). The production process using the electric arc furnace is presented in Figure 01.

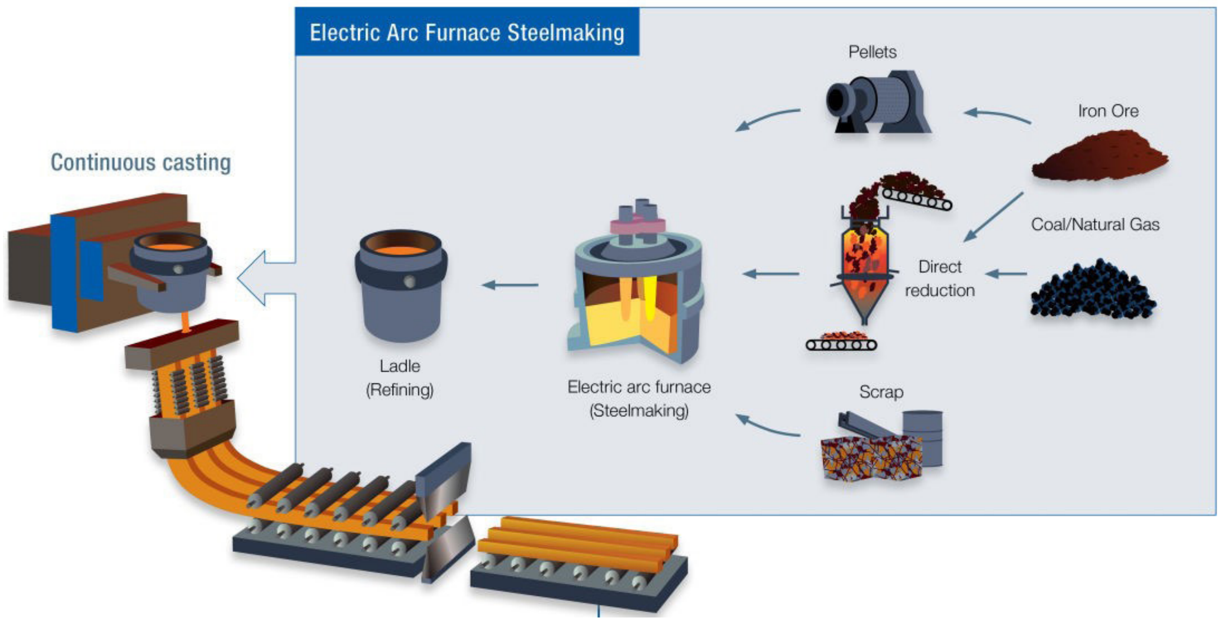

Figure 1: Steel production process using electric arc furnace.
Source: EUROFER (2020)

During the steel refining process, oxygen gas is directly injected into the molten steel to oxidize the present impurities, so that these oxidized impurity compounds combine with the lime added during the refining process, forming a layer of molten slag that develops on the surface of the furnace (TEO et al., 2020). The still-liquid slag, after chemical adjustments, is removed from the furnace and poured into specific containers, and later the material is transferred to an external area, where it is cooled by water spraying (PENTEADO et al., 2019).

Arribas et al. (2015) describe that, after being removed from the furnace and cooled, EAF slag becomes a rocky, rigid, black-colored material, composed mainly of calcium, iron, and silicon oxides, as well as containing aluminum, magnesium, manganese, and phosphorus oxides.

2. ACCELERATED CARBONATION

Accelerated carbonation uses CO_2 gas to react with oxides, primarily calcium and magnesium, present in a material. The reaction of CO_2 with the oxides in the material creates carbonated products, which provide greater strength and chemical stability after the process (LI et al., 2021).

Biava et al. (2023) highlight that the carbonation of alkaline industrial wastes is an urgent issue, aimed at reducing CO_2 emissions and promoting a circular economy. Ko et al. (2015) explain that artificial methods, such as accelerated carbonation, can speed up the chemical reactions associated with free CaO, improving the volumetric stability of BOF slags and expanding their potential applications. Chang et al. (2020) investigated accelerated carbonation as an innovative method for CO_2 capture and storage, similar to natural weathering processes, where Ca/Mg silicates react with carbon dioxide to form calcium or magnesium carbonates. During mineral carbonation, CO_2 can react with alkaline minerals and form stable carbonate precipitates, which has been the focus of many researchers in recent years (LI et al., 2021).

Meng et al. (2022) describe carbon sequestration in construction materials as a promising strategy to reduce greenhouse gas emissions and mitigate climate change, while also improving the durability and mechanical properties of concrete. Yi et al. (2021) emphasizes that accelerated carbonation, which involves the capture of CO_2 in the form of carbonates, is currently a safe and effective way to carry out carbon sequestration.

2. 1. Methods of accelerated carbonation

Carbonation treatments can be classified into two main methods: Gas-Solid Carbonation (or dry carbonation) and Aqueous Carbonation (or fluid-solid carbonation) (LI and WU, 2022). According to Biava et al. (2024), the gas-solid method resembles the natural weathering process, where calcium and magnesium oxides and hydroxides react with CO_2 to form calcite ($CaCO_3$), magnesite ($MgCO_3$), and/or dolomite ($CaMg(CO_3)_2$).

This type of carbonation can be understood as a mineral CO_2 sequestration process carried out under a controlled relative humidity condition (LI and WU, 2022). Furthermore, the gas-solid method requires higher temperatures due to its slower reaction kinetics compared to aqueous carbonation (DRI, 2023). Therefore, this process is conducted dry, typically in autoclave chambers, with the humidity defined in the sample. Figure 02 shows a schematic of the gas-solid process, where the molding water participates in the CO_2 diffusion process into the matrix, forming a film around the slag particles and providing an environment for CO_2 solution.

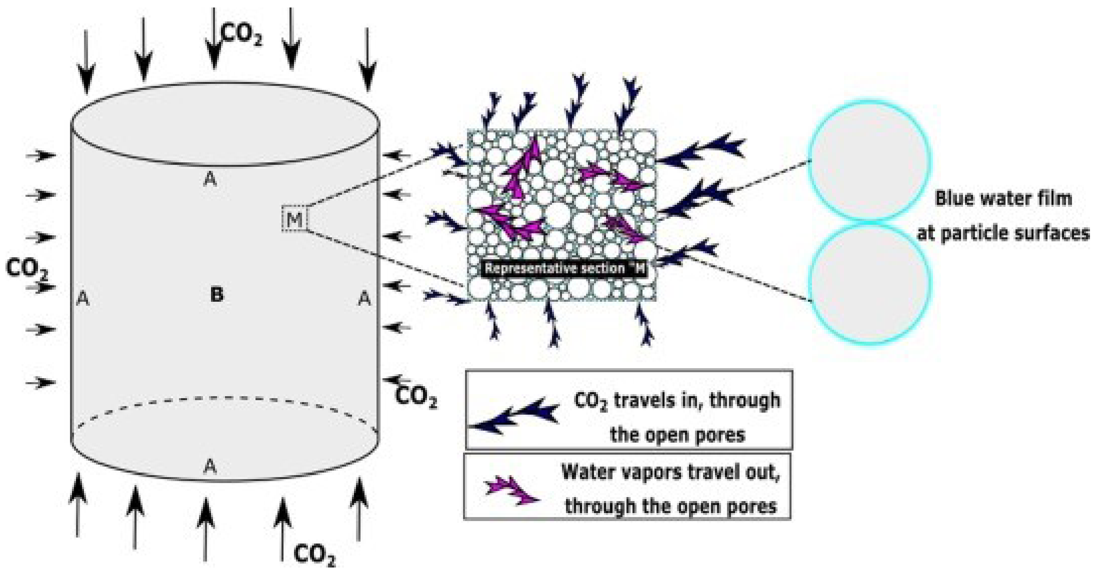

Figure 2: CO_2 diffusion process in the accelerated carbonation process through water film.
Source: Srivastava et al. (2021).

In aqueous carbonation, the samples are exposed to water with CO_2, allowing the reactions to occur in the liquid phase. Compared to gas-solid carbonation, the liquid-solid method tends to be more efficient, as continuous agitation increases the mass transfer rate and the efficiency of the reactions (PU et al., 2023).

Given the difference in the CO_2 diffusion approaches in the matrix between the two methods mentioned, there is also a need for the proper arrangement of equipment to ensure the effectiveness of the process. Figure 03 shows the typical arrangements for the two types of processes discussed.

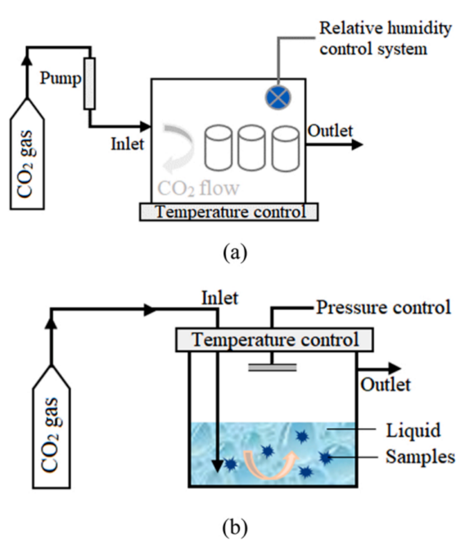

Figure 3: Equipment arrangement for the gas-solid and liquid-solid accelerated carbonation process.
Source: EUROFER (2020).

As shown in Figure 03, the accelerated carbonation process shares similarities between the equipment used in both types of processes. Both the gas-solid carbonation method (Figure 03-a) and the liquid-solid carbonation method (Figure 03-b) require a setup that includes a chamber to receive gases from the CO_2 cylinder, with control over pressure and temperature. The main difference observed is in the exposure of the water bodies to a specific humidity in the gas-solid method, while in the accelerated liquid-gas carbonation technique, the test specimens are immersed in water where CO_2 is dissolved.

2.2. Factors influencing accelerated carbonation

The accelerated carbonation process involves several parameters that can be adjusted to optimize the characteristics of the final sample. As highlighted by Yi et al. (2021), factors such as particle size, rotation speed, gas flow rate, pressure, temperature, reaction time, and the liquid-solid ratio influence the carbonation of slag.

In recent years, research on accelerated carbonation in slags has focused on understanding how test conditions affect carbonation efficiency. In a review of the process, Srivastava et al. (2021) note that most recent studies conducted carbonation experiments lasting between 2 and 24 hours, finding that the strength gain is significant between 2 and 4 hours after the start of the process.

Temperature also plays an important role in increasing the strength of carbonated slags but needs to be adjusted to factors such as sample humidity and pressure, which enhance CO_2 permeability in the material. Ko et al. (2015) observe that although increasing temperature can promote carbonation reactions, it also reduces CO_2 solubility in water, which can decrease the carbonation rate at higher temperatures. Additionally, as the temperature increases, carbonation rises to a maximum point, after which it starts to decrease with further temperature increases (SRIVASTAVA et al., 2021).

To ensure the efficient formation of carbonated compounds, it is essential to adjust the temperature range during the accelerated carbonation process. Yi et al. (2021) explain that high temperatures can destabilize HCO_3-, resulting in lower concentrations of HCO_3- and consequently lower carbonation. Srivastava et al. (2021) suggest that the ideal temperature range for hardening/carbonation of steelmaking slags is between 50 and 80°C.

Furthermore, the gas pressure used in the process has a significant influence on the solubility and strength of the compounds formed in the reaction. Yi et al. (2021) explains that increasing the CO_2 pressure favors carbonation, although the solubility of calcite also increases considerably with higher CO_2 pressures.

2. 3. Effect of accelerated carbonation on the microstructure of slag

The analysis of the microstructure of samples containing steel slags subjected to the accelerated carbonation process has been crucial for improving the activation method. This is because, in addition to the particularities related to particle morphology, each type of slag presents relevant differences due to variations in oxide concentration in its composition.

Mo et al. (2019), using scanning electron microscopy (SEM) to analyze the preparation of calcium carbonate binders through the activation of steelmaking slag with CO_2, observed a significant reduction in the total pore volume in the carbonated slag paste compared to the non-carbonated paste. However, it was found that a higher water-to-binder ratio increased the pore volume in the steelmaking slag paste.

In the same study by Mo et al. (2019), it was identified that certain particles, such as calcium silicate and some portions of magnesian slag, which did not undergo carbonation or hydration, remained attached to the carbonated products. Additionally, it was observed that, in some cases, uncarbonated or unhydrated periclase particles (magnesium oxide mineral) were surrounded by the dense substance of the carbonation products.

Librandi et al. (2019) conducted leaching and carbonation tests on steel slag samples of the BOF and EAF types to evaluate the progression of the carbonation reaction under different pressures and reaction times. In the tests, a configuration was used that exposed the samples to 100% CO_2 at a temperature of 50 °C and pressures of 1.3 or 10 bar, varying the time between 15 minutes and 4 hours. The results showed that the EAF slags exhibited higher compressive strength compared to the BOF slags, despite lower CO_2 absorption. The authors attributed this performance to differences in the microstructure formed in each type of slag, as distinct compositions generate different phases that influence carbonation.

Weide (2024), when evaluating the effects of different temperatures, pressures, and process time on the accelerated carbonation of an EAF-based binder, observed changes in the morphology of the slag after the process. Furthermore, the author noted the densification of the carbonation products generated by the process, particularly in the fracture zone of the test specimens.

2. 4. Final considerations

Accelerated carbonation demonstrates great potential for enhancing the use of electric arc furnace (EAF) slag as a material of interest in the construction industry. The process promotes the formation of stable carbonated products, contributes to the densification of the microstructural matrix, and improves the chemical stability of the material, attributes that expand its applicability and durability in various applications. Additionally, the use of CO_2 as an activating agent makes the process an environmentally sustainable approach, as it not only adds value to an industrial waste but also contributes to the mitigation of carbon emissions.

This scenario opens new possibilities for the development of innovative and sustainable materials in construction, aligning with the demand for solutions that integrate technical efficiency and environmental responsibility. Thus, accelerated carbonation represents a promising alternative for the reuse and valorization of industrial waste, enhancing its functionality and promoting a circular economy in the sector.

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HOW TO CITE THIS ARTICLE:

WEIDE, H.; LÜBECK, A.; VARGAS, A. S.; NETO, A. B. S. S.; BERTUOL, D. A. Use of eletric arc furnace steelmaking slag in accelerated carbonation. **MIX Sustentável**, v.11, n.2, p.165-175. ISSN 2447-3073. Disponível em: <http://www.nexos.ufsc.br/index.php/mixsustentavel>. Acesso em: _/_/_.
SUBMITTED ON: 20/01/2025
ACCEPTED ON: 15/06/2025
PUBLISHED ON: 14/10/2025
RESPONSIBLE EDITORS: Lisiane Ilha Librelotto e Paulo Cesar Machado Ferroli

Record of authorship contribution:
CRediT Taxonomy (http://credit.niso.org/)

HW: conceptualization, data curation, formal analysis, investigation, methodology, resources, validation, visualization, writing - original draft and writing - review & editing.

AL: conceptualization, formal analysis, funding acquisition, methodology, project management, supervision, validation and writing - review & editing.

ASV: conceptualization, funding acquisition, methodology, project management, supervision, validation and writing - review & editing.

ABSSN: validation and writing - review & editing.

DAB: project management, supervision, validation and writing - review & editing.

Conflict declaration: nothing to declare.