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Circular Economy: Adding Value to the Post-Industrial Waste through the Transformation of Aluminum Dross for Cement Matrix Applications

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Abstract: In light of globalization and escalating environmental concerns, society is increasingly confronted with the challenge of implementing the concept of a circular economy, which promotes the recycle of waste materials and offers a promising solution. Aluminum dross, a byproduct of the aluminum production process, poses environmental issues when not properly managed. Therefore, this study examined the technical and financial feasibility of implementing an industrial process for the recovery and transformation of aluminum dross into raw materials for use in cementitious materials. From a technical perspective, two processes were evaluated: washing and the grindability of the material. An X-ray diffraction analysis allowed to verify an approximately 88% reduction in AlN (a compound that produces ammonia gases when reacting with water) after washing the material. The most efficient grinding process was achieved using an impact mill. The financial feasibility study was carried out through cash flow forecasting, which revealed that a minimum selling price of USD 0.12 per kilogram of processed material could generate a return rate of 9.7% over a five-year period. These results present opportunities for the metal and construction industries to develop products with low CO_2 emissions by reintegrating aluminum dross into a productive cycle. Moreover, this work serves as a valuable reference for policymakers and environmental authorities seeking to formulate new legislation or incentives that encourage companies to invest in environmentally focused projects.

Keywords: aluminum dross; waste management; circular economy; feasibility study; cement–matrix composites; industrial symbiosis

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1. Introduction

Aluminum is one of the most commonly used materials in manufacturing, construction, transportation, and packaging, among other industries, and it has a significant impact on the world economy. Global aluminum production grew by 139% in the last decade, reaching its peak in 2023 (International Aluminium Institute, 2023) [1], with countries such as China, India, and Russia leading the production. While the increased use of aluminum brings dynamism to international markets, it also leads to negative environmental impacts. For example, during the production process, waste such as white aluminum dross (AD) is generated. This waste is classified as hazardous due to the heavy metals that can leach from landfills into water sources. Additionally, one of its components, aluminum nitride (AlN), undergoes a transformation into ammonia gas (NH_3) when exposed to water. This transformation not only affects the environment but also poses risks to human health due to its irritating and corrosive nature. Considering the aforementioned context, it is necessary to seek alternatives that strike a balance between economic growth, social welfare, and environmental issues. This entails developing profitable and sustainable strategies in the long term, such as the recycling of production waste within circular economy models (Moreno, 2018) [2].

Dross is an inevitable residue generated during the aluminum smelting process as a result of the reaction between the liquid aluminum surface and the atmosphere. It is categorized into three types based on the production technique: white, black, and saline dross (David & Kopac, 2013) [3]. White dross is produced during the production of primary and secondary aluminum in extrusion plants, rolling mills, and foundries. Its name stems from its light color. On the other hand, black and saline dross are produced in recycling processes and are characterized by their dark color. Black dross typically has a granular shape and contains more salts and gases compared to white dross, while saline dross has fewer metal residues and more impurities.

The structure and composition of dross cannot be predicted precisely, as various factors such as temperature, alloy composition, and atmospheric conditions influence the oxidation process. However, dross generally consists of aluminum oxides, residual metallic aluminum, nitride, carbide, aluminum sulfide, salts, and some alloying elements (Dai, 2012) [4]. The chemical composition of AD (aluminum dross) varies depends on the alloying elements present in the casting process. However, it is typically composed mainly of aluminum oxide (Al_2O_3), spinel ($MgAl_2O_4$), and sodium chloride (NaCl) in higher proportions. Other reported compounds include silicon dioxide (SiO_2), sodium superoxide (Na_2O), ferric oxide (Fe_2O_3), aluminum metal, diaoyudaoite ($NaAl_{11}O_{17}$), aluminum oxide nitride (Al_5O_6N), hibonite ($CaAl_{12}O_{19}$), fluorite (CaF_2), and calcite ($CaCO_3$). Additionally, AD may contain traces of silicon (Si), aluminum carbide (Al_4C_3), magnesium fluoride (MgF_2), sodium tetrachloroaluminate ($NaAlCl_4$), potassium tetrachloroaluminate ($KAlCl_4$), magnesium oxide (MgO), parascandolaite ($KMgF_3$), and elpasolite (K_2NaAlF_6). Other minor crystalline phases identified through X-ray diffraction analysis (XRD) include cryolite (Na_3AlF_6) and potassium chloride (KCl) (Mahinroosta & Allahverdi, 2018; Srivastava & Meshram, 2023) [5,6].

There are opportunities for the reincorporation of AD into various production chains due to its Al_2O_3 content, which can be utilized as a mineral addition in the production of construction materials, among other applications. Several studies in the literature have reported the use of AD as a source of Al_2O_3. For instance, it has been employed in the manufacturing of calcium aluminate cement (Ünlü & Drouet, 2002) [7] and refractories (Ibarra Castro et al., 2009) [8] as well as in the production and synthesis of different composite materials (Ewais et al., 2009; Huang et al., 2014; Kim et al., 2009; Murayama et al., 2009; Yoshimura et al., 2008) [9–13]. AD has also been used as a substitute for cementitious material (Pereira et al., 2000) [14] and in the production of cellular concrete (Araújo & Tenório, 2005; Hwang & Song, 1997) [15,16], aluminous cement manufacturing (Ewais et al., 2009) [9], partial replacement of fine aggregate in mortars (Borhan & Janna, 2016; Llanos & Rodríguez, 2011; Pereira et al., 2000; Puertas et al., 1999) [14,17–19], concrete block production (Shinzato & Hypolito, 2005) [20], and conventional concrete manufacturing (Elinwa & Mbadike, 2011; Mailar et al., 2016; Ozerkan et al., 2014; Reddy & Neeraja, 2016) [21–24].

The results of these studies indicate the potential to explore circular economy alternatives with this hazardous waste, thereby contributing to the reduction of the 2.5 million tons of dross that are annually disposed of in landfills worldwide. These landfills generate undesirable heat, liquid leachate with heavy metals, and approximately 40 million m^3 of toxic, flammable, and foul-smelling gases such as ammonia, phosphine, hydrogen sulfide, and methane (David & Kopac, 2013) [3]. However, it should be noted that while the physical, chemical, and mechanical properties of certain applications for the reuse of dross have been studied, no technical and financial feasibility studies for its industrial-scale production have been conducted so far. Thus, this project aims to contribute with a proposal for the application of white dross, facilitating its reincorporation into a closed production cycle. To achieve this, the physicochemical characterization of the material was conducted to identify its potential uses. Subsequently, an industrial-scale production process was designed for a specific application case in a Colombian aluminum manufacturer. Finally, a financial feasibility analysis was carried out to assess its implementation.

2. Materials and Methods

2.1. Materials

The present study utilized AD obtained from Alumina S.A, a company located in Santiago de Cali, Colombia. This AD is categorized as white dross, originating from primary and secondary foundries. It is noteworthy to mention that this waste is classified as hazardous due to the potential leaching of heavy metals into groundwater from landfills, and the emission of hydrogen gases (H_2), NH_3, and methane (CH_4) upon interaction with aqueous substances, which are hazardous to both health and the environment (Dai, 2012; Siddique Pasley, 2003; Tang et al., 2022) [4,25,26].

2.2. Methods

In the present study, the methodology depicted in Figure 1 was followed. This diagram illustrates a sequential approach used in the research process. Initially, various applications of AD were explored through a comprehensive literature review, and the Disney method, which involves four thinking styles sequentially employed to analyze problems and generate ideas, was applied. This approach led to the identification of five feasible alternatives. Subsequently, the analytic hierarchy process (AHP) method was employed to determine the most favorable alternative. Following the selection of the preferred alternative, treatments and laboratory tests were conducted to obtain transformation parameters for AD. Finally, the industrial-scale process design and a corresponding financial analysis were carried out to assess the technical and financial viability of AD recovery and transformation in the case study.

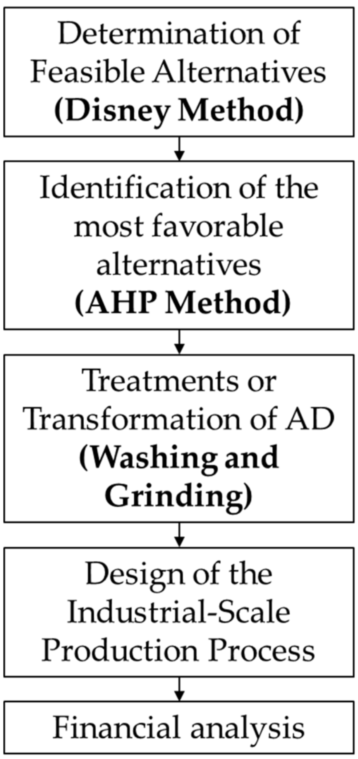


Figure 1. Flowchart of the developed methodology.

2.2.1. Identification of the Most Favorable Alternatives

A multi-criteria selection process was conducted using the AHP method based on the identified feasible alternatives (Saaty, 2008) [27]. Experts from various fields participated in defining the evaluation criteria and their respective weights of importance, as presented in Table 1.

Table 1. Selection criteria application of the AHP method.

Criterion	Weight	Score	Scale
C1: Associated implementation cost	10%	0	High cost
		1	Average cost
		2	Low cost
C2: Technical feasibility of implementation	16%	0	High level of implementation difficulty
		1	Medium difficulty level
		2	Low difficulty level
C3: Availability of information on the alternative	6%	0	No information
		1	Information is limited
		2	High amount of information available
C4: Compliance with design constraints established by stakeholders	41%	0	Affects or worsens properties
		1	Does not affect or improve properties
		2	Properties are maintained or improved
C5: Environmental impact	28%	0	High environmental impact
		1	Average environmental impact
		2	Low environmental impact

The research paper evaluated the identified alternatives based on five criteria. Criterion C1 assessed the costs of implementing AD in the alternative. Criterion C2 evaluated the feasibility of implementing the alternatives in terms of equipment, materials, and workspace. Criterion C3 was based on information from the literature review. Criterion C4 evaluated if the alternative could affect the final product's properties and performance, while criterion C5 assessed energy consumption and waste generated by the alternatives.

Then, scores on a scale of 0 to 2 for each criterion were assigned. Criteria C1, C2, and C5 were scored based on high cost, high difficulty, or high environmental impact, receiving a score of zero. Criteria C3 and C4 were evaluated based on high information availability and compliance with specifications, receiving a score of two. After scoring each alternative, a pair comparison matrix was constructed, and the priority vector's consistency was verified. The alternative with the highest total hierarchical analysis score was then selected.

2.2.2. Transformation of Aluminum Dross (Laboratory Scale)

After identifying the most promising alternative, the required chemical treatments and physical transformations were carried out to prepare the AD for industrial use. In this regard, a washing process was initially conducted on the AD; the material was distributed on a surface, and approximately 20 L of water were added daily for five days. Subsequently, the washed aluminum dross (WAD) was dried in an oven at a temperature of 120 °C for 24 h. Chemical analyses were conducted using XRD and EDS techniques to evaluate the composition of the AD before and after washing. The XRD analysis was performed using a Bruker model D8 Advance series 1 with CuK-α radiation (λ = 1.5406 Å), employing a step size of 0.02° for each 3 s. In addition, scanning electron microscopy (SEM) was employed to examine the morphology of the material, utilizing a JOEL model JSM-6490 with a gold sample coating. The effect of washing on the material's morphology was also assessed using SEM in the same electron microscope.

Furthermore, to meet the particle size requirements outlined in ASTM C618-19 (Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete) [28], it was necessary to evaluate the grinding process for WAD to ensure it met the specified size criteria. Specifically, at least 66% of the material should pass through a sieve size of 325 (particle size < 45 μm). To prepare the AD for reincorporation, it was important to analyze its grindability in different equipment and methods to identify the most efficient particle reduction mechanisms.

Two grinding methods were examined: ball mill grinding and impact grinding. Ball mill grinding was conducted using a mill with a capacity of 500 g, operating at a speed of 90 rpm. Various grinding times were tested, including 15, 30, 45, 60, 90, 120, and 150 min, in order to assess the effect of grinding duration on the material. In contrast, impact grinding was performed using a ring mill with a capacity of 100 g. The grinding times evaluated were 2, 4, 6, 8, and 10 min. For durations exceeding 2 min, the intervals of grinding were followed by 10 min of rest, as impact grinding tends to cause significant wear on the mill.

2.2.3. Development of an Industrial Process for Transforming Aluminum Dross

Based on the findings, a production process was proposed, including the required machinery and personnel. To determine the plant layout, the systematic layout planning (SLP) method was applied (Suhardini et al., 2017) [29]. This involved defining the macro and micro location, creating a relationship matrix to establish distances between working areas, and using a diagram of relationships to determine the appropriate order for the plant's different areas. Finally, the Guerchet method was used to calculate the areas of occupation for each equipment and propose a general distribution for the plant.

Additionally, to determine the operational parameters, various equipment options were evaluated, and a choice was made based on the minimum installed capacity needed for a scenario where a Colombian aluminum manufacturer applies the circular economy principle, as the aim is to encourage waste-generating companies to implement such processes and develop new business ventures. Production times and workforce requirements were established by analyzing process activities and equipment capabilities using a logistics process simulation software (SIMIO version 9.1).

2.2.4. Assessing the Financial Viability of Utilizing Aluminum Dross in the Chosen Application

After defining and validating the requirements for implementing the AD recovery production process, the necessary investments and operating costs were estimated. Using this information, a 5-year projection of the project's income statement and cash flow was created. Financial evaluation indicators such as net present value (NPV), internal rate of return (IRR), and benefit/cost ratio (B/C) were then calculated (Ross et al., 2010) [30]. As there is currently no active market for AD that is suitable for reincorporation into other industrial applications, the sale price that meets the minimum viability conditions for a project (NPV = 0) was determined. This sale price is important for potential investors and allows for the development of a market for AD as recovered waste material in the construction sector by industrial symbiosis.

3. Results and Discussion

This section presents the outcomes of the analysis and selection of the application alternative and proposes a transformation process for the reuse of AD. The feasibility of implementing this process has been validated through a case study conducted in a Colombian aluminum manufacturing company.

3.1. Exploring Potential Applications of Aluminum Dross and Selecting an Optimal Use

The utilization of dross as an engineering product or as a component in an engineered product system is a subject of interest due to various reasons. Firstly, recycling Al_2O_3 from dross can offer an alternative source to many primary materials. Secondly, if the dross can be directed towards a valuable product, aluminum smelters can profit by charging an entry fee for handling and processing of residual dross, which can be utilized for producing new or existing products, thereby improving some of its physical, mechanical, or chemical characteristics (Crespo, 2015) [31].

To achieve the above objectives, an analysis of possible uses of WAD was conducted, employing the ideation technique known as the Disney method. The method involved exploring various alternatives through the dreamy, realistic, and critical phases and ultimately evaluating the possible risks (Appendix A).

After applying the Disney method, it was determined that five alternatives successfully passed through each phase of the analysis. The selected alternatives for further investigation were identified as follows: NMP refractories without additions, preparation of gamma alumina (γ-Al_2O_3) via a hydrometallurgical process, partial replacement of Portland cement for concrete production, replacement of Portland cement in the production of mortars, and production of polypropylene compound and aluminum dross. These options are marked with an asterisk (*) in Table A1.

Table 2 presents the matrix used to determine the final decision vector, which represents the best alternative considering the priority vectors of the criteria, the priority vectors of the alternatives for each criterion, and the assigned importance values for each criterion. The analysis resulted in the identification of the two most favorable alternatives for the utilization of AD: A4 (27.8%) and A3 (24.5%). These alternatives involve the partial replacement of Portland cement for the production of mortars and concrete, respectively. Based on these findings, a circular economy approach was implemented, focusing on the recovery of AD for its incorporation into cementitious matrices such as mortars and concrete. Appendix B shows the procedure that was carried out to obtain Table 2.

Table 2. Final decision vector determination matrix (best alternative).

Alternatives	Vector of Priorities by Criterion					Final Vector	Best Alternative
	C1	C2	C3	C4	C5		
A1	5.6%	35.8%	9.1%	7.7%	28.1%	17.4%	A4 A3
A2	13.0%	6.5%	9.1%	23.1%	5.1%	13.8%	
A3	34.2%	15.5%	27.3%	23.1%	28.1%	24.5%	
A4	34.2%	35.8%	27.3%	23.1%	28.1%	27.8%	
A5	13.0%	6.5%	27.3%	23.1%	10.8%	16.4%	
Vector Criteria	9.9%	16.1%	6.2%	41.6%	26.2%		

3.2. Circular Economy Proposal for the Recovery of Aluminum Dross

Pilot processing tests for use in cementitious matrices: Pilot processing tests for the utilization of AD in cementitious matrices were conducted to validate its suitability for such applications. It is important to note that AD primarily consists of aluminum oxide (15–30% Al_2O_3), but it may also contain approximately 8.0% AlN, a compound that produces ammonia gases upon contact with water (Attia et al., 2018; López-Delgado et al., 2020) [32,33]. The presence of AlN in cement-based mixtures poses risks to both worker safety and the formation of voids within the cementitious matrix due to the trapped gas (Dai, 2012; Lemos Micolta et al., 2020; Mahinroosta & Allahverdi, 2018) [4,5,34].

To address this issue, a "washing" or inactivation process was implemented to reduce the percentage of aluminum nitrides in the AD before its incorporation into cementitious matrices. This washing process aimed to minimize the risks associated with ammonia gas generation and ensure the integrity and performance of the cement-based materials. The AD underwent a series of processing steps to prepare it for use in cementitious matrices. Initially, the collected AD was subjected to sieving using mesh #10 (Figure 2a–c). This sieving process helped to remove any larger particles or impurities present in the material.

Figure 2. (**a**) AD at the collection site, (**b**) initial sieve, (**c**) AD, (**d**) washing process, and (**e**) drying process.

For the subsequent washing process, the AD was dispersed and evenly distributed on a suitable surface. Approximately 20 L of water per day were added to the AD over a period of 5 days (Figure 2d). After the washing process, the wet AD was dried in an oven at a temperature of 120 °C for 24 h (Figure 2e). This drying step aimed to remove excess moisture from the material.

In order to confirm the removal of AlN from AD and determine the effect of the washing process on chemical and morphological characteristics, dross evaluation was performed before and after washing using XRD and SEM. The results of the chemical characterization conducted by X-ray diffraction (XRD) are presented in Table 3. It was observed that the percentage of AlN decreased from 18.2% in AD to 2.2% in WAD, confirming the successful removal of aluminum nitrides through the washing process. Additionally, a significant increase in the presence of gibbsite was observed, which can be attributed to the interaction between aluminum phases (Al) and water (H_2O) used during the washing process (Singh, 1982) [35]. Furthermore, compounds such as aluminum oxide, iron oxides, and quartz showed an increase in their percentage, while the percentages of aluminum and spinel decreased. These findings provide valuable insights into the changes in the chemical composition of the AD following the washing process.

Table 3. XRD results with percentage values of the presence of chemical compounds in AD and WAD.

Compound	Chemical Formula	Content (%)	
		AD	**WAD**
Gibbsite	$Al(OH)_3$	3.7	27.5
Aluminum Nitrides	AlN	18.2	2.2
Aluminum Oxide	Al_2O_3	14.8	17.1
Aluminum	Al	6.3	3.86
Diaoyudaoite	$NaAl_{11}O_{17}$	0	0.81
Iron Oxides	Fe_2O_3	0.3	2.4
Quartz	SiO_2	1.5	5.2
Spinel	$MgAl_2O_4$	34	25.5

On the other hand, Figure 3 displays the surface morphology of the AD particles, revealing an apparent presence of aluminum oxide, spinel, and aluminum nitrides. Additionally, the micrographs of WAD demonstrated the presence of other crystal structures derived from aluminum oxide, such as corundum. These findings are consistent with previous studies (Braulio et al., 2011; Chaplianko & Nikichanov, 2021; Zuo et al., 2021) [36–38]. Notably, the micrographs indicated a change in the material's morphology following the washing process, with an increased presence of structures exhibiting a crystalline morphology.

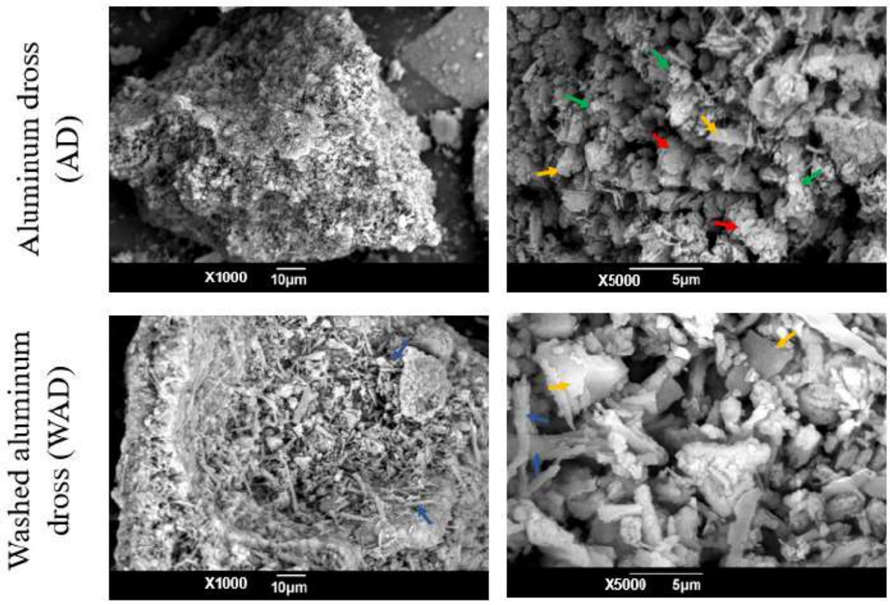


Figure 3. SEM of AD and WAD. Aluminum oxide (orange arrow), spinel (red arrow), aluminum nitride (green arrow), and corundum (blue arrow).

The results of the millability test conducted in the ball mill are presented in Figure 4. The findings indicate that even with the maximum grinding time evaluated (150 min), only 18% of the particles achieved the desired size of 45 µm. The influence of time on the particle size change was not clearly observed. In a study conducted by Ramezani and Neitzert in 2012 (Ramezani & Neitzert, 2012) [39] on the grinding process of aluminum powder using a planetary ball mill, it was observed that prolonged grinding time led to morphological changes in aluminum particles, resulting in their transformation into flakes and a substantial increase in size from approximately 32 µm to over 1400 µm within just one hour. These findings provide insights into the behavior observed in Figure 4, which could be attributed to a lamination process involving the soft phases present in the WAD, such as aluminum (Al).

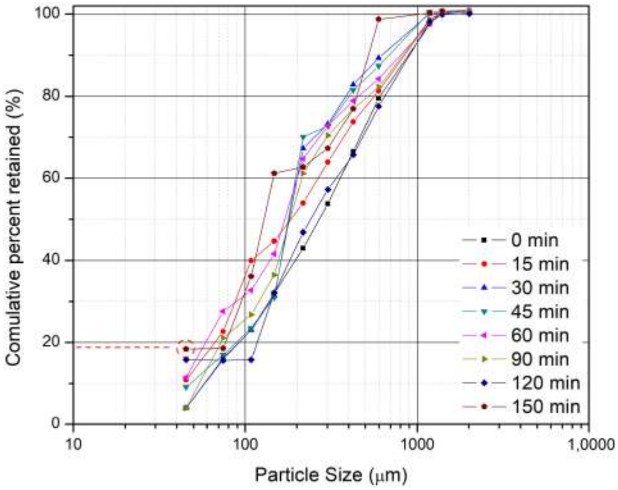
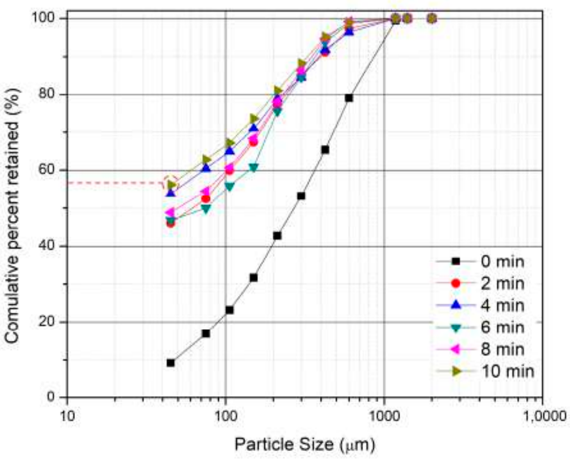
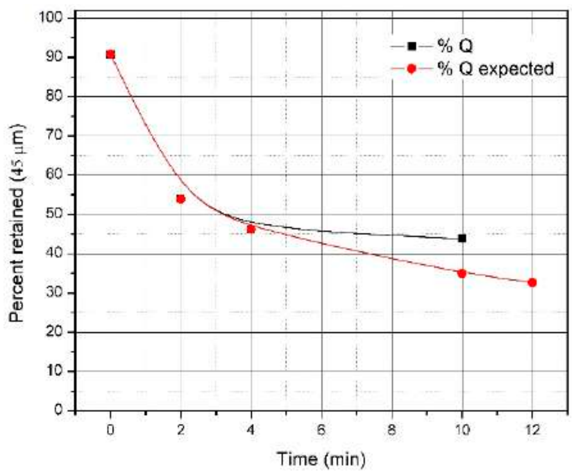


Figure 4. Granulometric distribution curves of WAD for different process times (ball mill).

Figure 5a illustrates the granulometric distribution curves of the WAD material processed in the impact mill. This grinding method yielded a particle size distribution where up to 56.21% of the particles were smaller than 45 μm, achieved within a processing time of 10 min. Although the obtained results do not fully meet the particle size requirements set by ASTM C618-19, a projection based on the kinetic analysis of grinding proposed by Leyva Ramírez et al. (Leyva Ramírez et al., 2009) [40] demonstrated that a particle size distribution with 66% of material below 55 μm (maximum retained in sieve 325 of 34%) could be achieved within a time frame of 12 min (Figure 5b). While no specific studies were found regarding the vibrational impact mill grinding process for aluminum dross or pure aluminum, ref. (Karakas & Kanca, 2020) [41] conducted a study on the grindability of alpha iron oxide using this technique. They observed a reduction in particle size by approximately 76.6%. This suggests that the ring mill, which imparts more energy to the system compared to a ball mill (Plescia & Tempesta, 2017) [42], has the potential to break down flakes and achieve smaller particle sizes despite the deformation phenomenon mentioned earlier.



(**a**)



(**b**)

Figure 5. (**a**) Granulometric distribution curves of aluminum dross for different process times (**left**). Impact mill (rings); (**b**) grinding kinetics (**right**).

3.3. Development of an Industrial Process for Transforming Aluminum Dross

Proposal to implement at a production process for the recovery of aluminum dross on an industrial scale: The process design and operational scheme were developed based on the results obtained from the laboratory pilot test and the analysis of available equipment options in the market. In order to achieve this, the necessary machinery for dross transformation was identified, the plant layout was designed, and the required workforce for operation was defined. To validate the design, data from a specific case study in a Colombian aluminum production company were utilized. The objective is to encourage the implementation of circular economy processes by the companies responsible for generating the waste while also enabling the development of new business opportunities. Additionally, the analysis presented in this proposal may be of interest to potential investors seeking to establish the production process as an independent business model.

Production process flow and equipment: Figure 6 presents the flowchart with the activities associated with the AD recovery process. This dross transformation allows the waste to become raw material to be used as a partial replacement for Portland cement.

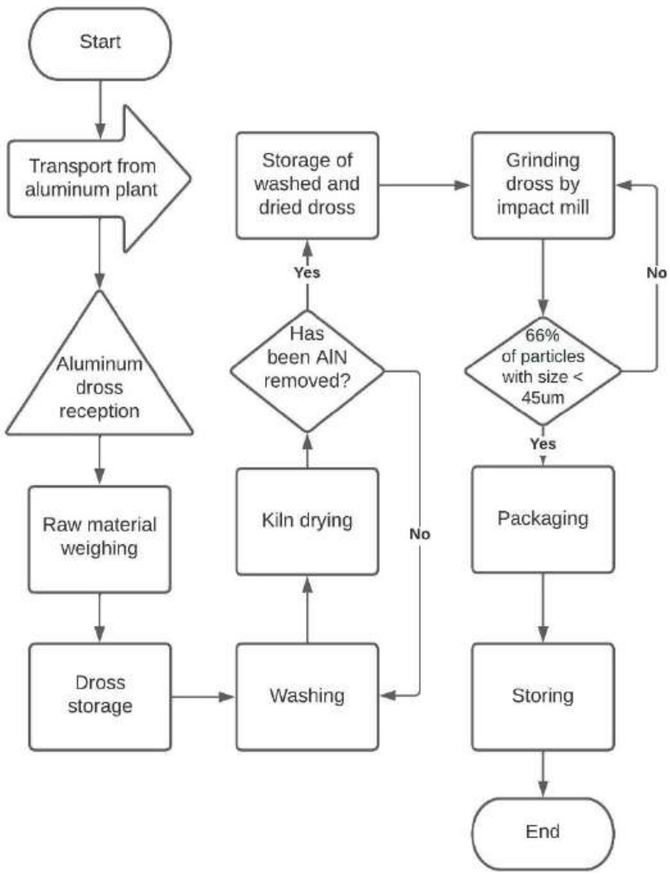


Figure 6. Dross transformation flowchart.

The process consists of several activities, including transportation, raw material reception, six operations, three storage stages, and two operational decisions. Depending on the location of the recovery plant, the material may need to be transported internally or externally from the aluminum production plant. If road transport is required, a dry bulk truck equipped with a rear valve for material extraction is necessary. In the analyzed case, 75 tons of AD are transported internally on a monthly basis from the main plant to the recovery plant.

Upon arrival at the reception area, the truck undergoes inspection and weighing. The material is then transferred through a hose to a conical bottom storage silo with automatic dosing and cumulative weighing capabilities, which are desirable features for storing this type of material. The silo is connected to a pool with a washing wheel where the dross-washing process takes place. An endless screw transports the fine dross from the bottom of the tank to a drain wheel, which recovers, drains, and discharges the material into another endless screw connected to a tilting rotary furnace model FARB-2, where the dross is dried.

The dry dross is stored in another silo designated for the product in the process, which will supply the ALPA MZ500 impact mill. This mill is used to reduce the particle size of the dross to meet ASTM C618-19 standards. The vibratory mill rapidly rotates the material, subjecting it to powerful impacts and frictional forces, resulting in the production of ultra-fine and uniform powder. This stage is crucial, as it ensures that the particle size of the dross is suitable for replacing cement in the manufacturing of mortars.

The milled dross is stored in a final silo for the finished products and then undergoes the packaging and storage activities. The transformed dross is packed in semi-extendable Kraft paper bags with filling valves. The paper used weighs between 82 and 95 g/m^2 and is designed with anti-tear technology to minimize damage during transport and handling. Micro perforations are incorporated into the bags to eliminate air accumulation during the filling process. Although the bags have a maximum capacity of 50 kg, it is recommended to pack them in 30 kg bags to ensure better ergonomic conditions for workers during loading (Hernández & Nieves, 2015) [43]. These bags are then arranged on pallets measuring 1 m x 1.2 m and stored in the designated storage area. Table 4 presents a comprehensive list of the equipment chosen for the various stages of the dross recovery process, including their respective installed capacities and acquisition prices.

Table 4. Equipment required in the process.

Process	Machine	Speed (kg/h)	Capacity (kg/mth)
Raw material inspection and weighing	Floor scale	N/A	80,000
Raw material storage	Storage silo	N/A	30,000
Drying	Tilting rotary furnace FARB-2	667	118,667
In-process product storage	Storage silo	N/A	30,000
Milling	Vibratory mill MZ 500	532	94,667
Finished product storage	Storage silo	N/A	30,000
Packing	Manual packing	421	75,000

The production capacities per hour for each activity were estimated based on the installed capacities of the equipment and the process configuration, as illustrated in Table 5.

Table 5. Capacity by process activities.

Activity	Capacity
Washing	686 kg/h
Drying	667 kg/h
Milling	479 kg/h
Packed	421 kg/h
Storage (total capacity)	30,000 kg

With the specified processing capacities, the equipment utilization for the washing tanks, rotary furnace, vibratory mill, and packaging ranges between 40% and 60%, resulting in a processing rate of 3125 kg per day.

Location and Plant Layout: Considering that the waste-generating plant is situated in the Valle del Cauca department, potential locations in proximity to this area were reviewed. Utilizing Logware software version 5.0, the optimal coordinates for the recovery plant were determined. The chosen location for the plant is within the ACOPI industrial zone in the city of Yumbo.

Subsequently, the space requirements for establishing the plant were assessed. Based on the process requirements, eleven specific areas were defined: truck entrance, raw material reception and storage area, washing area, drying zone, storage area for washed and dry dross, grinding area, storage area for milled dross, packing area, storage area for packed dross, office areas (management/customer service), and washrooms/dressing rooms. These areas were further analyzed using the relationship matrix presented in Figure 7.

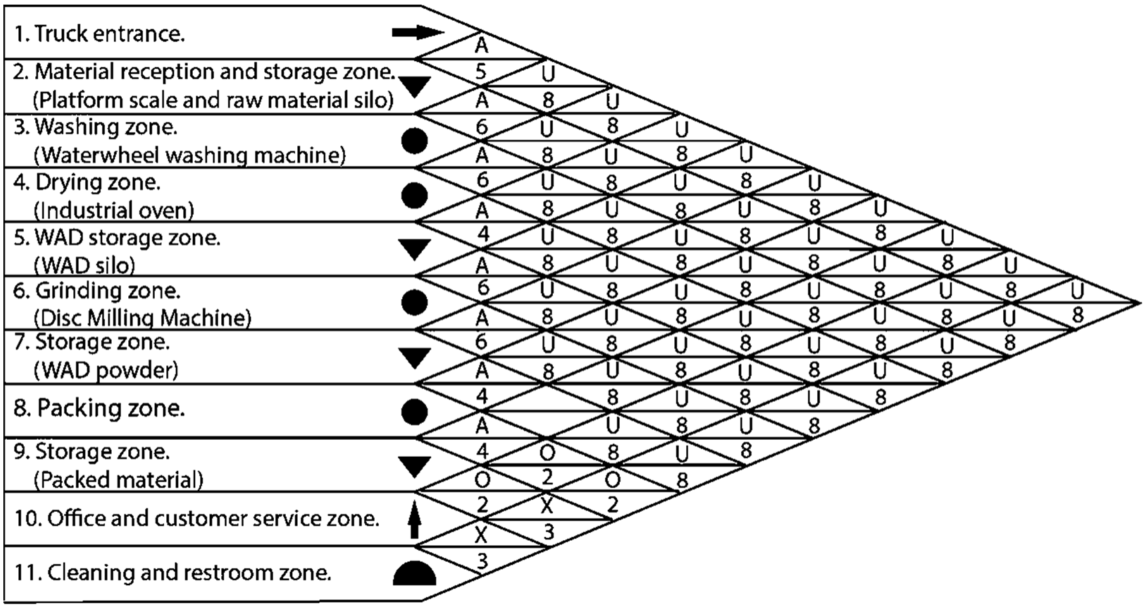


Figure 7. Relationship matrix.

The relationship diagram shown in Figure 8 was established to determine the appropriate distances between different zones within the plant. The first space is used for a transport activity which is represented by a horizontal arrow. Triangles represent storage activities, circles refer to operations, vertical arrow denotes administrative areas and the half oval refer to service areas.

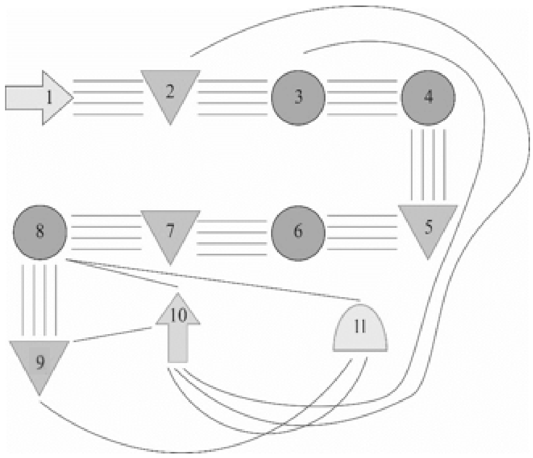


Figure 8. Relationship diagram.

This diagram served as the foundation for the general distribution of the plant, which can be seen in Figure 9.

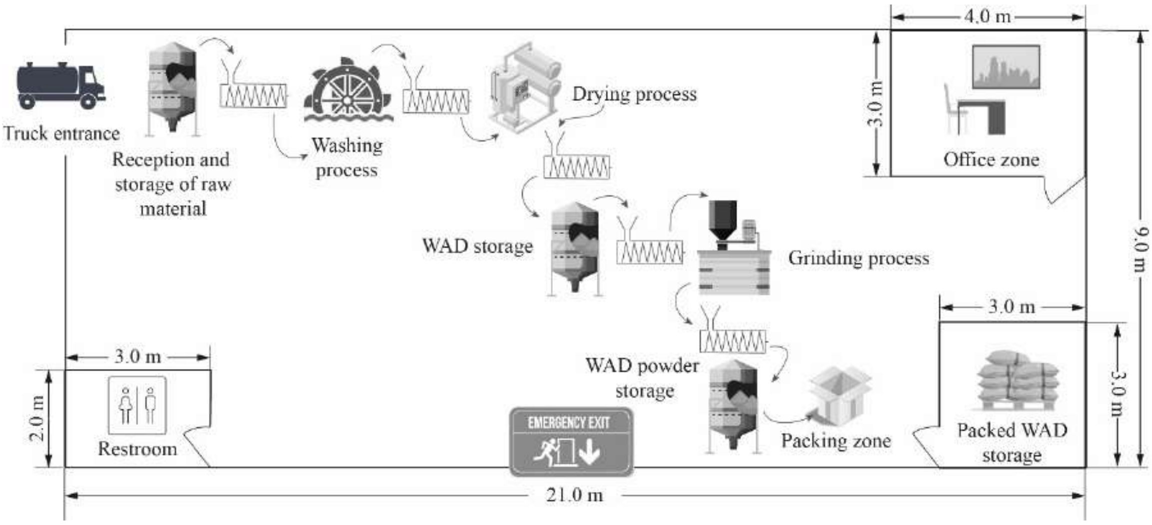


Figure 9. General plant layout.

To calculate the required areas, the Guerchet method was applied, considering the equipment dimensions and the space requirements for work and storage areas. The finished product storage area considered the size and capacity of pallets for stacking the packaged material. Based on these considerations, it was determined that the plant requires an area of 283 m^2. Figure 10 presents the theoretical plant distribution in equivalent surface units (ESU), with a conversion base of four used for the dimension conversions.

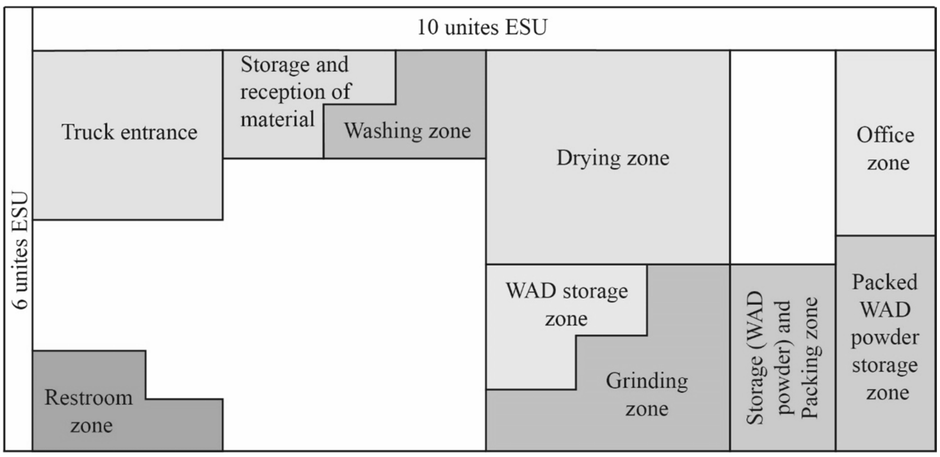


Figure 10. Theoretical plant layout.

Workforce Requirements: Based on the technical specifications of the equipment and the installed capacity of the process, parameters such as processing time and speed were established. By utilizing SIMIO software, the process was simulated using the waste generation amount of 75 tons per month as per the application case. The simulation revealed that the process requires 12 h to complete. However, considering preparation times, cleaning, active breaks, and administrative activities, this translates to two work shifts of 8 h each. Each shift requires two operatives to execute all process activities. Therefore, a total of four operatives needs to be hired. Additionally, the hiring of a plant manager is necessary to oversee process control and staff inspection. It is important to note that the workforce analysis focused solely on the personnel required for production and did not consider commercial or administrative activities.

3.4. Financial Analysis for the Application Case

Once the resources required for the AD transformation were determined, the total investment value for equipment and adaptations was calculated at USD 43,000 (Meneses-Núñez et al., 2022) [44]. Subsequently, a financial projection of the income statement was conducted, serving as the basis for projecting cash flow over a 5-year period, as presented in Table 6. The cash flows were projected with a constant inflation rate of 3.6%, based on the projections from the Colombian central bank at the time the study. Additionally, a tax rate of 35% was considered in accordance with the tax regulations for 2022.

Table 6. Projected cash flow.

Project Cash Flow	0	1	2	3	4	5
Operational Profit		7.527	10.848	11.393	11.957	12.542
Operating taxes		2.635	3.797	3.987	4.185	4.390
Net Operating Income		4.893	7.051	7.405	7.772	8.152
+ Depreciation or amortization		4.283	4.283	4.283	4.283	4.283
Gross Cash Flow		9.176	11.335	11.689	12.055	12.435
− Fixed Asset Investments	42.835					
Project Free Cash Flow	42.835	9.176	11.335	11.689	12.055	12.435

Among the most significant direct costs, workforce expenses account for 45% of the total production cost, followed by energy costs representing 19.5% of the total. In this particular application case, no cost was assigned to the raw material, as the waste generator itself will be responsible for transforming it into a reusable material.

Regarding the total investments required, it was determined that 50% of the financing would be obtained from financial institutions at an annual effective rate of 8.7%. This rate was based on the financing rates available to the company in the application case from the financial sector. With this capital structure in place, a weighted average cost of capital (WACC) of 9.7% annually was calculated.

Using these data, the sales value per kilogram of recovered dross was determined to satisfy the expression NPV = 0, forming the basis for projecting the cash flow income. It was found that the sale price must be at least USD 0.12 per kilogram for the project to be feasible. This price corresponds to having an internal rate of return (IRR) equal to or greater than the WACC and a benefit-to-cost ratio of 1. According to financial theory, this implies that the project's revenues compensate for investments and operating costs and generate returns that are at least equal to the cost of capital.

These findings not only demonstrate the feasibility of the specific project in the Colombian case but also contribute to the broader field of research by showcasing a circular economy application that goes beyond technical validation. Analyzing the financial implications of implementing such a project highlights the potential for developing new markets with a stronger environmental focus. Calculation of the minimum market price serves as an initial step that reveals opportunities for the expansion of environmentally-oriented markets. In fact, the City Hall of Santiago de Cali (Colombia) is evaluating a circular economy model for the construction sector, which stimulates the use of sustainable building materials containing by-products coming from different local industrial sectors [45]. Although initial evaluation has been oriented towards the environmental and economic waste valorization coming from the steel production and coal combustion factories [46], the local aluminum industry has a great potential to generate supplementary cementitious materials as reported here.

4. Conclusions

The chemical characterization through XRD revealed that the washing process resulted in a significant reduction in the AlN content, decreasing from 18.2% in AD to 2.3% in WAD. This finding holds considerable importance as it is well known that AlN, when exposed to water, produces ammonia gases, which can be harmful to the health of operators. Furthermore, when used in cementitious materials, the accumulation of these gases during mixing with water can lead to void formation, potentially compromising the mechanical properties of the materials.

The impact mill yielded superior results, achieving up to 56.21% of particles smaller than 45 µm in just 10 min of processing. Kinetic analysis projected that 66% of material with particle sizes below 55 µm can be obtained in 12 min. This is crucial to satisfy the particle size requirements stipulated by ASTM C618-19 for the use of WAD in cementitious matrices.

With the chosen equipment's capacity, an estimated 80,000 kg of aluminum dross can be recycled monthly. A manufacturing plant of 283 m^2 can be allocated to accommodate various operation stages, ensuring ample space for the 11 defined areas involved in the process. These capacity and facility requirements are pivotal considerations for the practical implementation of AD recycling. To execute the proposed process in the case study, an investment of USD 43,000 is required. Cash flow analysis revealed that a minimum selling price of USD 0.12/kg of processed material can generate a return rate of at least 9.7% over a five-year period. These findings hold significance for aluminum factories, cement producers, investment institutions, policymakers, and environmental authorities, as they illustrate the potential for cultivating a new market for this material, with both economic and environmental implications at the forefront.

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Abbreviations

Al	Aluminum
Al_4C_3	Aluminum carbide
AD	Aluminum dross
AlN	Aluminum nitride
Al_2O_3	Aluminum oxide
Al_5O_6N	Aluminum oxide nitride
NH_3	Ammonia
ASTM	American Society for Testing and Materials
AHP	Analytic hierarchy process
B/C	Benefit/cost ratio
$CaCO_3$	Calcite
CaO	Calcium oxide

ACOPI	Colombian Association of Micro, Small, and Medium Enterprises
CR	Consistency ratio
CuK-α	Copper k-α
Na_3AlF_6	Cryolite
$NaAl_{11}O_{17}$	Diaoyudaoite
K_2NaAlF_6	Elpasolite
EDS	Energy-dispersive X-ray spectroscopy
ESU	Equivalent surface units
Fe_2O_3	Ferric oxide
CaF_2	Fluorite
γ-Al_2O_3	Gamma alumina
$CaAl_{12}O_{19}$	Hibonite
H_2	Hydrogen gases
IRR	Internal rate of return
MgF_2	Magnesium fluoride
MgO	Magnesium oxide
CH_4	Methane
NPV	Net present value
NMP	Non-metallic products
$KMgF_3$	Parascandolaite
KCl	Potassium chloride
$KAlCl_4$	Potassium tetrachloroaluminate
PV	Priority vector
SEM	Scanning electron microscopy
Si	Silicon
SiO_2	Silicon dioxide
NaCl	Sodium chloride
Na_2O	Sodium superoxide
$NaAlCl_4$	Sodium tetrachloroaluminate
$MgAl_2O_4$	Spinel
SLP	Systematic layout planning
WAD	Washed aluminum dross
λ	Wavelength
WACC	Weighted average cost of capital
XRD	X-ray diffraction analysis

Appendix A

Table A1. Disney Method: Recovering Alternatives for Aluminum Dross.

Dreamer (Why Not?)	Realistic (How?)	Critical (What is Wrong?)
Guarantee Creativity	**Ensures Feasibility**	**Prevents Possible Risks**
Expanded clay aggregates (Bajare et al., 2012) [47]	Removal of impurities by heat treatment, preparation of clay pastes and non-metallic products (NMP) samples, drying, and finally synthesis in an oven at 1170–1210 °C.	• Risk of not having the necessary implements for the process; • Risk of not achieving the removal of impurities; • Risk of increased costs.
*NMP refractories without additions (Ramaswamy et al., 2019) [48]	Washing the NMP at 200 °C to remove salts, calcination at 100 °C, and NMP compaction and calcination at 1500 °C. Thermal shock tests at 660 °C.	• Risk of not having the necessary implements for the process.; • Risk of not achieving salt removal; • Risk of increased costs.

Table A1. *Cont.*

Dreamer (Why Not?)	Realistic (How?)	Critical (What is Wrong?)
Guarantee Creativity	**Ensures Feasibility**	**Prevents Possible Risks**
Preparation of gamma alumina (γ-Al_2O_3) by pyrometallurgical process (Mahinroosta & Allahverdi, 2018) [5]	The NMP is fed to the plasma flame, and argon is used as the carrier gas. The particle size to be obtained is 8 µm.	• Sophisticated and expensive process; • Risk due to the difficulty of implementation.
*Preparation of gamma alumina (γ-Al_2O_3) by hydrometallurgical process (Shen et al., 2021). [49]	These processes consist of three steps: alkaline or acid solution of NMP, precipitation of the filter liquid, and calcination of the precipitate.	• Risk of not having the necessary implements for the process; • Risk of not achieving the removal of impurities; • Risk of increased costs.
Replacement of aluminum powder as a foaming agent for synthesizing light cellular concrete (Liu et al., 2017). [50]	Grinding and sieving to achieve a particle size of 45 µm.	• Risk of not having the necessary implements for the process; • Risk of increased costs.
*Partial replacement of Portland cement for concrete production (Elinwa & Mbadike, 2011; Javali et al., 2017; Mailar et al., 2016; Ozerkan et al., 2014; Reddy & Neeraja, 2016) [21–24,51]	The dross should be ground, sieved using a 90 µm sieve, and a shutdown process should be carried out.	• Risk of not having the necessary implements for the process; • Risk of not achieving contact with cement companies.
*Replacement of Portland cement in mortar production (Dai & Apelian, 2017; Pereira et al., 2000) [14,52]	The dross should be washed in distilled water, dried on a heating plate, and then added to the mortar mixture.	• Risk of not having the necessary implements for the process; • Risk of not achieving contact with cement companies.
Production of ceramics based on magnesium titanate and aluminum (Ewais & Besisa, 2018) [53]	Grinding and sieving to achieve a particle size less than 90 µm; powders must be mixed using a mill, impurities are removed with boiling water and then with cold water, and the synthesized materials are obtained by cooking at 1300 °C.	• Risk of not having the necessary implements for the process; • Risk of increased costs.
*Production of polypropylene compound and aluminum dross (Adeosun et al., 2012; Samat et al., 2017) [54,55]	Lumps of dross should be crushed and sieved into particles of size from 53 µm to 150 µm.	• Risk of not having the necessary implements for the process; • Risk of increased costs; • Risk of not achieving contact with polypropylene companies.
Production of silicate-based glass (Mahinroosta & Allahverdi, 2018) [5].	The NMP-washing process must be carried out, and the residue or mineral glass of low silicon content must be melted in a CaO–Al_2O_3 system.	• Risk of not having the necessary implements for the process; • Risk of increased costs; • Risk due to the difficulty of implementation.

Appendix B

The scores assigned to the five selected alternatives in the AHP are presented in Table A2. It is noteworthy that Alternative 1 had the highest associated cost due to the high energy consumption required in the sintering process of refractories. In terms of "ease of implementation", Alternatives 1 and 4 were classified as having a low level of difficulty in implementation, as the necessary equipment and spaces for the development of these applications, such as mills, muffles, and sieves, are available for this study. In contrast, in the "environmental impact" criterion, Alternatives 1, 3, and 4 were evaluated as having a low impact. This is because the substitution of raw materials like cement with post-industrial waste like AD leads to a dual benefit of reducing the use of materials with high carbon footprint and utilizing a waste that could cause environmental harm if disposed of improperly.

Table A2. Evaluation of AHP criteria for each alternative.

	Alternatives	Criteria				
		C1: Cost	**C2: Ease of Implementation**	**C3: Availability of Information**	**C4: Specification Compliance**	**C5: Environmental Impact**
1	NMP refractories without additions	0	2	1	1	2
2	Preparation of gamma alumina (γ-Al_2O_3) by hydrometallurgical process	1	0	1	2	0
3	Partial replacement of Portland cement for concrete production	2	1	2	2	2
4	Replacement of Portland cement in mortar production	2	2	2	2	2
5	Production of polypropylene composite and AD	1	0	2	2	1

For the purpose of establishing the relationships between the alternatives and criteria, a visual tool (Table A3) was employed to ensure the proportionality and transitivity of the paired comparisons assigned to the AHP methodology, thereby affirming the consistency of the results. The table shows the proportional relationship between the reference and the comparison, be it an alternative or criterion. Moving columns to the right indicates a directly proportional relationship between the number of movements (e.g., C2 = 3C3), whereas moving columns to the left signifies an inversely proportional relationship (e.g., A1 = 1/5 A3).

Table A3. Visual tool to establish comparisons between criteria and alternatives.

		More Preference than Reference						←		**Reference**	→	**Less Preference than Reference**						
		1/9	**1/8**	**1/7**	**1/6**	**1/5**	**1/4**	**1/3**	**1/2**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Criteria comparison								**C4**	**C5**	**C2**	**C1**	**C3**						
Comparison of alternatives by criterion	C1					A3 A4		A2 A5		A1								
	C2									A1 A4		A3		A2 A5				
	C3							A3 A4 A5		A1 A2								
	C4							A2 A3 A4 A5		A1								
	C5									A1 A3 A4		A5		A2				

After establishing the relationships between criteria and alternatives using the visual tool, the assigned values were transferred to the AHP comparison matrix (Table A4). This allowed the determination of the priority vector (PV), which represents the relative importance of the criteria when compared to each other and the alternatives when compared within each criterion. Additionally, the consistency ratio (CR) was calculated for each of the 5 × 5 paired matrices using the AHP. It is worth noting that the consistency ratios for all cases were found to be less than 10%, indicating that the comparisons adhere to the principles of transitivity and proportionality.

Table A4 shows the relative importance of the selection criteria when compared to each other. It is evident that C4 (compliance with specifications) holds the highest significance, with a priority of 41.6%, followed by C5 (environmental impact) with 26.2%. Additionally, when comparing the alternatives within each criterion, certain patterns emerge. For C1 (cost), Alternatives A3 and A4 have the lowest cost priority, both at 34%. In terms of C2 (reliability of implementation), A1 and A4 exhibit higher priority (36%). Regarding C3 (availability of information), A3, A4, and A5 indicate a higher level of information availability. In terms of C4 (compliance with specifications), all alternatives require compliance at a priority of 27% except for A1. Lastly, A1, A3, and A4 are noted for their higher environmental impact (C5), with a priority of 28%.

Table A4. Matrix of comparison by pairs according to criteria and alternatives for each criterion.

Criteria	C1	C2	C3	C4	C5	PV	CR
C1	**1**	1/2	2	1/4	1/3	9.9%	1.4%
C2	2	**1**	3	1/3	1/2	16.1%	
C3	1	1/3	**1**	1/5	1/4	6.2%	
C4	4	3	5	**1**	2	41.6%	
C5	3	2	4	1/2	**1**	26.2%	

C3	A1	A2	A3	A4	A5	PV	CR
A1	**1**	1	1/3	1/3	1/3	9.1%	0.0%
A2	1	**1**	1/3	1/3	1/3	9.1%	
A3	3	3	**1**	1	1	27.3%	
A4	3	3	1	**1**	1	27.3%	
A5	3	3	1	1	**1**	27.3%	

C1	A1	A2	A3	A4	A5	PV	CR
A1	**1**	1/3	1/5	1/5	1/3	5.6%	1.2%
A2	3	**1**	1/3	1/3	1	13.0%	
A3	5	3	**1**	1	3	34.2%	
A4	5	3	1	**1**	3	34.2%	
A5	3	1	1/3	1/3	**1**	13.0%	

C4	A1	A2	A3	A4	A5	PV	CR
A1	**1**	1/3	1/3	1/3	1/3	7.7%	0.0%
A2	3	**1**	1	1	1	23.1%	
A3	3	1	**1**	1	1	23.1%	
A4	3	1	1	**1**	1	23.1%	
A5	3	1	1	1	**1**	23.1%	

C2	A1	A2	A3	A4	A5	PV	CR
A1	**1**	5	3	1	5	35.8%	1.2%
A2	1/5	**1**	1/3	1/5	1	6.5%	
A3	1/3	3	**1**	1/3	3	15.5%	
A4	1	5	3	**1**	5	35.8%	
A5	1/5	1	1/3	1/5	**1**	6.5%	

C5	A1	A2	A3	A4	A5	PV	CR
A1	**1**	5	1	1	3	28.1%	0.9%
A2	1/5	**1**	1/5	1/5	1/3	5.1%	
A3	1	5	**1**	1	3	28.1%	
A4	1	5	1	**1**	3	28.1%	
A5	1/3	3	1/3	1/3	**1**	10.8%	

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