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Characterization Of The By-Product Blast Furnace Slag Before Its Application In The Manufacture Of Blast Furnace Portland Cement

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Abstract:
Background: *The cement industry is a significant contributor to greenhouse gas emissions. In 2022, Brazil emitted approximately 580 kg of CO_2 per ton of cement produced, slightly below the global average of 608 kg/t (SNIC, 2023). Initiatives like the Roadmap Net Zero aim to achieve carbon neutrality in the sector by 2050 (SNIC, 2023), driving the need for sustainable alternatives. A promising solution is the partial replacement of clinker with supplementary cementitious materials, such as granulated blast furnace slag (GBFS). This study focuses on characterizing GBFS from a steel plant in western Maranhão, Brazil, to assess its suitability for producing blast furnace Portland cement (CP III-E 32) according to the NBR 16697 standard (ABNT, 2018).*
Materials and Methods: *We subjected the slag, a byproduct of pig iron production, to physical, chemical, mineralogical, and environmental analyses. These tests evaluated its compatibility with clinker and gypsum in cement formulations. We followed standardized protocols to determine particle size distribution, chemical composition (via XRF), mineral phases (XRD), and pozzolanic activity. The results were compared with the requirements for CP III-E 32 cement.*
Results: *The characterized slag exhibited favorable properties, including high amorphous content (indicating reactivity) and chemical composition within the limits for GBFS (CaO/SiO_2 ratio ~1.2, Al_2O_3 ~12%). Pozzolanic activity index exceeded 75% at 28 days, meeting normative criteria. Environmental tests confirmed low heavy metal leaching potential. These findings support its use as a clinker substitute in proportions up to 50% for CP III-E 32 production.*
Conclusion: *The blast furnace slag from Maranhão demonstrated technical viability for producing sustainable cement, reducing clinker content without compromising performance. This approach aligns with global decarbonization goals, offering a practical pathway to lower CO_2 emissions in the construction sector.*
Key Word: *Blast Furnace Slag; Supplementary Cementitious Materials; Clinker; Portland Cement; Carbon Emissions.*

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I. Introduction

Blast Furnace Slag (BFS), a byproduct of pig iron production, is the focus of this study. It originates from a steel plant located in Açailândia, Maranhão, Brazil, which is part of an expanding industrial hub driven by mining and steel production. According to Almeida Júnior et al. (2024), mining in the region began in the 1980s, with five industries stimulated by iron extraction in the Carajás Mountains, located 371 km away. The studied plant is situated in Açailândia (Figure 1), 4.3 km from BR-222 highway, playing a key role in the production and utilization of this byproduct.

Consequently, Açailândia serves as a multimodal integration hub, connecting railway, road, and port systems, facilitating industrial output flow. Its strategic location, approximately 560 km from the Port of Itaqui—one of Brazil's largest ports—ensures efficient export and import operations, reinforcing its importance in the national logistics landscape.

Regarding road infrastructure, Açailândia benefits from two major connections. The BR-222 links the municipality to western Maranhão, connecting strategic areas for regional development. Simultaneously, the BR-010, known as the Belém-Brasília Highway, crosses the city and enables efficient cargo transportation to various regions of the country.

Figure 1: Map showing the collection location of the Blast Furnace Slag byproduct

Source: Adapted from Google Earth, 2025

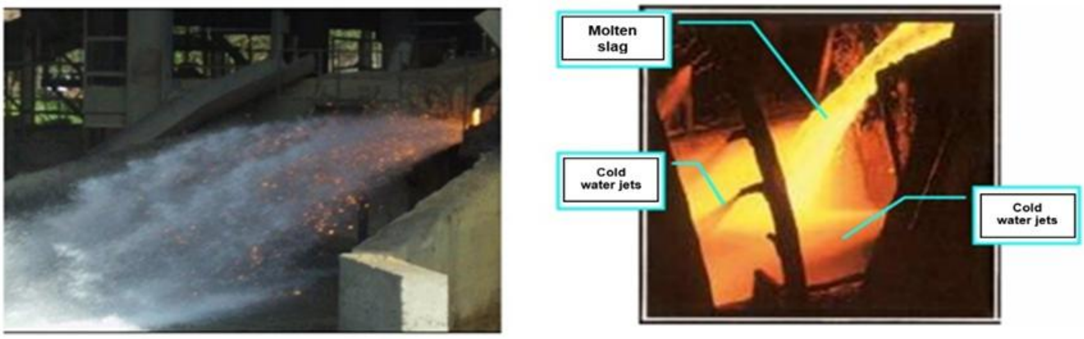
II. Material And Methods

Materials

Blast Furnace Slag (BFS) is a byproduct generated during pig iron production in steelmaking units called blast furnaces. The process begins with charging the blast furnace with iron ore, coke, and fluxes such as limestone and dolomite. The burning coke reaches temperatures exceeding 1500°C, promoting ore melting and impurity separation. Reactions between fluxes and impurities result in liquid slag formation, which floats on molten pig iron due to its lower density (THOMAZ, 2012; PIMENTEL et al., 2017).

After separation, molten iron is directed to molds for steel production while slag is transferred to large containers and subsequently poured. Slag cooling follows distinct techniques that determine its properties. Rapid cooling with water jets produces granulated slag (Figure 2), while slow air cooling yields crystallized slag (THOMAZ, 2012).

Figure 2 : BFS cooling with high-pressure water jets



Source: Adapted from CVB, 2024; THOMAZ, 2012

Although BFS chemical composition remains unchanged after cooling, its physical properties and reactivity vary according to the cooling process. Rapidly cooled granulated slag exhibits a glassy, amorphous structure with high reactivity, unlike crystallized slag. These characteristics make granulated blast furnace slag widely recognized as suitable for cement compositions (DINA, 2014; ÖZBAY et al., 2016; Liu et al., 2024).

The chemical composition of BFS, though subject to variations depending on raw materials and furnace operating conditions, consists predominantly of calcium oxide, silicon dioxide, aluminum oxide, and magnesium oxide (Gomes, Tavares & Correa, 2020). Furthermore, this slag can be classified as acidic or basic depending on its oxide ratios. Acidic BFS shows silica oxide (SiO_2) predominance over calcium oxide (CaO), resulting in lower alkaline reactivity and restricted cement applications. In contrast, basic BFS with higher calcium oxide concentration demonstrates elevated reactivity, making it widely used in the cement industry (Ahmad et al., 2022).

According to the Indian Bureau of Mines (2018), slag quantities generated during pig iron and steel production vary substantially, being primarily influenced by raw material composition and furnace type. Typically, with iron ore grades between 60-65%, blast furnace slag production ranges from 300-540 kg per ton of pig iron. In steelmaking, slag generation is approximately 150-200 kg per ton of liquid steel. For lower-grade ores, slag production can reach up to one ton per ton of pig iron. Proportionally, steel slag represents about 20-30% of the country's crude steel production mass.

Blast Furnace Slag plays a fundamental role in construction, being used not only in cement production but also as paving aggregate and concrete component. In cement manufacturing, its application as partial Portland clinker substitute is strategic, preserving natural resources while significantly reducing CO_2 emissions - construction's major environmental impact contributor. According to Mancini et al. (2021), partial clinker replacement with supplementary materials like pozzolans, calcined clays, and industrial byproducts (including fly ash and ground granulated blast furnace slag) constitutes an efficient approach to mitigate environmental impacts without compromising mechanical performance or durability. The following materials were employed in this research:

• **Clinker**

The clinker used was provided by a cement plant located in Açailândia, Maranhão state, Brazil. This material was specifically supplied for the purposes of the present study.

• **Gypsum**

The gypsum (hydrated calcium sulfate) utilized was also furnished by the aforementioned cement plant, reinforcing the technical-scientific partnership established for this investigation.

• **Blast Furnace Slag (BFS)**

Similarly to the materials described above (clinker and gypsum), the blast furnace slag was likewise supplied by the cement plant in Açailândia, MA. It should be noted that all materials used in this study are routinely employed by this company in the production of CP III-type cement.

Methods

For the characterization of the blast furnace slag (BFS) used in this research, tests were conducted on samples in two conditions: "Raw" BFS (as collected directly from the factory) and Processed BFS (treated by the author at UFPA's laboratory).

We performed tests on raw BFS according to the standards specified in Table 1 while the analyses conducted after the slag grinding and sieving process adhered to the norms presented in Table 2.

Table 1 : Standards used for characterization tests of raw BFS

Standards for Blast Furnace Slag Characterization ("Raw Condition")		
Characterization	**Test**	**Method**
Physical	Particle size distribution	NBR 17054 (ABNT, 2022)
	Specific gravity determination	NBR 16917 (ABNT, 2021)
Pozzolanic activy evaluation	Pozzolanic Activity Index (PAI) with cement	NBR 5752 (ABNT, 2014)
	Pozzolanic Activity Index (PAI) with lime	NBR 5751 (ABNT, 2015)

Source: Author, 2025

Table 2 : Standards Used in Characterization Tests of BFS After Grinding

Standards for Characterization of Processed Blast Furnace Slag		
Characterization	**Test**	**Method**
Physical	Fineness (Blaine method)	NBR 16372 (ABNT, 2015)
	Consistency index	NBR 13276 (ABNT, 2016)
	Specific gravity	NBR NM 23 (ABNT, 2000)
	Laser granulometry	Internal procedure
Chemical	X-ray fluorescence spectrometry (XRF)	NBR 14656 (ABNT, 2023)
	Hydraulicity	NBR 16697 (ABNT, 2018)
Pozzolanic Activity Evaluation	Pozzolanic Activity Index (PAI) with lime	NBR 5751 (ABNT, 2015)
	Pozzolanic Activity Index (PAI) with cement	NBR 5752 (ABNT, 2014)
Mineralogical	X-ray diffraction (XRD)	Internal procedure
Environmental	Leaching tests	NBR 10005 (ABNT, 2004)
	Solubility tests	NBR 10006 (ABNT, 2004)
	Waste classification	NBR 10004 (ABNT, 2004), Annex F

Source: Author, 2025

III. Result

Sample Preparation

The characterization process of the blast furnace slag (BFS) used in this research was divided into two stages. Initially, samples were separated for testing both in the "raw" condition (Figure 3) and processed condition (Figure 4). The processed BFS refers to a sample that underwent laboratory treatment to acquire the necessary characteristics for use as a supplementary cementitious material in the CP III cement analyzed in this study.

Figure 3 : Raw blast furnace slag

Source: Author, 2025

Figure 4 : Processed Blast Furnace Slag

Source: Author, 2025

We initiated the beneficiation process by dry grinding the slag at the Experimental Laboratory of Construction Materials (LEMAC) of UFPA. A ball mill was used, equipped with a porcelain jar and balls, brand EMIC, operating at 12 rpm with a capacity of 7 liters (Figure 3.3.C). After grinding, the material had a powdery appearance and was sent to the next stage of beneficiation. This subsequent stage was also conducted at LEMAC and consisted of sieving the ground material using a No. 200 mesh sieve (75 µm).

Figure 5 : Ball mill equipment belonging to the LEMAC/UFPA laboratory

Source: Author, 2025

In addition to EAF slag, the clinker and gypsum used in the formulation of the aforementioned cement were also subjected to the same beneficiation procedure. The equipment rotation speed remained at 12 rpm for all materials. The grinding media load also remained the same, consisting of 5 kg of balls for every 1 kg of material, with the proportion divided into 2/3 small balls and 1/3 large balls (BARROS, 2025). However, the grinding times varied for each material:

Clinker

For the grinding of clinker, a time of 3 hours was established. This duration was sufficient to reach the desired particle size distribution, that is, particles with a diameter equal to or smaller than that of cement, passing through the 75 µm sieve, as described by Farias et al. (2023).

Gypsum

For the grinding of gypsum, a time of 30 minutes was used, as suggested by Farias et al. (2023), who indicated that this duration was sufficient to achieve the desired fineness suitable for use in cement formulation.

Granulated blast furnace slag

The grinding time adopted for the granulated blast furnace slag was also 3 hours, based on the study by Farias et al. (2023), which showed that this duration was sufficient for the material to reach a particle size equal to or smaller than that of Portland cement.

Characterization of Raw EAF Slag

Physical Characterization

Particle Size Distribution

In this study, slag sourced from an industry located in the state of Maranhão was used. After collecting the material, we conducted characterization tests on the raw EAF slag. One of the first tests was the determination of the particle size distribution, carried out at the laboratory of the Federal Institute of Pará – Belém Campus. We conducted the test according to the criteria established by the NBR 17054 standard (ABNT, 2022), and the results are presented in Table 3.

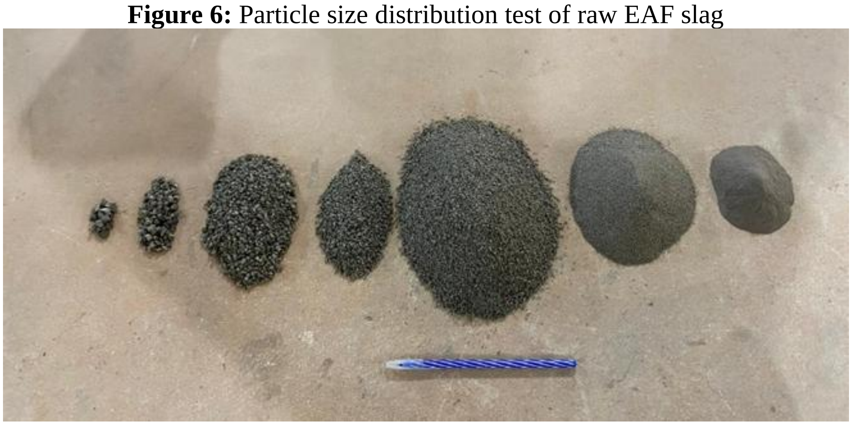
Table 3: Particle Size Distribution Test of Raw EAF Slag

Granulometric Composition of Raw EAF Slag						
Sieve Opening (mm)	**Retained Mass (g)**	**Retained Percentage (%)**	**Cumulative Percentage (%)**	**Passing Percentage (%)**	**Maximum Diameter (mm)**	**Fineness Modulus**
6.3	5.78	0.39	0.39	99.61	6.3	2.08
4.75	22.11	1.48	1.87	98.13		
2.36	175.73	11.78	13.64	86.36		
2.00	100.29	6.72	20.37	79.63		
0.60	845.15	56.63	77.00	23.00		
0.15	275.00	18.43	95.43	4.57		
Pan (Bottom)	68.23	4.57	100.00	0.00		

Source: Author, 2025

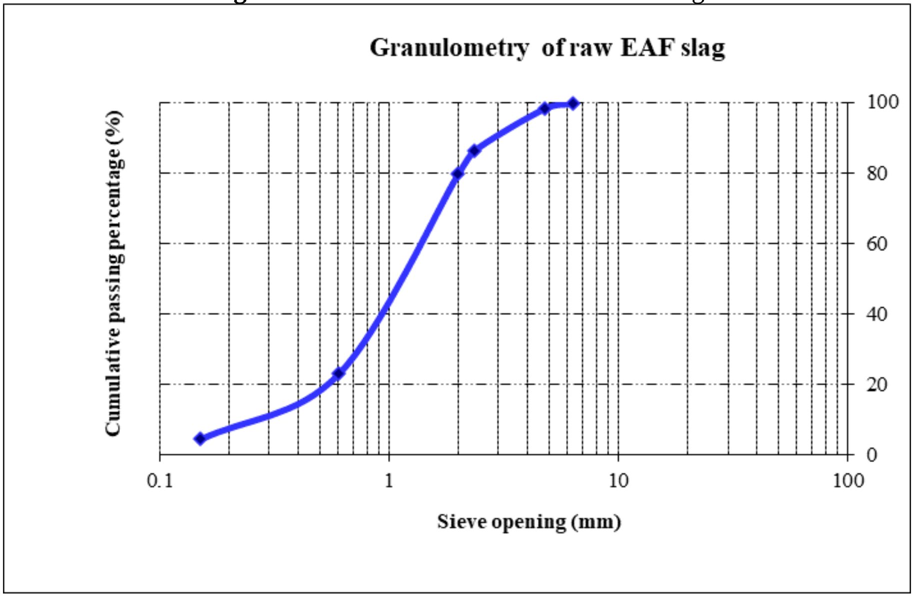
After the aforementioned data collection, it was possible to generate a graph using the information from the test, allowing for a better analysis of whether the particle size distribution of the raw EAF slag is uniform, as illustrated in Figure 7 and in the photograph shown in Figure 6.

Figure 6: Particle size distribution test of raw EAF slag



Source: Author, 2025

Figure 7: Particle size distribution of raw slag



Source: Author, 2025

Based on the experimental results obtained in the laboratory, presented in Table 3, the fineness modulus of the slag sample was calculated in accordance with the criteria established by the NBR 17054 standard (ABNT, 2022). It was also possible to determine the maximum particle diameter of the sample. The measured data indicate that the slag analyzed in this study has a fineness modulus of 2.08 and a maximum diameter of 6.30 mm.

Determination of Specific Gravity

To determine the specific gravity of the raw EAF slag, the NBR 16917 standard (ABNT, 2021) was used. The test was conducted at the laboratory of the Federal Institute of Pará, and the specific gravity was determined to be 2.54 g/cm³ for the raw EAF slag.

Evaluation of Pozzolanic Activity

Pozzolanic Activity Index (PAI) with Lime

We performed the Pozzolanic Activity Index (PAI) test with lime following the procedures established by the NBR 5751 standard (ABNT, 2015), at the laboratory of the Federal Institute of Pará. The main objective was to verify whether the studied blast furnace slag, in its raw state, shows reactivity with calcium hydroxide, which could indicate the occurrence of secondary reactions during the cement hydration process.

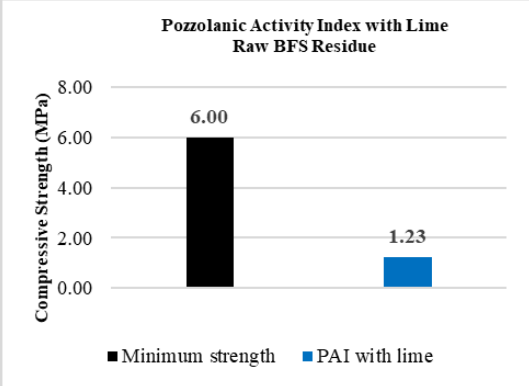
As illustrated in the graph shown in Figure 8, it can be observed that the minimum strength required by the standard, 6.00 MPa, was not achieved. The raw EAF slag sample showed an axial compressive strength of only 1.23 MPa, indicating the absence of significant pozzolanic activity in its raw form.

Pozzolanic Activity Index (PAI) with Cement

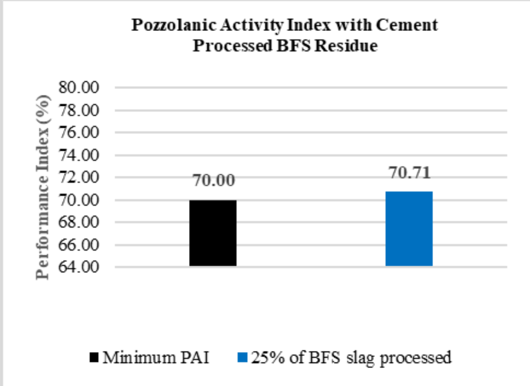
The PAI test with cement was conducted following the parameters of the NBR 5752 standard (ABNT, 2014), and carried out at the laboratory of the Federal Institute of Pará. The purpose of this test is to assess the mechanical performance index at 28 days, that is, to determine whether the analyzed material contributes to strength gain at 28 days in the tested mixture.

As shown in the graph in Figure 8, in the PAI test with cement, the raw EAF slag sample also did not meet the normative requirements. The average compressive strength obtained was 45.67 MPa, corresponding to approximately 65.24% of the minimum strength required by the standard, which is 70 MPa.

Figure 8: Graphs showing pozzolanic activity test results: (i) Pozzolanic Activity Index with lime using raw blast furnace slag; (ii) Pozzolanic Activity Index with cement using raw blast furnace slag



(i)



(ii)

Source: Author, 2025

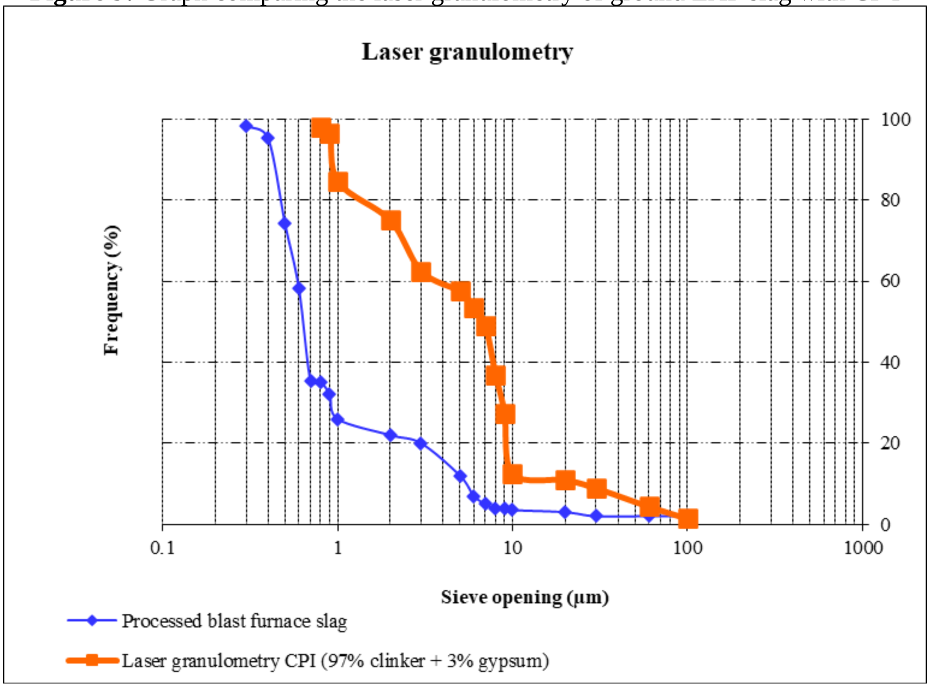
Characterization of Processed EAF Slag
Physical Characterization
Specific Gravity

The specific gravity test was conducted according to NBR NM 23 (ABNT, 2000) at the laboratory of the Federal Institute of Pará, Belém Campus. In this test, the specific gravity of the processed EAF slag was determined to be 3.33 g/cm³.

Laser Granulometry

This test was carried out at the laboratory of a cement factory located in Currais Novos, Rio Grande do Norte. Figure 9 presents a graph generated from the data obtained in this test. The graph shows a comparison between the particle size distribution of the processed EAF slag and that of a Portland cement type CP I.

Figure 9: Graph comparing the laser granulometry of ground EAF slag with CP I



Source: Author, 2025

Determination of Specific Surface Area by the Blaine Method

The Blaine method was used in this study to determine the specific surface area of the ground EAF slag. According to the standard that supports this test, NBR NM 76 (ABNT, 1996), the minimum required value for a material to be considered suitable for classification as a cementitious material is equal to or greater than 2600 cm²/g. The EAF slag analyzed in this study achieved a specific surface area of 4350 cm²/g, as shown in Table 4.

Table 4: Test result for determining the fineness of EAF slag

Fineness Determination by the Air Permeability Method	
	Specific Surface Area (cm²/g)
Standard Limit	**≥ 2600**
Ground Pig Iron Slag	**4350**

Source: Author, 2025

Chemical Characterization

X-ray Fluorescence Spectrometry (XRF)

The X-ray fluorescence (XRF) test was carried out in accordance with NBR 14656 (ABNT, 2023), at the laboratory of a cement factory located in Currais Novos, Rio Grande do Norte. Regarding the chemical characterization, the XRF test revealed the presence of the elements listed in Table 5, along with their respective percentages. A predominance of silica (SiO_2) was observed, with a content of 40.48%.

Table 5: Chemical composition from the XRF test of EAF slag

X-Ray Fluorescence					
Chemical Components					
SiO2 %	**Al2O3 %**	**Fe2O3 %**	**CaO %**	**MgO %**	**SO3 %**
40,48%	14,90%	4,57%	33,80%	4,48%	0,13%

Source: Author, 2025

Hydraulicity

The classification of slag is based on the ratio between the oxides of Calcium, Magnesium, and Aluminum relative to Silicon oxide. Hydraulicity was calculated according to NBR 16697 (ABNT, 2018) using the data from the XRF test. The result of the test showed a hydraulicity index of 1.28%.

Consistency Index

This test was conducted at the laboratory of the Federal Institute of Pará, following the guidelines of NBR 13276 (ABNT, 2016). The test resulted in a flow diameter of 16.5 cm using 200 ml of water. No bleeding was observed in the mortar, and it exhibited good cohesion, indicating that in the fresh state, its components did not segregate and remained homogeneous, as shown in Figure 10.

Figure10: Consistency index test on the processed EAF slag sample (i) mortar molded in the truncated cone (ii) mortar after flow table drops

(i) (ii)

Source: Author, 2025

Evaluation of Pozzolanic Activity

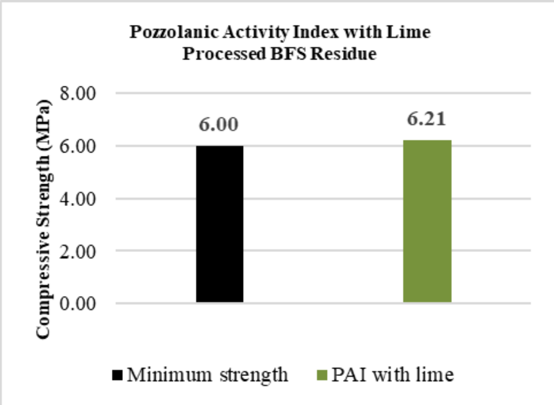
Pozzolanic Activity Index (PAI) with Lime

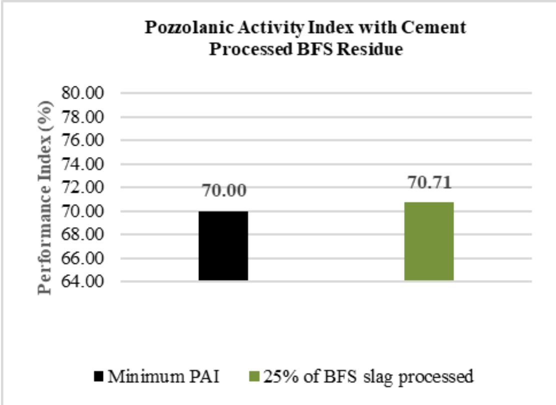
The PAI test with lime was conducted in accordance with ABNT NBR 5751:2015 at the laboratory of the Federal Institute of Pará. The objective was to analyze whether the processed EAF slag reacts with calcium hydroxide, potentially leading to secondary reactions during cement hydration. The minimum required strength at 28 days for this test is 6.0 MPa, and the sample with processed EAF slag reached 6.21 MPa at 28 days, as shown in the graph in Figure 11.

Pozzolanic Activity Index (PAI) with Cement

The PAI test with cement was conducted according to the parameters of NBR 5752 (ABNT, 2014) at the laboratory of the Federal Institute of Pará, using a sample of processed EAF slag. The objective of this test is to assess whether the studied material contributes to strength gain at 28 days when included in the tested mixture. According to the normative parameters, the minimum performance index for this test must be 70.00%. At 28 days, the mixture containing processed EAF slag achieved a performance of 70.71%, as shown in Figure 11.

Figure11: Graphs showing pozzolanic activity test results: (i) Pozzolanic Activity Index with lime using beneficiated blast furnace slag ; (ii) Pozzolanic Activity Index with cement using beneficiated blast furnace slag





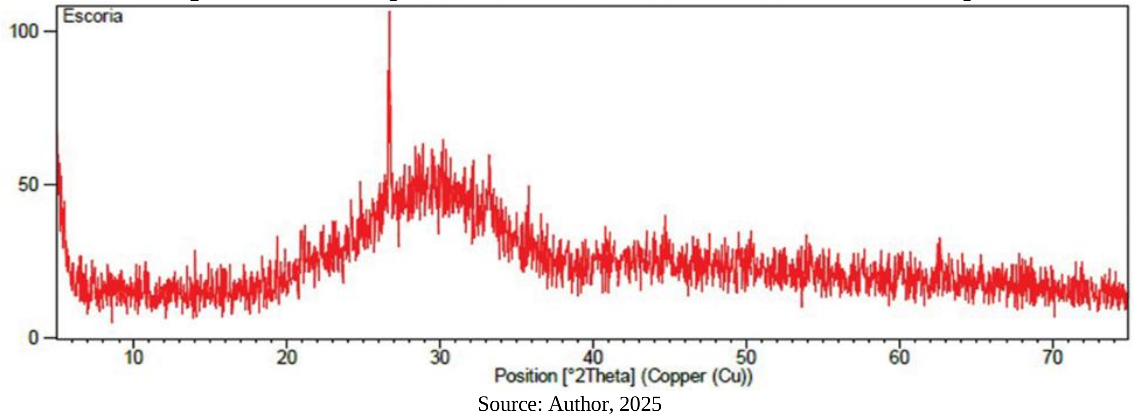
Source: Author, 2025

Mineralogical Characterization

X-ray Diffraction (XRD)

The mineralogical characterization of the materials was obtained through X-ray Diffraction (XRD), as shown in Figure 12, to determine the crystalline structure. The test was conducted using a BRUKER D2 Phaser device with a copper (Cu) Kα radiation anode (λ = 1.54184 Å), equipped with a Lynxeye detector (1D mode). The equipment operated at 30 kV and 10 mA, with a power output of 300 W. The scan range was from 5° to 75° 2θ, with a step size of 0.02° and a step time of 0.2 s, using the powder method. The test was performed at the Mineralogy Laboratory of the Faculty of Materials Engineering at the Federal University of the South and Southeast of Pará (Unifesspa).

Figure 12: Mineralogical Characterization, XRD Test, Processed EAF Slag



Source: Author, 2025

Environmental Characterization

Leaching

We conducted the leachate extraction test following the recommendations of NBR 10005 (ABNT, 2004), at the laboratory of a cement factory located in Currais Novos, Rio Grande do Norte. The objective of this test is to assess the potential for contamination by heavy metals or other toxic compounds. The results of the test are shown in Table 6. After analysis, it was verified that the regulatory limits were met.

Table 6: Environmental Test – Leachate Extraction on a Sample of Processed EAF Slag

Processed Blast Furnace Slag			
NBR 10.005 – Procedure for Obtaining Leachate Extract from Solid Waste			
Element	**Permitted Concentration (mg/L) (According to Annex F of NBR 10.004)**	**Measured Concentration (mg/L)**	**Status**
Cadmium	0.5	0.005	Below Maximum Limit
Copper	-	0.035	The element is not listed in the standard annex
Chromium	5	0.3971	Below Maximum Limit
Iron	-	16.686	The element is not listed in the standard annex
Manganese	-	46.696	The element is not listed in the standard annex
Zinc	-	0.3545	The element is not listed in the standard annex

Source: Author, 2025

Solubility

The solubilized extract test is another assessment included in the environmental analyses. Its purpose is to identify substances that may be released under usage or disposal conditions. The test was conducted in accordance with NBR 10006 (ABNT, 2004) at the laboratory of a cement factory located in Currais Novos, Rio Grande do Norte. The data obtained from the test are presented in Table 7, and all analyzed elements were found to be below the regulatory limits.

Table 7: Environmental Test – Solubilized Extract from a Sample of Processed EAF Slag

Processed Blast Furnace Slag			
NBR 10.006 – Procedure for Obtaining Solubilized Extract from Solid Waste			
Element	**Permitted Concentration (mg/L) (According to Annex F of NBR 10.004)**	**Measured Concentration (mg/L)**	**Status**
Cadmium	0	-0.0122	Concentration below the equipment detection limit
Copper	2	-0.0076	Concentration below the equipment detection limit
Chromium	0.1	0.0058	Below Maximum Limit
Iron	0.3	-0.0854	Concentration below the equipment detection limit
Manganese	0.1	0.0065	Below Maximum Limit
Zinc	5	0.1087	Below Maximum Limit

Source: Author, 2025

IV. Discussion

The obtained results demonstrate the potential of beneficiated blast furnace slag (BFS) as a supplementary cementitious material. The beneficiation process of BFS proved effective in improving the material's fineness and specific surface area. According to CUNHA (2022), after beneficiation, the material's reactivity increases, which is supported by its pozzolanic activity indices—both with lime (6.21 MPa) and cement (70.71%)—exceeding the limits established by the Brazilian standards NBR 5751 and NBR 5752.

The chemical composition of the beneficiated BFS, with its high silica content (40.48%) and predominantly amorphous structure, promotes the formation of hydrated compounds (C-S-H), essential for cement's mechanical strength development. This indicates that slag beneficiation contributed to the activation of latent phases, as noted by Lothenbach et al. (2011) and Boeira & Beck (2007).

Our environmental tests (leaching and solubilization) confirmed that beneficiated BFS poses no significant contamination risks, complying with the limits set by NBR 10004. From a mineralogical perspective, the absence of crystalline peaks in the XRD analysis reinforces the predominance of glassy phases, crucial for its reactivity in cementitious systems.

In summary, the results demonstrate that beneficiated slag serves as both a sustainable and technically viable alternative for partial clinker replacement in CP III-type cements. This approach not only reduces CO_2 emissions but also advances circular economy practices within the cement industry.

V. Conclusion

The beneficiated blast furnace slag analyzed in this study exhibits suitable physical, chemical, mineralogical, and environmental characteristics for its application as a supplementary cementitious material in the production of Portland cement CP III-E 32.

The high fineness, specific surface area exceeding normative requirements, and amorphous structure contributed to the material's satisfactory technical performance, as evidenced by pozzolanic activity tests. Additionally, environmental stability was confirmed, ensuring safe usage.

Thus, the beneficiated BFS (blast furnace slag) can be considered a promising alternative to reduce clinker demand and associated CO_2 emissions in cement production, supporting more sustainable practices in civil construction. We recommend future studies for industrial-scale validation and optimization of slag percentages in blast furnace Portland cement manufacturing.

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