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IMPORTANCE OF THE CHARACTERIZATION OF COAL-DERIVED ASH FOR APPLICATION IN THE ARCHITECTURE, ENGINEERING, AND CONSTRUCTION INDUSTRY

IMPORTÂNCIA DA CARACTERIZAÇÃO DE CINZA ORIUNDA DO CARVÃO MINERAL PARA APLICAÇÃO NA INDÚSTRIA DA ARQUITETURA, ENGENHARIA E CONSTRUÇÃO

IMPORTANCIA DE LA CARACTERIZACIÓN DE CENIZAS PROVENIENTES DEL CARBÓN MINERAL PARA SU APLICACIÓN EN LA INDUSTRIA DE LA ARQUITECTURA, LA INGENIERÍA Y LA CONSTRUCCIÓN

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ABSTRACT
The growing demand for sustainable solutions in the Architecture, Engineering, and Construction (AEC) industry encourages the use of residues from industrial processes as alternative materials to Portland cement—whose production is highly CO_2-emissive—or in the manufacture of cementitious matrices. Among these residues, ashes resulting from the combustion of mineral coal in thermoelectric power plants stand out, as they represent a significant environmental liability. In this context, the present study aimed to chemically, mineralogically, and morphologically characterize bottom ash generated at the Pecém Thermoelectric Power Plant (Ceará, Brazil) after beneficiation, in order to identify potential applications for this processed residue. The methodological procedures included ash beneficiation through granulometric fragmentation and sieving; determination of chemical composition by X-ray fluorescence; identification of mineralogical composition by X-ray diffraction; and morphological analysis by scanning electron microscopy. The results showed that the beneficiated coal bottom ash is rich in SiO_2, Al_2O_3, and Fe_2O_3, meeting the chemical requirements of NBR 12653 for classification as a Class C pozzolan. In addition, the presence of an amorphous halo in the diffractogram and a spherical morphology with vitreous, friable particles confirmed its pozzolanic potential. Therefore, the beneficiated bottom ash presents suitable characteristics for partial replacement of Portland cement in mortars, concretes, and

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other cementitious matrices, contributing to the reduction of environmental impacts and to the achievement of sustainable production and consumption targets established in Sustainable Development Goal 12.

Keywords: Bottom Ash. Pozzolanic Material. Sustainability in Civil Construction.

RESUMO

A crescente demanda por soluções sustentáveis na indústria da Arquitetura, Engenharia e Construção incentiva a utilização de resíduos oriundo de processos industriais como materiais alternativos ao cimento Portland, cuja produção é altamente emissora de CO_2, ou na confecção de matrizes cimentícias. Entre esses resíduos, destacam-se as cinzas advindas da queima do carvão mineral em usinas termelétricas, que representam um passivo ambiental significativo. Neste contexto, a presente pesquisa teve como objetivo caracterizar química, mineralógica e morfologicamente a cinza pesada gerada na Usina Termelétrica do Pecém/CE, após processo de beneficiamento, a fim de identificar quais usos podem ser dados a este resíduo beneficiado. Os procedimentos metodológicos adotados foram beneficiamento da cinza pelos processos de fragmentação granulométrica e peneiramento; determinação da composição química por fluorescência de raios X; obtenção da composição mineralógica por difração de raios X, e identificação da morfologia por microscopia eletrônica de varredura. Os resultados alcançados evidenciaram que a cinza de carvão mineral pesada beneficiada apresenta composição rica em SiO_2, Al_2O_3 e Fe2O3, atendendo aos requisitos químicos da NBR 12653 para classificação como pozolana Classe C, ademais a presença de halo amorfo no seu difratograma e a morfologia esférica com presença de partículas quebradiças vítreas confirmaram o seu potencial pozolânico. Então, a cinza pesada beneficiada possui características adequadas para ser usada em substituição parcial ao cimento Portland em argamassas, concretos e demais matrizes cimentícias, contribuindo para a redução de impactos ambientais e para o cumprimento das metas de produção e consumo sustentáveis previstas no Objetivo de Desenvolvimento Sustentável 12.

Palavras-chave: Cinza Pesada. Material Pozolânico. Sustentabilidade na Construção Civil.

RESUMEN

La creciente demanda de soluciones sostenibles en la industria de la Arquitectura, la Ingeniería y la Construcción (AIC) impulsa el uso de residuos provenientes de procesos industriales como materiales alternativos al cemento Portland—cuya producción es altamente emisora de CO_2—o en la elaboración de matrices cementicias. Entre estos residuos, se destacan las cenizas provenientes de la combustión del carbón mineral en centrales termoeléctricas, que representan un pasivo ambiental significativo. En este contexto, la presente investigación tuvo como objetivo caracterizar química, mineralógica y morfológicamente la ceniza pesada generada en la Central Termoeléctrica de Pecém (Ceará, Brasil), tras un proceso de beneficiamiento, con el fin de identificar los posibles usos de este residuo procesado. Los procedimientos metodológicos incluyeron el beneficiamiento de la ceniza mediante fragmentación granulométrica y tamizado; la determinación de la composición química por fluorescencia de rayos X; la obtención de la composición mineralógica por difracción de rayos X; y la identificación de la morfología mediante microscopía electrónica de barrido. Los resultados evidenciaron que la ceniza pesada de carbón mineral beneficiada presenta una composición rica en SiO_2, Al_2O_3 y Fe_2O_3, cumpliendo los requisitos químicos de la norma NBR 12653 para su clasificación como puzolana de Clase C. Además, la presencia de un halo amorfo en el difractograma y la morfología esférica con partículas vítreas frágiles confirmaron su potencial puzolánico. Por lo tanto, la ceniza pesada beneficiada presenta características adecuadas para su uso como sustituto parcial del cemento Portland en morteros, hormigones y otras matrices cementicias, contribuyendo a la reducción de impactos ambientales y al cumplimiento de las metas de producción y consumo sostenibles previstas en el Objetivo de Desarrollo Sostenible 12.

Palabras clave: Ceniza Pesada. Material Puzolánico. Sostenibilidad en la Construcción Civil.

1 INTRODUCTION

The Architecture, Engineering and Construction (AEC) industry is one of the industries that consumes the most natural resources, including energy, soil and water, in addition to being responsible for significant generation of solid waste and emission of greenhouse gases [1,2]. The growing concern of this sector to become sustainable has driven the development of strategies such as the use of new technologies and sustainable materials, capable of reducing the consumption of these natural resources and promoting the proper management of the waste generated [2].

Portland *cement* is the raw material used in the manufacture of concrete, considered the most used construction material on the planet [3], consequently, cement becomes one of the most used inputs, corresponding to one of the materials that causes great negative impacts on the environment [4]. This corresponds to a hydraulic binder obtained by grinding Portland clinker, resulting from the burning at high temperatures of calcareous and clayey materials [5]. Therefore, its production method results in high carbon dioxide (CO_2) emissions, contributing to global warming and climate change. Corresponding to one of the biggest challenges for the AEC industry to become sustainable, as the need for a large amount of Portland cement goes against environmental sustainability, but the great demand for concrete production requires its use, and consequently CO2 emissions.

In this sense, the partial replacement of Portland cement and the addition of alternative materials from the processing of solid waste to concrete is an effective strategy to reduce CO2 emissions, as they reduce cement consumption, contributing to the AEC industry meeting Sustainable Development Goal (SDG) number 12 by 2030.

At the same time, thermoelectric plants that use coal as an energy source produce tons of waste from the combustion process of this fossil fuel and the improper disposal of this waste represents a relevant environmental problem, as it can cause contamination of soil and surface water, in addition to requiring large areas for deposition [6]. Among the residues are light ash captured in precipitation systems and heavy ash deposited at the bottom of boilers [7].

As these wastes generated by thermoelectric plants have potential for use in cement-based products [6], this research aimed to carry out the chemical, mineralogical and morphological characterization of the heavy ash generated by the Pecém Thermoelectric Power Plant, located in São Gonçalo do Amarante/CE, to identify which uses can be given to this processed waste. The relevance of this research stems from the need to demonstrate that the techniques of characterization of materials are important to contribute to the AEC industry achieving SDG 12 regarding sustainable production and consumption, because the introduction of processed waste in new production chains only occurs correctly when its properties, determined through their characterization, contribute to the durability and technical performance of the alternative materials that will be developed with them.

2 THEORETICAL FOUNDATION

2.1 CHARACTERISTICS THAT MATERIALS MUST HAVE TO BE USED IN THE PRODUCTION OF CONCRETE TO REDUCE THE CONSUMPTION OF PORTLAND CEMENT

Materials used in the production of concrete, either as a partial replacement for *Portland* cement or incorporated directly into cement, should be classified as Supplementary Cementitious Materials (MCS). These materials consist of mineral additions that, when incorporated into *Portland* cement or employed in concrete as a partial substitute for cement, have the purpose of improving the technological performance of cementitious materials [8,9]. They must have adequate availability, economic viability and compatible technical performance, considering their chemical, mineralogical and hydration properties [10].

These materials can be classified as pozzolanic when they have pozzolanic activity, or as cementing, when they have their own hydraulic capacity, and also as *filler*, when the material does not have significant chemical activity [8]. It should be noted that limestone filler is used as MCS because it is a carbonate material chemically compatible with Portland cement, which can optimize the packaging of particles and reduce the water content, resulting in better mechanical properties of the composite [11]. Limestone *filler* falls under the definition of MCS because NBR 12653 [12] allows fine mineral materials, even without significant chemical reaction, to be used to supplement cement performance.

Table 1 presents the characteristics that MCSs may possess according to their classification.

Table 1

Characteristics of the different MCSs that are added to composite cement. Source: Adapted from Neville (2016)

Material	Cementitious Characteristic
Granulated blast furnace	Latent hydraulicity, sometimes hydraulic

slag	
Natural pozzolan (class N)	Latent hydraulicity with *Portland cement*
Siliceous flywheel ash (Pozzolan class F)	Latent hydraulicity with *Portland cement*
High limescale fly ash (Pozzolan class C)	Latent hydraulicity with *Portland cement*
Silica fume (Artificial Pozzolan)	Physical action, to a large extent, and latent hydraulicity with *Portland cement*
Limestone filler (Inorganic material)	Physical action but mild latent hydraulicity with *Portland cement*

Meanwhile, inert materials are not considered MCS [13], such as powdery waste generated in the extraction and processing of quartzite according to the parameters of NBR 12653 [12].

2.1.1 Pozzolans

Pozzolans are siliceous or silice-aluminous materials that, although they have little or no agglomeration capacity alone, when finely ground react chemically with lime in the presence of water, forming stable compounds with cementing properties, and materials that are by themselves binders are not included in this category [14].

Pozzolans are materials that have pozzolanic activity [8]. This activity refers to the ability of siliceous or silicoaluminous materials to react with calcium hydroxide ($Ca(OH)_2$) in the presence of water, forming hydrated calcium silicate (C-S-H), which are compounds with cementitious properties and contribute, for example, to the increase of compressive and flexural strength, to advanced ages, to the increase of resistance to sulfates and reduction of porosity and permeability, when added to concrete, mortars and pastes [12].

Several materials can present pozzolanic activity, such as silica fume, natural pozzolans and fly ash [8]. NBR 12653 [12] determines that in order to qualify as Class N (natural and artificial pozzolans), Class C (fly ash produced by the burning of mineral coal in thermoelectric plants) and Class E (any pozzolans, not included in classes N and C) the material must comply with the physical and chemical requirements established in Table 2.

Table 2

Chemical and physical requirements for pozzolanic materials

Chemical Requirements (%)	Pozzolanic Material Class		
	N	C	E
SiO_2+Al_2O_3+Fe_2O_3	≥ 70	≥ 70	≥ 50
SO_3	≤ 4	≤ 5	≤ 5
Moisture content	≤ 3	≤ 3	≤ 3
Loss to fire	≤ 10	≤ 6	≤ 6
Alkalis available in Na_2O	≤ 1.5	≤ 1.5	≤ 1.5
Physical Requirements (%)	**Pozzolanic Material Class**		
	N	**C**	**E**
Material retained in the sieve 45 µm	< 20 %	< 20 %	< 20 %
Performance index with *Portland cement* at 28 days, in relation to the control	≥ 90 %	≥ 90 %	≥ 90 %
Pozzolanic activity with lime at seven days	≥ 6 MPa	≥ 6 MPa	≥ 6 MPa

Source: Adapted from NBR 12653 (ABNT, 2014)

Because they are generally by-products of different industrial processes, pozzolanic materials such as silica fume and fly ash can present great variability in their characteristics, depending on the region of origin and production conditions [15].

2.1.2 Latent cementitious activity materials

Materials with latent cementitious activity, or cementing, are those that have the ability to form hydrated products, in a similar way to Portland cement [16]. One of the main materials of latent cementitious activity is blast furnace granulated slag, which is a by-product of the pig iron production process, obtained by sudden cooling that generates a glass phase composed mainly of calcium silicates and aluminosilicates [5].

The reactivity of blast furnace slag depends on its chemical composition, fineness, and vitreous phase content, as these are factors that control its solubility and the formation of hydrated products, characteristics necessary to promote some type of physical, chemical, or thermal activation capable of overcoming its naturally slow hydration and allowing its effective use as a cementitious material [17].

2.2 INERT MATERIALS – FILLER EFFECT

Filler is a finely divided material that does not have chemical activity, being inert, but promotes the physical effect of packaging, in which very fine particles fill the voids between the larger particles, favoring the densification of the cement paste and the nucleation of the hydration products [15,18].

According to Mehta and Monteiro, these materials cannot be used as a substitute for *Portland cement*, but they can be used in the manufacture of concrete as a partial substitute for fine aggregate, contributing to improve the packaging of the cementitious matrix and promoting better mechanical behavior [13].

Powdery materials that do not have pozzolanicity or cementing activity, but have sufficiently fine granulometry, can be used to promote the filler effect in concretes and mortars (cementitious matrices) [19]. The main result of this effect is the increase in the compactness of the mixture, promoted by the incorporation of fine and ultrafine particles, which optimize the particle size distribution and improve the densification of the cementitious matrix [9].

2.3 IMPORTANCE OF USING COAL ASH

The relevance of investigating and promoting the use of ash as a partial substitute for *Portland* cement lies in two crucial challenges: promoting industrial waste management and mitigating the carbon footprint of the AEC industry. According to Bertolini, the burning of fossil fuels generates carbon dioxide (CO2), which, although not an immediate risk to human health, its large-scale release is a significant factor contributing to the worsening of the greenhouse effect [20].

Portland *cement* is produced from calcareous and clayey raw materials, and can incorporate additions, and its production involves high-temperature processes, reaching approximately 1450 °C [18]. In this context, the use of coal ash emerges as a relevant strategy, as it allows reducing the extraction of natural resources.

In addition, these ashes can be incorporated into new production chains, such as in the manufacture of bricks, paving, environmental barriers and ceramic products, as long as their properties are properly defined in the processing process. This is because, as highlighted by Mehta and Monteiro [13], the materials used in the production of concrete must be characterized, as the properties of concrete depend directly on the properties of its constituents. Therefore, characterizing each material is essential to predict the performance of concrete in the fresh and hardened state [19].

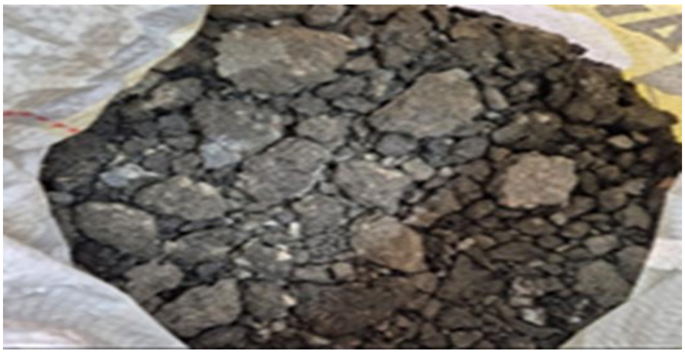
3 MATERIALS AND METHODS.

3.1 MATERIAL

The material used in this research was ash from the coal burning process at the Pecém Thermoelectric Power Plant (UTE Pecém), located in the municipality of São Gonçalo do Amarante/CE. Precisely, the bottom ash (Figure 1), which corresponds to the coarsest fraction of the waste generated in the combustion of coal. It is noteworthy that it receives this name because its granulometry does not allow them to rise with the gases and ends up accumulating at the bottom of the furnace because it is heavy.

Figure 1

Gray background generated by the Pecém TPP. (Authors, 2025)



3.2 METHODS

The methodology adopted in this research followed the workflow presented in Figure 2.

Figure 2

Workflow adopted in the research (Authors, 2025)

3.2.1 Processing

The coal ash collected at the Pecém TPP was benefited through: processes of reduction of the size of its particles and sieving in ABNT sieve number 200. The fragmentation of the particles occurred in the Los Angeles Abrasion machine of the Asphalt Mixtures Laboratory of the Federal Rural University of the Semi-Arid (UFERSA/Mossoró), using 12 spheres for an approximate period of 20 minutes. The processed ash remained in the granulometry of powdery material (Figure 3).

Figure 3

Pecém ash after processing in the laboratory. (Authors, 2025)

3.2.2 Chemical Characterization

The chemical composition of the processed ash was determined by X-ray fluorescence spectrometry (XRF), a technique that is based on the principle of X-ray absorption by the material, which causes the internal ionization of the atoms and generates a characteristic radiation known as "fluorescence". The test was carried out in a Universal Machine, a Shimadzu EDX 720 spectrometer, at the Materials Technology Laboratory (LTM) of the Federal University of Campina Grande (UFCG).

To determine the volatile material content of the processed waste, the *Loss on Ignition* test was carried out at a temperature of 1050 °C at a level of 2 hours, this took place at the Wood Technology Laboratory of UFERSA/Mossoró.

3.2.3 Mineralogical Characterization

The mineralogical characterization was obtained by means of the X-ray diffraction (XRD) technique. This technique is based on the interaction of X-radiation with the crystalline arrangement of the material, resulting in characteristic diffraction patterns that allow the identification of the mineral phases present. A Shimadzu XRD-6000 diffractometer was used, equipped with CuKα radiation, operating at a voltage of 40 kV and a current of 30 mA, in fixed *time scan mode*, with a step of 0.02°, a counting time of 0.6 s, and a scanning range of 5º to 60º with a 2θ angle. The trial was carried out at the LTM of UFCG.

3.2.4 Morphological and surface characterization

The morphological and surface analysis of the processed ash was performed by Scanning Electron Microscopy (SEM) at the Electron Microscopy Laboratory of the Center for Research in Plant Sciences of the Semi-arid Region (CPVSA) of UFERSA/Mossoró. The equipment used was TESCAN model VEGA 3, with an electron beam voltage of 30 kV, in different resolutions, expanding in 5kx, 10kx, 25kx, 40kx with a scale that varies according to the magnification (1 μm; 2 μm, 5 μm and 10 μm).

4 RESULTS AND DISCUSSIONS

4.1 CHEMICAL CHARACTERIZATION

Table 3 shows the chemical composition of the processed coal ash.

Table 3

Chemical composition of the processed coal ash. (Authors, 2025)

OXIDES	%
SiO_2	53,04
Al_2O_3	22,04
Fe_2O_3	9,38
CaO	4,43
SO_3	2,22
K_2O	2,03
Na_2O	1,95
MgO	1,50
TiO_2	0,84
BaO	0,70
SrO	0,15
MnO	0,05
ZrO_2	0,04
Rb_2O	0,01
Y_2O_3	0,00
CO_2	0,00
PF	1,64

*FP = Loss to Fire

Table 3 shows that the processed coal ash is mainly formed by silica (SiO2) and alumina (Al2O3), and these substances are responsible for its pozzolanic reactivity when used as a partial substitute for *Portland cement* in concrete. It complies with NBR 12653 [12], regarding SiO2 + Al2O3 + Fe2O3 ≥ 70 (84.46%); SO3 ≤ 5 (2.22%) and PF ≤ 6 (1.64%).

4.2 MINERALOGICAL CHARACTERIZATION

Figure 4 shows the diffractogram of heavy coal ash after processing.

Figure 4

Diffractogram of the processed heavy ash. (Authors, 2025)

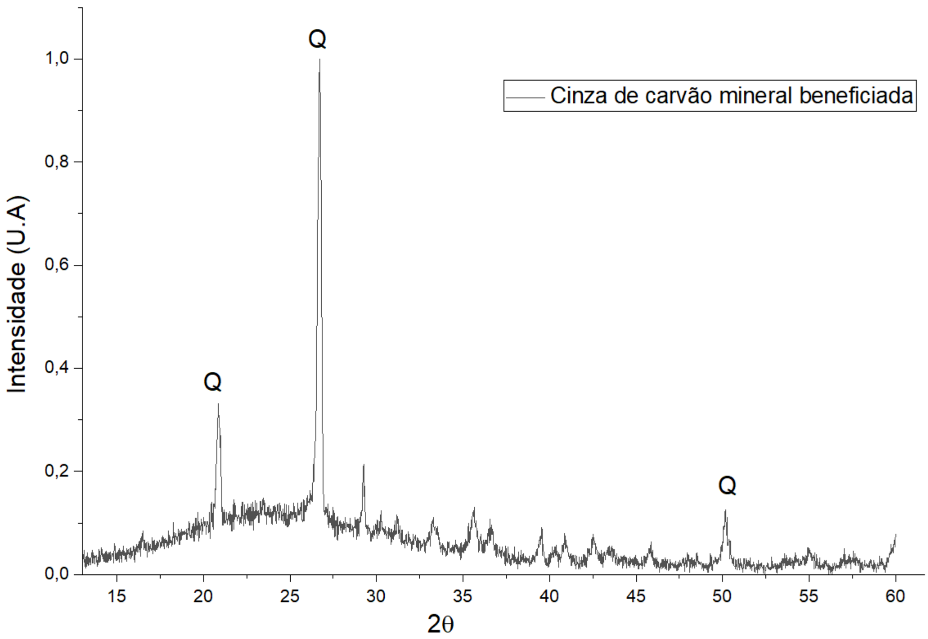


Figure 4 shows the formation of an amorphous halo between 15º and 40º, indicative of pozzolanic activity of the material, in addition to crystalline quartz peaks that are formed in the burning of coal at temperatures below 1000°C. The result obtained in the diffractogram is similar to that achieved by Cirino et *al.* [21] for light gray and not to those obtained by him for heavy gray (background gray). It is believed that this fact occurred because there was a reduction in the particle size of heavy ash in *the Los Angeles* abrasion and 200 mesh screening, making the material lighter.

4.3 MORPHOLOGICAL AND SURFACE ANALYSIS

Figure 5 presents the micrographs obtained for different magnifications, which allow a better morphological and surface visualization of the material studied.

Figure 5

a) Micrograph - Magnification of 4.99 kx b) Micrograph - Magnification 20.0 kx. (Authors, 2025)

a) b)

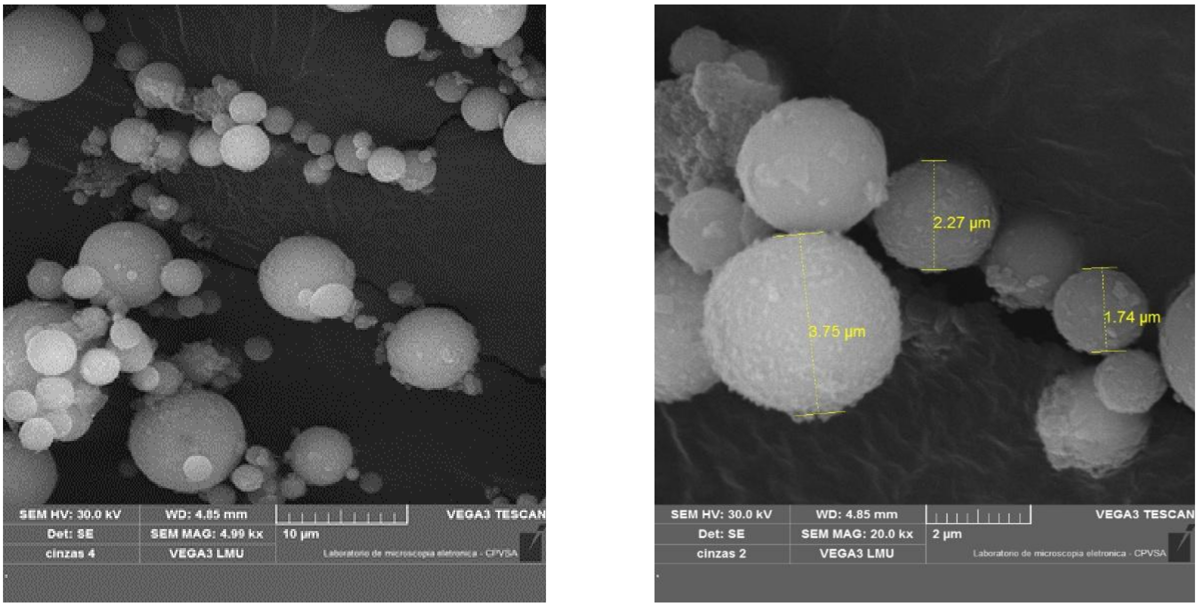


Figure 5a presents a low magnification, i.e., it shows the microstructure of the processed coal ash 4,990 times larger than its actual size. It shows its general morphology, which is made up of a diversity of spongy spherical particles.

While, Figure 5b shows the same material, but 20,000 times larger than the actual size. This makes it possible to verify the presence not only of spongy spherical particles but also of brittle and irregular particles formed from the aluminosilicate vitreous matrix. This fact indicates a mixture of crystalline and amorphous phases, corroborating the results obtained in the mineralogical characterization.

Figure 5b also shows the average sizes of the spherical particles that constitute the material studied, and that these are variable, with particles of diameter 1.74 μm, 2.27 μm and 3.75 μm. The morphology found is spherical with brittle particles. It is important to highlight that when there is the presence of spherical morphology, there is a tendency for grain sliding, a fact that can increase the workability and fluidity of cementitious compounds, according to

Cirino et *al*. [21].

5 FINAL CONSIDERATIONS

According to the research carried out, it is concluded that the heavy ash from the Pecém/CE Thermoelectric Plant, after undergoing processing, is classified as pozzolanic material belonging to class C according to NBR 12653. In addition, it has a spherical morphology with the presence of vitreous brittle particles, which gives it better reactivity when used in cementitious matrices, providing improvement in the properties of the construction materials made with it.

The formation of the amorphous halo in the diffractogram of the processed heavy ash corroborates the results obtained in the chemical characterization and the morphology presented, as it is indicative of pozzolanic activity of the material studied.

In view of the reactivity of the material, it is inferred that the processed heavy ash can be used in the manufacture of mortars, concretes and other cementitious matrices in partial replacement of *Portland* cement because it belongs to class C, which corresponds to materials with hydraulic/pozzolanic reactivity, thus contributing to promote the gain in strength and durability of the products made with it.

Finally, it is also concluded that this processed waste, in addition to promoting gains in the properties of mortars, concretes and other cementitious matrices, can have an adequate final destination when it is inserted in the production chain of cementitious matrices used in the construction processes of the Architecture, Engineering and Construction industry. In this way, contributing to the reduction of environmental impacts and to the fulfillment of the sustainable production and consumption goals set out in SDG 12.

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