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Incinerated biomedical waste ash in concrete production: A case study on hazardous material immobilization

Cinzas de incineração de resíduos biomédicos na produção de concreto: Um estudo de caso sobre a imobilização de materiais perigosos

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ABSTRACT

Inadequate management of Incinerated Biomedical Waste Ash (IBWA) poses a major challenge for the environment and public health. Simultaneously, the increasing demand for natural resources in civil construction calls for sustainable alternatives. Specifically in the context of Alagoas, Brazil, where healthcare waste production has increased, and where final disposal requires licensed landfills, the search for alternatives becomes pressing. This study investigated the technological and environmental feasibility of incorporating IBWA into concrete matrices, partially replacing river sand. The objective was a dual-benefit solution: hazardous waste valorization and natural aggregate conservation. The IBWA, sourced from an incinerator in Alagoas that treats various types of healthcare waste (with the exception of group C), were subjected to detailed characterization by particle size distribution, X-ray Fluorescence (XRF), X-ray Diffraction (XRD), and Thermogravimetric Analysis (TGA). For performance evaluation, concrete specimens were molded with sand replaced by IBWA at 0% (control), 5%, 10%, 15%, and 20% by mass. The results showed that the IBWA predominantly exhibited particle sizes similar to medium sand, with smaller particles acting to optimize contact points within the cement matrix, serving as a filler. The XRF chemical analysis indicated a high proportion of Calcium (53.232%) and Iron (19.658%), and a limited Silica content (5.408%), suggesting low pozzolanic activity. XRD confirmed the crystalline nature with the presence of Calcite and Calcium Silicates. In terms of mechanical performance, concrete with a 5% replacement of sand with IBWA maintained compressive strength significantly close to the control mix (15.55 MPa vs. 16.89 MPa at 28 days). However, increasing IBWA proportion (above 5%) resulted in a progressive reduction in compressive strength and increased porosity. As a result, water absorption tests indicated higher absorption at greater ash contents. Scanning Electron Microscopy (SEM) complemented the analyses, confirming particle morphology and distribution. The study concluded that the incorporation of IBWA in low proportions is technically promising for non-structural applications. This provides a viable route for sustainable hazardous waste management and innovation in construction materials.

Keywords: Waste valorization; Circular economy; Contaminant immobilization; Environmental remediation.

RESUMO

A gestão inadequada de Resíduos Biomédicos Incinerados (RBI) representa um desafio ambiental e de saúde pública global. Paralelamente, a crescente demanda por recursos naturais na construção civil exige alternativas sustentáveis. Especificamente no contexto de Alagoas, Brasil, onde a geração de resíduos de serviços de saúde tem aumentado e a destinação final exige aterros licenciados, a busca por alternativas se torna um desafio urgente. Este estudo investigou a viabilidade tecnológica e ambiental da incorporação de cinzas de RBI em matrizes de concreto, substituindo parcialmente a areia de rio, visando uma solução mútua para a valorização de resíduos e a conservação de agregados naturais. As cinzas, provenientes de uma incineradora de Alagoas que trata diversos tipos de resíduos de serviços de saúde (exceto o grupo C), foram submetidas a caracterizações detalhadas de granulometria, Fluorescência de Raios X (FRX), Difração de Raios X (DRX) e Termogravimetria

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(TGA). Para a avaliação de desempenho, foram moldados corpos de prova de concreto com substituição de areia por RBI em composições de 0% (referência), 5%, 10%, 15% e 20% em massa. Os resultados revelaram que as cinzas de RBI possuem granulometria predominantemente na faixa de areia média, com partículas menores otimizando os pontos de contato na matriz cimentícia. A análise química por FRX indicou alta proporção de Cálcio (53,232%) e Ferro (19,658%), e um teor limitado de Silício (5,408%), sugerindo baixa atividade pozolânica. A técnica de DRX confirmou a natureza cristalina com a presença de Calcita e Silicatos de Cálcio. Em termos de desempenho mecânico, o concreto com 5% de substituição de areia por RBI manteve a resistência à compressão significativamente próxima ao traço de referência (15,55 MPa vs. 16,89 MPa aos 28 dias). Contudo, o aumento da proporção de RBI (acima de 5%) resultou em uma redução progressiva da resistência e um aumento da porosidade. Isto foi evidenciado pelos ensaios de absorção de água, que mostraram maior absorção em maiores teores de cinzas. A Microscopia Eletrônica de Varredura (MEV) complementou as análises, confirmando a morfologia e distribuição das partículas. Conclui-se que a incorporação de RBI em baixas proporções é tecnicamente promissora para aplicações não estruturais, fornecendo uma rota viável para a gestão sustentável de resíduos perigosos e a inovação em materiais de construção.

Palavras-chave: Valorização de resíduos; Economia circular; Imobilização de contaminantes; Remediação ambiental.

1. INTRODUCTION

Advances in materials science and engineering have provided health sciences with a wide range of tools aimed at practicality, safety, and human comfort, leading to unprecedented innovations in healthcare technologies [1–2]. Despite this striking new technological scenario, many countries still rely on medical procedures of the last century, with extensive use of disposable materials. Due to the infectious nature of hospital procedures, much of these post-use materials must be disposed of appropriately to minimize contamination and avoid unhealthy environments. Generally, these materials are incinerated, producing a significant quantity of Incinerated Biomedical Waste Ash (IBWA) with no established purpose, yet demanding considerable attention [3]. This challenge is compounded by the global increase in urban populations, which has led to a rise in accidents (work, traffic, and domestic) and the emergence of new diseases, causing overcrowding in hospital units. The threat of new viruses and their increasingly infectious variants, as evidenced by the devastating effects of the COVID-19 pandemic, further strains health systems, from supply logistics to waste disposal [4].

In addition to these waste management challenges, the construction industry faces its own environmental pressures, driving the search for sustainable materials and new avenues for waste utilization. Over the last few decades, several studies have demonstrated the flexibility of concrete and its derivatives—mortar and other cementitious products—to incorporate by-products of diverse natures and chemical compositions [5]. Many of these studies were motivated by an interest in integrating various production chain by-products into a stable cementitious matrix, aiming for appropriate disposal, valorization, or even improved final product performance. Furthermore, production pressures and the availability of raw materials have propelled the search for new inputs and composites, pushing the state of the art in the built environment to new frontiers. An unprecedented range of arrangements and combinations has become possible, with various chemical compositions—from inorganic to organic—already tested. This yields impressive results and opens new perspectives on sustainable reuse of waste byproducts [6]. The exponential growth of the human population, coupled with a construction model heavily reliant on cement composites, has indeed overloaded natural reserves of inputs like sand, water, and cement, making the emergence of more environmentally friendly construction technologies essential [7].

Towards this goal, polymeric materials such as plastics have been widely studied [8]. Natural fibers are also promising, with Brazil being a center of intense research [9]. Discarded cement kraft paper packaging has also found its applications [10]. On the inorganic chemical spectrum, various ceramic materials have been explored, including eggshells [11], mollusk shells [12], ceramic waste [13], slag [14], glass [15], among other residues [16]. Among wastes with great potential for incorporation into concrete, combustion ash stands out, particularly those resulting from the combustion of organic material for energy production [17–19] or for the disposal of contaminated material [20-21]. Specifically, sugarcane bagasse [22], coconut fibers [23], rice straw [24], and other incinerated agro-industrial waste [25] have been systematically studied. However, these ashes and biomass incineration products generally do not possess the hazardous chemical nature associated with IBWA. IBWA can release dioxins, furans, and unstable halogenated compounds during burning [26]. The resulting material may also contain heavy metals, hazardous chemicals, and reactive leachable substances [27]. Therefore, the immobilization of IBWA in a cementitious matrix represents a safe, viable, and low-cost alternative.

This study, by investigating the behavior of concrete produced with the incorporation of IBWA, specifically replacing river sand, significantly advances on two critical fronts. From a technological perspective, it explores the capacity of the cementitious matrix to encapsulate and stabilize complex waste, minimizing the leaching of contaminants such as heavy metals and halogenated compounds. This represents a high-level materials engineering challenge, as the heterogeneous composition of IBWA and the need to maintain the physical-mechanical properties of concrete demand rigorous analyses and dosage optimizations. Environmentally, the research directly contributes to reducing the demand for natural aggregates, such as river sand, whose excessive extraction leads to serious ecological problems. More importantly, it offers a valorization route for hazardous waste that would otherwise require specialized and high-cost landfills with continuous environmental risks. Thus, not only does this study seek a more sustainable disposal solution for IBWA, but it also aims to develop a construction material with an improved environmental profile and potential for application in various infrastructures, in the possibilities of non-structural concrete.

2. MATERIALS AND METHODS

The experimental part focused on the collection and processing of the Incinerated Biomedical Waste Ash (IBWA), followed by its evaluation using X-ray Fluorescence (XRF) and X-ray Diffraction (XRD) techniques. Moreover, granulometric analysis was performed to understand the average sizes of the material. In addition, mix designer studies were conducted for the production of concrete, varying the percentage of replacement of fine aggregate with IBWA. Subsequently, the specimens were subjected to technological tests such as water absorption and compressive strength tests at 28 days. Images were also obtained by Scanning Electron Microscopy (SEM) of the fracture surface. The flowchart below synthesizes the key steps of the study (Figure 1).

2.1. Raw material and IBWA processing

In the production of the concrete, CP II-Z-32 cement was used. Crushed stone with a maximum size of 12.5 mm was utilized as coarse aggregate. The sand obtained from the region of Palmeira dos Índios, Alagoas, Brazil, served as the fine aggregate [28].

The IBWA used to replace sand in the concrete production was provided by a company in the state of Alagoas, which collects waste from all human and animal health units (doctors' offices, dentists' offices, hospitals, clinics, laboratories, pharmacies, blood banks, and research centers). A quantity of 10 kg of IBWA was collected, and 6.7 kg were incorporated into the cement matrix for molding the test specimens and for other analyses. The biomedical waste is autoclaved and incinerated in furnaces that operate at temperatures of 800ºC and 1000ºC, with a flow rate of 2.5 tons/day. The materials based on carbon are reduced to gases and inert materials (ashes and metal slags) with heat generation, and the residues subjected to thermal treatments eliminate pathogens due to the high temperature. After thermal treatment, the IBWA is finally disposed of in Class I and Class II landfills, according to the company. The equipment used in the thermal treatment service can be visualized in Figure 2.

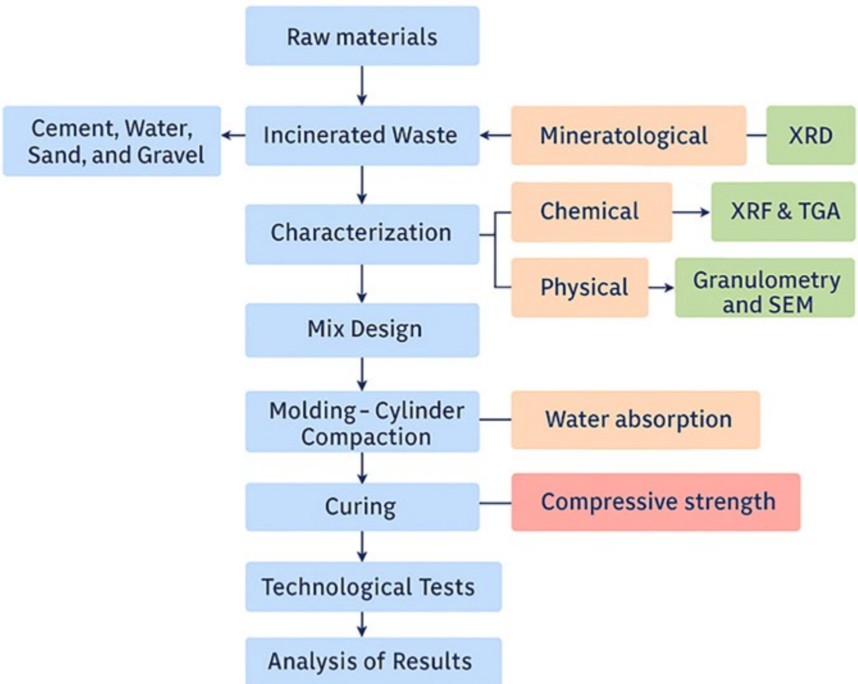

Figure 1: Experimental flowchart: processing, characterization, and concrete production with IBWA incorporation.

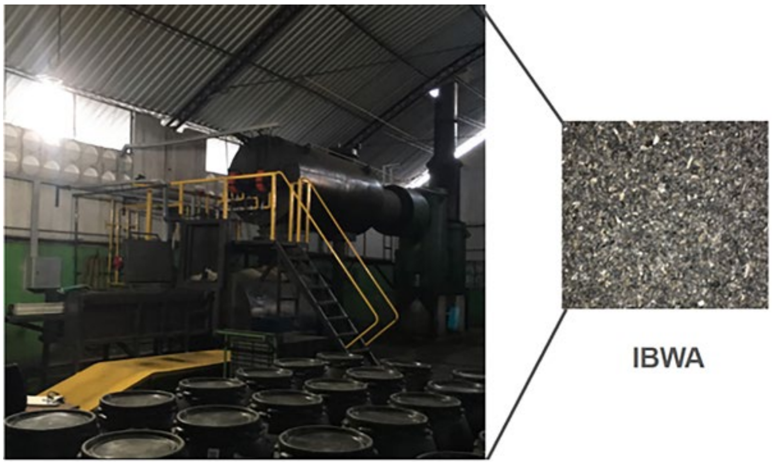

Figure 2: Industrial furnaces used for IBWA production.

2.2. Characterization of materials

2.2.1. IBWA characterization

The chemical analysis of IBWA ashes was conducted via X-ray Fluorescence (XRF); using a Shimadzu EDX-700 spectrometer in a vacuum atmosphere, employing a semiquantitative method. This non-destructive procedure determines the elements present in the sample by measuring the intensity of X-rays emitted after radiation excitation. Each characteristic X-ray has a unique energy pattern, allowing for element identification and quantification. The chemical structuring of the incinerated residues was thus obtained through XRF spectrometry.

For X-ray Diffraction (XRD) of the powdered ceramic by-product, a Shimadzu XRD-6000 Diffractometer was used to identify the mineralogical phases present, with Cu-kα radiation (λ = 1.54056 Å), 40 kV voltage, 30 mA current, and a sweep angle (2θ) from 10° to 80°. Diffraction results from radiation scattered by diffusion centers with spacing similar to the radiation wavelength, used to determine material structures or identify known chemical substances. Results were processed by the X'Pert HighScore Plus software, to isolate and verify compound peaks in the sample.

Thermogravimetry Analysis (TGA) was performed on a Shimadzu TG-50 device at the Laboratory of Physical Properties of Ceramic Materials - UFRN (in Natal, Brazil). Its aim was to compute the variation in sample mass during temperature increase, which occurred between 26.09ºC and 801.76ºC. TGA monitors mass change as a function of temperature, while Differential Thermal Analysis (DTA) indicates endothermic and exothermic peaks where no mass loss occurs. The TG-50, equipped with a furnace, a scale, and a temperature programmer, generates a graph of the sample's mass variation.

2.2.2. Aggregate characterization

Concrete mix proportions were calculated using the Brazilian Portland Cement Association (ABCP) method for an expected compressive strength of 25 MPa. Cylindrical test specimens (10 cm diameter and 20 cm height) were molded according to NBR 5738/2015 [29]. Aggregate volume and mass were calculated, and the final mix proportion adopted was 1:2:2:0.55, representing the proportions by mass of cement, sand, and crushed stone, respectively, and the water/cement ratio (mass of water per mass of cement).

In the laboratory, 20 cylindrical specimens (10 cm diameter and 20 cm height) were molded, consisting of 5 distinct compositions, with 4 replicas for each. The compositions were formulated with varying percentages of fine aggregate (sand) replacement by IBWA ashes at 0% (reference mix), 5%, 10%, 15%, and 20% by mass. The proportion and specific masses of cement, sand, and crushed stone were rigorously defined for each mix, ensuring consistency in the production of test specimens for comparative evaluation [30].

Concrete components (cement, water, fine aggregate, coarse aggregate, and incinerated waste) were manually mixed and homogenized to ensure uniformity. Each component was carefully weighed. Therefore, the incinerated residue was manually sieved to ensure a fine particle size, which is essential for its role as a fine aggregate substitute. After molding, the specimens were wet-cured for 24 hours before demolding, thus preparing them for performance tests.

2.3. Concrete tests

2.3.1. Water absorption tests

The water absorption test followed NBR 9778 [31] guidelines. Five specimens, one for each mix, were submerged in water for 24 hours. After immersion, they were weighed in a saturated surface-dry condition. Subsequently, they were oven-dried at 110°C for 24 hours for controlled drying. This procedure was repeated at two-hour intervals until the discrepancy between two successive determinations was less than 0.5% of the previous measurement. Water absorption percentage was calculated based on dry and saturated masses.

2.3.2. Compressive strength test

The compressive strength of the specimens was measured in accordance with the recommendations of NBR 5739 [32]. Tests were performed at 14 and 28 days to evaluate the progression of compressive strength over time. The load was applied continuously, without shock, with a constant increase in stress, until the rupture of the test specimen. Mechanical strength tests were conducted at the Construction Materials Laboratory of the Federal Institute of Alagoas of Palmeira dos Índios, using an EMIC DL30000F hydraulic compression testing machine.

2.3.3. Microscopy of the fracture surface

The morphology of the fracture surfaces of the specimens was analyzed using Scanning Electron Microscopy (SEM). Small samples were metallized with a thin gold layer and subjected to an electron beam to capture magnified images, allowing for the perception of micrometric details. Analyses were performed at various magnifications (38×, 400×, 1000×, and 7000×) for a deeper understanding of the microscopic arrangement and particle morphology.

3. RESULTS AND DISCUSSION

This section details and analyzes the results obtained from the characterization of Incinerated Biomedical Waste Ash (IBWA) and the performance of the concrete that incorporated them. Initially, the physical-chemical and morphological properties of the IBWA will be presented. Subsequently, the discussion will focus on the mechanical (compressive strength) and durability (water absorption) properties of concrete with different IBWA contents. Finally, results from microscopic observations (Scanning Electron Microscopy – SEM) of the material's microstructure will be discussed. All findings will then be compared with, and contextualized within, the latest and most relevant scientific literature in the field of sustainable materials and hazardous waste management.

The particle size distribution analysis of IBWA revealed a uniform distribution, with approximately 70% of the sample concentrated in the diameter range between 0.30 mm and 2.4 mm, as shown in Figure 3.

This result indicates that a significant portion of the ashes exhibits a particle size distribution equivalent to that of medium sand, as specified by NBR NM 248 [28] for fine aggregates. The intrinsic fineness of these particles constitutes, in and of itself, an advantageous aspect, as larger surface areas promote optimized interactions among components within the cementitious matrix. This feature of the ash, which makes it analogous to a fine aggregate, is crucial for its viability as a sand substitute, as proposed in this study. Amran *et al.* [17] and Manan *et al.* [33] predominantly focus on fineness as a factor for pozzolanic reactivity and, consequently, for increasing matrix strength and densification. These authors report that ash fineness is vital for concrete performance. Finer particles increase surface area, which enhances the reactivity and pozzolanic activity of the ashes. This benefits compressive strength through accelerated pozzolanic reaction and the filler effect, leading to optimized formation of hydration products (C-S-H) and densifying the concrete's microstructure.

The elemental chemical composition of Incinerated Biomedical Waste Ash (IBWA) was determined by X-ray Fluorescence (XRF), revealing crucial insights into their constitution for concrete application purposes. The detailed results of this analysis are presented in Table 1.

Table 1 indicated calcium (Ca) as the predominant component (53.232%), followed by iron (Fe) (19.658%), and silicon (Si) (5.408%). The significant presence of calcium and iron is consistent with the nature of materials present in biomedical waste, such as bones and some plastics and metals, and their behavior during thermal treatment. These elements are also commonly found in Portland cement, which is primarily composed of $CaCO_3$, SiO_2, Al_2O_3, and Fe_2O_3, in addition to secondary constituents. The silica content in the IBWA (5.408%) is notably low when compared to cement, which contains about 17% to 25% silica in its composition. This low percentage of silica suggests that IBWA, despite the presence of Si, do not exhibit significant pozzolanic characteristics that would substantially contribute to strength via pozzolanic reactions, as occurs with other biomass ashes.

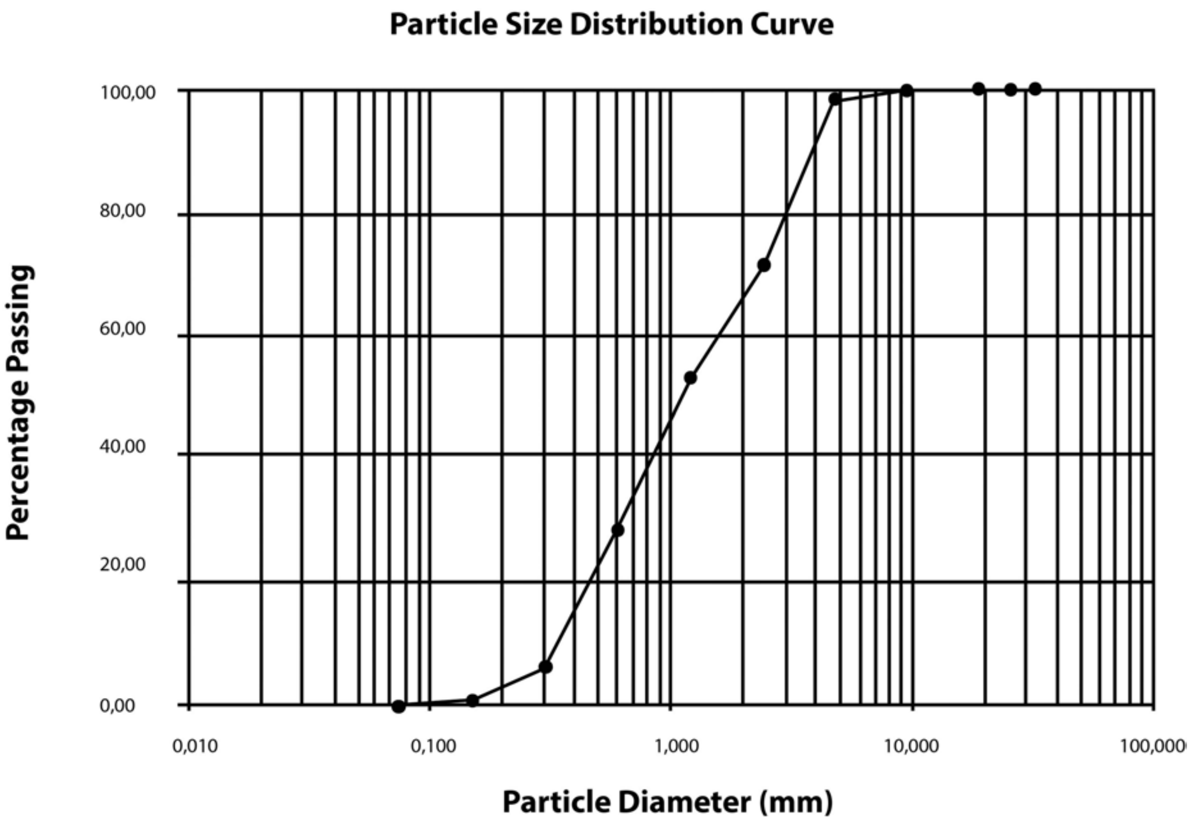

Figure 3: Particle size distribution of IBWA.

Table 1: Elemental chemical composition of IBWA via XRF.

MINERAL	Ca	Fe	Si	Al	Ag	P	Ti	Zn	K	Mg	S	Sr	Pb	Zr
%	53.232	19.658	5.408	4.875	3.110	2.639	2.606	2.088	1.808	1.190	0.749	0.749	0.631	0.584

IBWA composition differs from pozzolanic ashes like sugarcane bagasse [19] or coal fly ashes [17–18], which emphasize silica and alumina for pozzolanic activity. The nature of incinerated biomedical waste is crucial, as Bolan *et al.* (2023) and Wang *et al.* (2023) indicate the presence of heavy metals, dioxins, and furans [3, 27]. Although this study did not perform leaching tests on the final concrete, the chemical characterization of the ash, which revealed the presence of elements like Pb (0.631%) and Cr (0.125%), highlights the importance of hazardous material immobilization as an underlying aim and ongoing challenge in IBWA research [20–21, 33]. For a better understanding of the crystalline phases, the corresponding diffractogram is shown in Figure 4.

The predominantly crystalline nature of the studied material, evidenced by the sharp peaks in the X-ray diffractogram (Figure 4), reinforces that IBWA do not possess significant pozzolanic properties. Chemically, pozzolanic properties fundamentally depend on the presence of silica (SiO_2) and alumina (Al_2O_3) in an amorphous phase. The disordered (amorphous) structure of silica and alumina allows for greater solubility in an alkaline medium generated by Portland cement hydration. This reactivity in an alkaline medium forms secondary hydration products, mainly additional calcium silicate hydrates (C-S-H), which are primarily responsible for concrete strength and durability. The structure and reactivity of silica are crucial, with the amorphous form being preferable for optimizing pozzolanic properties [17]. The predominance of crystalline phases in IBWA, despite the presence of silicon, may explain the material's performance, as the poverty in chemically active silica necessary for pozzolanic reactions does not impart strength gains to concrete. The thermal behavior of the ashes was subsequently investigated through Thermogravimetric Analysis (TGA), as shown in Figure 5.

Thermogravimetric Analysis (TGA) and Differential Thermal Analysis (DTA) indicated a mass loss of approximately 24% in the IBWA between 26°C and 801.76°C. This mass loss, although small, can be

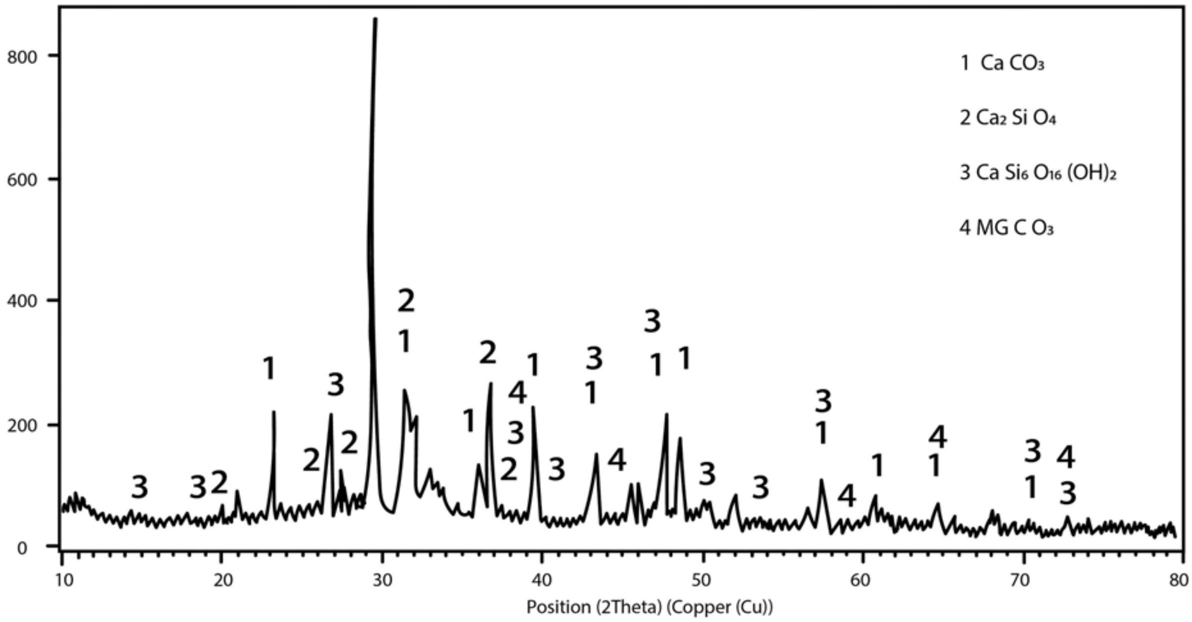

Figure 4: XRD of IBWA crystalline phases.

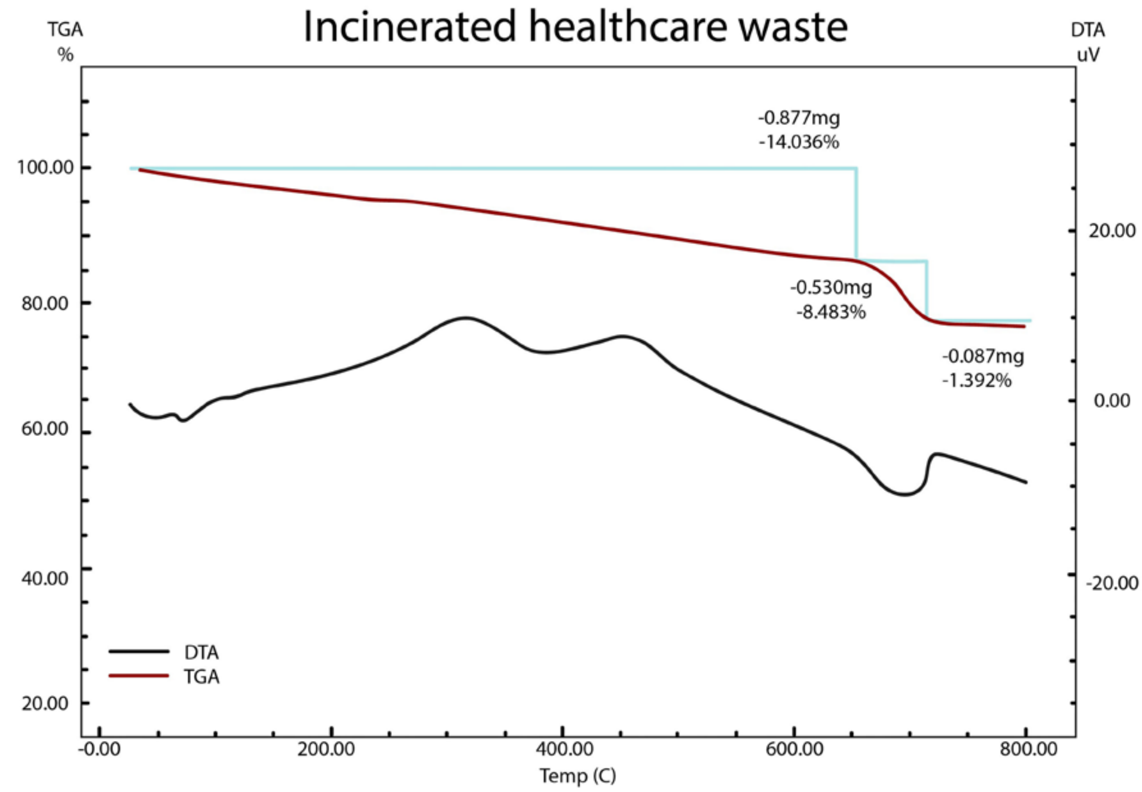

Figure 5: TGA and DTA curves of IBWA.

attributed to the elimination of adsorbed moisture (which occurs up to 150°C), the decomposition of biopolymers (in the 230–260°C range) and the possible presence of organic residues not entirely eliminated during initial incineration. The retention of about 76% of the original mass after prolonged heating at high temperatures is a positive feature, indicating a good thermal stability of the material. Based on the detailed information regarding the chemical composition and thermal stability of the ashes, mechanical tests for water absorption and compressive strength were subsequently performed, as shown in Figure 6.

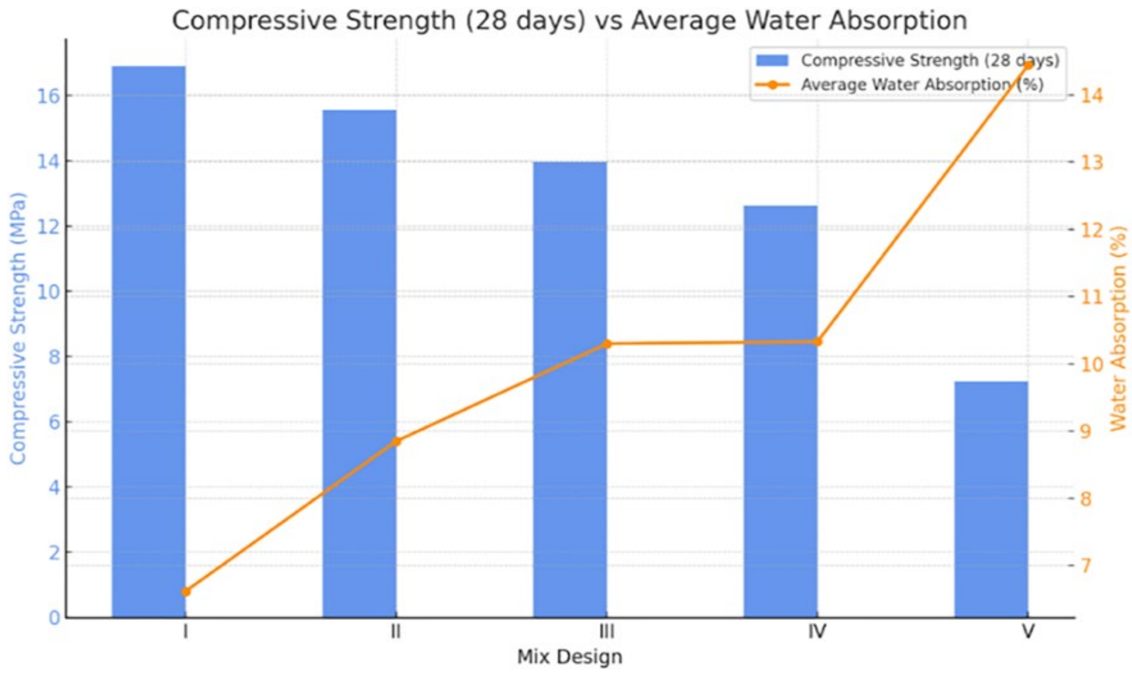

Figure 6: Water absorption and compressive strength of IBWA concrete.

The water absorption test results, presented in Figure 6, demonstrate a direct correlation between the increasing incorporation of IBWA and the increased water absorption, indicating higher porosity of the test specimens [31]. The reference mix (0% IBWA) registered an average absorption of 6.62%. The 5% ash mix exhibited an absorption rate of 8.85%, being the smallest variation compared to the reference mix among all incorporation percentages. For the 10% replacement mix, the average absorption was 10.30%; for 15%, it was 10.33%; and for 20%, it reached 14.44%. This increase in porosity is a concern, as most porous building materials tend to increase in volume with water absorption and develop fissures due to shrinkage during drying, compromising durability. These results would mean that the material incorporated with IBWA should be classified as concrete aimed at non-structural applications. The results indicate that, for higher percentages of substitution, there is a tendency for increased porosity. In general, this effect with the incorporation of ashes and other wastes is a widely reported phenomenon in the literature.

The results of the compressive strength test (Figure 6) demonstrated a gradual, yet consistent, reduction in concrete strength as the percentage of sand replacement by IBWA increased. The 5% ash mix exhibited an average compressive strength of 15.55 MPa at 28 days, a value that proved to be significantly close to that of the reference mix (16.89 MPa). This promising initial performance suggests the viability of incorporating the ash in low proportions without severely compromising the material's structural integrity. Such a finding aligns with the concept of developing lightweight and sustainable concrete from by-products. However, at the highest content, the 20% ash mix revealed notably lower strength (7.24 MPa at 28 days), which clearly indicates a limitation in the maximum viable replacement ratio [32].

This decrease in compressive strength can be attributed to the lower consistency of the ash compared to sand and, fundamentally, to its low pozzolanic activity, as previously discussed. Despite the strength reduction at higher ash proportions, it is crucial to note the practical applicability of these results. Even the mix with the lowest strength obtained (7.24 MPa at 28 days) still meets the strength requirements for ceramic blocks (≥ 1.5 MPa for horizontal holes and ≥ 3.0 MPa for vertical holes, according to NBR 15270-1/2005). This demonstrates that the partial replacement of fine aggregate by IBWA in small proportions is technically viable and can be applied in concrete requiring strengths comparable to that obtained with 5% IBWA (15.55 MPa at 28 days), suitable for non-structural and low-demand uses. For an in-depth understanding of the microstructural arrangement of IBWA ashes within the cementitious matrix, Scanning Electron Microscopy (SEM) images were obtained, as illustrated in Figure 7.

Scanning Electron Microscopy (SEM), as shown in Figure 7, displays the morphology of the incorporated residues within the cementitious matrix at different magnification scales, ranging from 2 µm to 500 µm, with zoom capabilities up to 7000x. These images confirmed the presence of small-diameter grains,

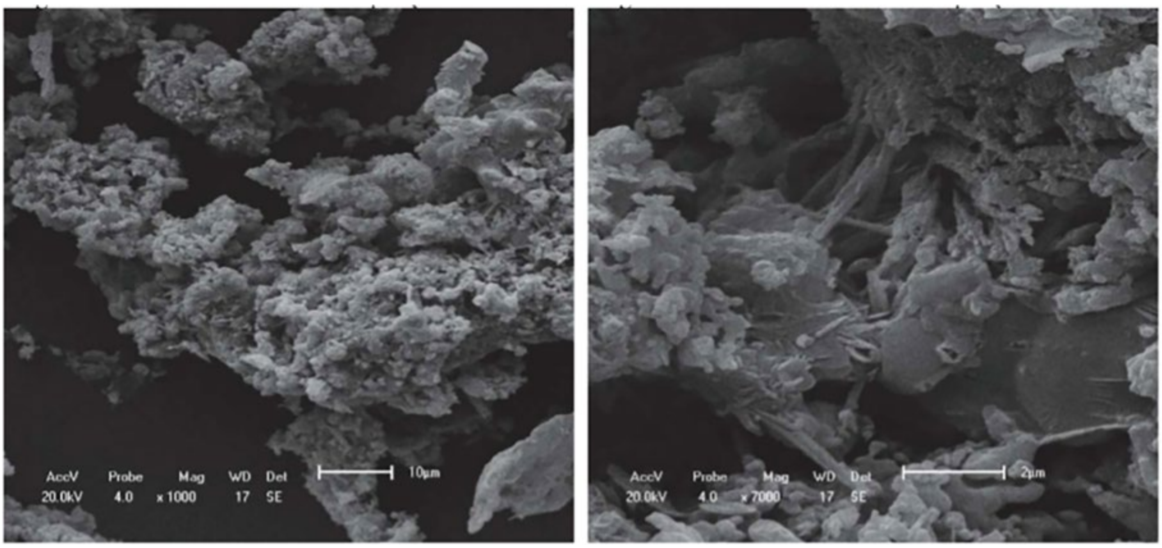

Figure 7: SEM micrographs of IBWA in the concrete matrix.

which corroborates the particle size distribution analysis results indicating the predominance of particles smaller than 2.40 mm. The overall morphology of the sample, mainly composed of calcium, iron, and silica, aligns with the results obtained from X-ray Fluorescence (XRF). The discussion regarding the presence of silica in an amorphous phase (characterized by the absence of a defined atomic structure), in contrast to other crystalline materials that exhibit crystals with typical dimensions and contours, constitutes an important finding that differentiates the behavior of silica present in these ashes from traditional pozzolanic materials, where the amorphous structure is crucial for reactivity.

The results are significant for waste management and materials engineering, for its characterization of Incinerated Biomedical Waste Ash (IBWA) and evaluation of their use in concrete. IBWA, rich in calcium and iron but low in silica, differs from conventional pozzolanic ashes, resulting in limited pozzolanic contribution to concrete. Despite this, their particle size distribution, similar to medium sand, allowed their incorporation as a fine aggregate, with promising results, indicating technical viability for non-structural applications. The presence of lead (Pb) at 0.631% and chromium (Cr) at 0.125% in the IBWA is critical, but the material's classification as non-hazardous by leaching (Class II A) [34], coupled with concrete's known ability to immobilize heavy metals, suggests a promising viability for encapsulating these elements. Future research should optimize dosages, mitigate porosity, and, fundamentally, prove contaminant immobilization through rigorous leaching tests for IBWA concrete to become a truly sustainable and safe solution.

The full utilization of 2.5 daily tons of Incinerated Biomedical Waste Ash (IBWA) in concrete for non-structural applications represents a promising solution for waste management and sustainability in civil construction [35]. At an incorporation rate of 5% IBWA (replacing sand), a hypothetical company could produce approximately 138.75 tons of concrete per day, maintaining compressive strength significantly close to the reference mix (15.55 MPa vs. 16.89 MPa at 28 days). In the 20% incorporation scenario, the production would be about 34.69 tons of concrete/day with reduced strength (7.24 MPa at 28 days). These scenarios are viable for the production of non-structural cementitious pieces such as interlocking blocks or slabs, meeting normative requirements for these applications. From a logistical standpoint, costs are favorable due to the consistent availability of IBWA, given the reduced acquisition of sand.

4. FINAL REMARKS

This study demonstrated the technical feasibility of incorporating Incinerated Biomedical Waste Ash (IBWA) into concrete matrices for non-structural applications, thereby representing a significant advance in waste management and sustainable materials engineering. The characterization of IBWA revealed its particle size compatibility with medium sand and a composition rich in calcium and iron, although with a low content of amorphous silica, which limits its pozzolanic activity compared to traditional ashes. The concrete's performance results were promising at low replacement ratios: the 5% IBWA mix maintained compressive strength significantly close to the reference mix (15.55 MPa vs. 16.89 MPa at 28 days), which indicates potential for non-structural cementitious pieces like interlocking blocks or slabs [35]. Despite increased porosity and water absorption at higher percentages of IBWA (up to 14.65% with 20% replacement), which raises durability concerns, the study validates IBWA incorporation. The ashes, classified as non-hazardous by leaching (Class II A), and concrete's intrinsic ability to encapsulate heavy metals like Pb (0.631%) and Cr (0.125%) offer a promising route for hazardous material immobilization. Thus, this study advances a sustainable alternative for high-risk waste disposal, reducing demand for natural aggregates and promoting the circular economy. The simulation of the total utilization of 2.5 daily tons of IBWA in non-structural concrete production points to potentially favorable logistics and costs.

5. ACKNOWLEDGMENTS

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