IOSR Journal of Business and Management (IOSR-JBM)
e-ISSN:2278-487X, p-ISSN: 2319-7668. Volume 27, Issue 8. Ser. 7 (August. 2025), PP 16-26
www.iosrjournals.org

Characterization Of Crushed Granite Powder From Tracuateua (Pa, Brazil) For Use As Supplementary Cementitious Material

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Abstract:
Background*: The search for sustainable materials in civil construction has driven research on mineral waste as alternatives to Portland cement. This study presents a comprehensive characterization of Crushed Granite Powder Residue (CGPR) from Tracuateua (PA, Brazil), evaluating its potential as a supplementary cementitious material. The research is part of the broader context of seeking sustainable solutions in civil construction, motivated by the environmental impacts associated with cement production, particularly* CO_2 *emissions. Tracuateua, in northeastern Pará, is a significant granite extraction hub, generating large quantities of mineral waste without proper disposal, highlighting the importance of valorizing such materials.*
Materials and Methods*: The methodology involved physical, chemical, and mineralogical characterization of Crushed Granite Powder (CGP) through tests conducted at UFPA laboratories and a specialized facility. Samples were tested in both raw and processed states, undergoing grinding, sieving, granulometric distribution analysis, fineness (Blaine), specific gravity, pozzolanic activity index (PAI), X-ray fluorescence (XRF), X-ray diffraction (XRD), and environmental leaching and solubility tests. CP II-F 32 cement, metakaolin, and silica fume were used as reference materials for comparison.*
Results*: The results indicated that CGP exhibits physicochemical properties compatible with recognized pozzolanic materials. Its composition revealed high levels of silica (71.10%), alumina (15.51%), and iron oxide (1.52%), totaling 88.13% of these oxides—exceeding the minimum required by Brazilian technical standards for pozzolanic classification. Pozzolanic activity tests showed satisfactory performance: compressive strength of 6.56 MPa with lime (above the 6 MPa requirement) and a 94.33% index when partially replacing cement (surpassing the 90% minimum). Granulometric and specific surface area analysis demonstrated that, after processing, CGP exhibits intermediate characteristics between Portland cement and industrial pozzolans, with good fineness and reactivity potential.*
Conclusion: *CGP is a promising alternative for partial cement replacement, aligning with circular economy principles by transforming an environmental liability into a sustainable resource. The study paves the way for future research on processing optimization and applications in mortars and concrete.*
Key Words*: Crushed Granite Powder, supplementary cementitious material, pozzolanic activity, sustainability.*

Date of Submission: 12-08-2025 Date of Acceptance: 22-08-2025

I. Introduction

The construction sector plays a pivotal role in global economic growth, driving employment, infrastructure development, and urbanization. However, this expansion presents substantial environmental challenges, particularly concerning sustainability. The construction industry consumes extensive natural resources, spanning from raw material extraction to structural demolition. These impacts underscore the urgent need for sustainable practices that harmonize economic advancement with environmental conservation. Portland cement remains one of the most extensively utilized materials in construction, serving as a fundamental component across all building phases—from foundations to finishes. Nevertheless, its production process generates significant environmental burdens, chiefly due to carbon dioxide (CO_2) emissions during clinker sintering, its primary raw material [16].

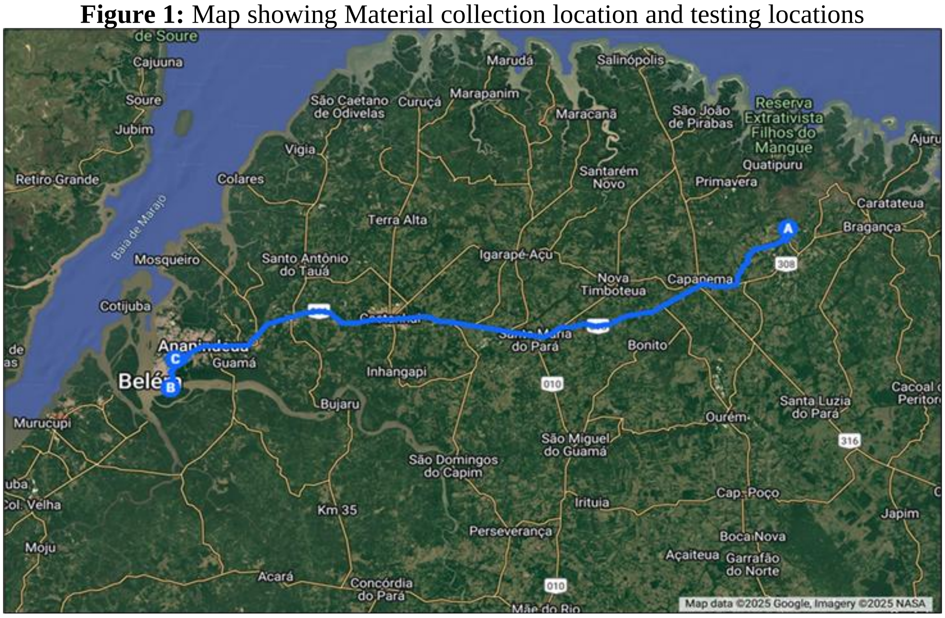
To address this challenge, numerous studies have explored sustainable alternatives to mitigate cement production's environmental footprint. Mineral admixtures have emerged as a technically viable solution, exhibiting properties conducive to more sustainable production [15]. Among potential sources of such supplementary materials, waste from steelmaking and mining operations is particularly noteworthy. As demonstrated by [12], mineral extraction enterprises are increasingly investing in research to valorize industrial byproducts. This strategy not only enhances operational efficiency but also reduces waste management costs, aligning with circular economy principles and sustainable development goals. In this context, *Crushed Granite Powder (CGP)* —a byproduct from granite aggregate extraction in Tracuateua, Pará—has shown promise as a partial Portland cement substitute. Its chemical composition, characterized by high SiO_2 (71.10%) and Al_2O_3 (15.51%) content, facilitates pozzolanic reactions that form calcium aluminates and iron silicates. These compounds enhance mechanical properties while reducing cement demand.

This study aims to comprehensively characterize CGP by investigating its physicochemical properties and evaluating its pozzolanic potential for cementitious applications. Mineralogical and morphological analyses will determine its chemical composition, crystalline structure, and particle size distribution. Special emphasis will be placed on its high fineness and specific surface area—critical parameters governing its behavior in cementitious systems. This research seeks to validate CGP as a sustainable partial cement replacement, simultaneously reducing non-renewable resource consumption and transforming an environmental liability into a valuable material. By adhering to circular economy principles, the study proposes a technically feasible and ecologically responsible solution for the construction industry.

II. Materials And Methods

The research was conducted in Belém, Pará, with tests performed at the Civil Construction Laboratory of the Federal University of Pará (LEC-UFPA), located at point B in Figure 1, and at the specialized laboratory - Totalmix Technological Control in Concrete and Mortar, located at point C in Figure 1. All experimental procedures strictly followed current technical standards. The methodological procedures adopted sought to ensure data quality and reproducibility, which are essential for characterizing the material and evaluating its performance when incorporated into cementitious matrices. To characterize the CGP used in this research, tests were performed on samples in two conditions: "Raw" CGP (collected directly from the factory) and Processed CGP (treated by the author in the laboratory). We performed tests according to the standards specified in Table 1. These analyses were performed after the grinding and sieving process of this material to comply with technical standards.

Figure 1: Map showing Material collection location and testing locations



Source: Adapted from Google Earth, 2025

The characterization of the CGP included various techniques to evaluate its physicochemical and mineralogical properties. The chemical composition was determined by X-ray fluorescence spectrometry (XRF), while the crystalline phases were identified by X-ray diffractometry (XRD). The particle size distribution of the raw material was evaluated according to the procedures established in NBR 17054 (ABNT, 2022). After the residue was ground, tests were conducted to determine the pozzolanic activity index, using both calcium hydroxide and Portland cement as references. This followed standardized methodologies, allowing for a profile of the material, covering its fundamental properties and its potential application as a supplementary pozzolanic material in concrete and mortar.

Table 1: Outline of the tests carried out in the research

Standards used in Granite Crushed Stone Powder characterization tests		
Characterization	**Test**	**Method**
Physical	Particle size distribution	NBR 17054 (ABNT, 2022)
	Fineness (Blaine method)	NBR 16372 (ABNT, 2015)
Evaluation of pozzolanic activity	Pozzolanic Activity Index (PAI) with cement	NBR 5752 (ABNT, 2014)
	Pozzolanic Activity Index (PAI) with lime	NBR 5751 (ABNT, 2015)
Chemical	X-ray fluorescence spectrometry (XRF)	NBR 14656 (ABNT, 2023)
Mineralogical	X-ray diffraction (XRD)	-
Environmental	Leaching tests	NBR 10005 (ABNT, 2004)
	Solubility tests	NBR 10006 (ABNT, 2004)

Source: Author, 2025

Materials

Crushed Granite Powder (CGP)

The material studied consists of residue from the granite crushing process, collected directly from a mineral processing plant located in the municipality of Tracuateua, in northeastern Pará. This region, located approximately 200 km from the capital, Belém, has a tradition of rock extraction and processing, with crushing operations duly registered since the 1990s. The precise location of the CGP production unit is represented at point A in Figure 1, which illustrates its geographic position within the regional context.

Figure 2: Gravel dust deposit near the plant in Tracuateua (PA, Brazil).

Source: Author, 2025

Silica Fume

The silica fume used in this study was sourced in Belém, Pará, Brazil. This highly reactive pozzolanic material is a byproduct of metallic silicon or ferrosilicon production, complying with the specifications of NBR 13956 (2019). It contains over 90% SiO_2, exhibits a loss on ignition (LOI) below 6%, and has an average particle size under 45 µm, ensuring its effectiveness as a mineral admixture in high-performance composites.

Metakaolin

The metakaolin used in this study was purchased in Belém, Pará, and produced from the controlled calcination of kaolin, a clay mineral rich in aluminosilicates. The material used meets the specifications of NBR

15895 (2019), presenting a SiO_2 + Al_2O_3 content greater than 85%, loss on ignition less than 2%, and an average particle size below 20 µm, characteristics that ensure its effectiveness in modifying cementitious matrices.

Fine Aggregate

The sand used in the study fully meets the requirements established by NBR 7214 (ABNT, 2015), characterized as a standardized natural material with a predominance of quartz grains with rounded to rounded morphology. The material was supplied by the Technological Research Institute of the State of São Paulo (IPT) and complies with all the physical and chemical parameters specified by the technical standard.

Portland Cement

CP II – F 32 cement was used to perform the pozzolanic activity determination tests described in the standard. This material was selected based on its specific technical properties: a characteristic compressive,strengthof 32 MPa at 28 days, a pozzolanic content of 6% to 10%, and an addition of 6% to 10% limestone filler as specified by standard NBR 11578 (ABNT, 2015). The material was purchased from accredited suppliers in the capital of Pará, ensuring the quality and origin of the input used in the research.

Water

The water used in the experiments was obtained from the public water supply system of the Belém Metropolitan Region, provided by the Pará Sanitation Company (COSANPA), and met the potability standards established by current Brazilian legislation (Ordinance GM/MS No. 888, 2021).

Methods

Particle Size Distribution of the Raw Waste

After collecting the material, characterization tests were performed on the waste, with particle size analysis being the first test performed. The particle size distribution test was performed at the Construction Materials Laboratory (LEMAC) of the Federal University of Pará (UFPA), strictly following the technical specifications established by Brazilian standard NBR 17054 (ABNT, 2022). Using the data collected during the test, a graph representing the particle size distribution of the raw material was constructed. This graphical representation allowed a more detailed assessment of the particle size composition of the crushed stone powder, providing essential information on the proportion of different particle sizes present in the material. Analysis of these results is essential for understanding the physical characteristics and their potential practical applications.

Grinding and Sieving of the Material

The Crushed Granite Powder Residue (CGPR) beneficiation process began with the dry grinding stage, conducted at the Experimental Laboratory of Construction Materials (LEMAC) of the Federal University of Pará. For this operation, an EMIC ball mill equipped with a porcelain jar and grinding ball system with a nominal capacity of 7 liters (Figure 3) was used. The equipment operated at a constant speed of 12 rpm throughout the process, a parameter maintained uniformly throughout all material comminution stages.The grinding body configuration followed proportions established by [13], maintaining a ball mass to material mass ratio of 5:1, distributed into specific fractions: 2/3 of the total consisting of smaller diameter balls and 1/3 of larger balls. The grinding time was set at 45 minutes, a parameter determined based on studies by [18], who demonstrated the effectiveness of this process in obtaining material with a particle size distribution equivalent to or finer than that of conventional Portland cement. After the comminution process, the Crushed Granite Powder (CGP) exhibited markedly powdery physical and morphological characteristics and was subsequently sieved. This additional step, also performed at LEMAC, consisted of separating the ground material through a standard 200-mesh sieve (75μm nominal opening), ensuring the uniformity required for subsequent characterization and application steps. The integrated process yielded 6 kg of material suitable for the research purposes.

Figure 3: Ball mill equipment at the LEMAC/UFPA laboratory

Source: Author, 2025

Specific Gravity and Specific Surface Area (Blaine)

The tests were conducted at the specialized laboratory - Totalmix Technological Control in Concrete and Mortar. The specific gravity of Crushed Granite Powder, Silica Fume, and Metakaolin were determined according to ABNT NBR 16605 (2017) and performed using Le Chatelier glassware.

The fineness of the materials was determined using the Blaine air permeability method, following the procedures established in ABNT NBR 16372 (2015). This test quantifies the specific surface area, defined as the total surface area per unit mass (expressed in cm^2/g or m^2/kg), a fundamental parameter for evaluating the material's reactivity and its bonding capacity in cementitious matrices, such as concrete and mortar.

Pozzolanic Activity Index (PAI) – Calcium Hydroxide and Cement

The pozzolanic activity of CGP was evaluated through mechanical tests on mortars containing hydrated lime and Portland cement, following the Brazilian technical standards NBR 5751 (2015) and NBR 5752 (2014), respectively. The study investigates the effectiveness of CGP as a pozzolanic material using two distinct approaches: one based on reaction with calcium hydroxide and the other as a partial replacement for Portland cement. In the test conducted in accordance with NBR 5751, pozzolanic activity was determined based on the mechanical strength of mortars composed of CGP, calcium hydroxide, standardized sand, and water. The amount of water was adjusted to achieve a consistency of 225 ± 5 mm, measured on the consistency table at the Civil Construction Laboratory of the Federal University of Pará (LEC-UFPA). The mortars were cured for seven days, and their compressive strength was assessed to verify that the material met the minimum requirement of 6.0 MPa, the standard value for classifying a material as satisfactory pozzolanic.

In the test based on NBR 5752, pozzolanic activity was determined by comparing the mechanical performance of two mortars: a reference mortar composed exclusively of Portland cement, sand, and water, and another in which 35% of the cement volume was replaced by CGP. Both mortars were prepared with a 1:3 mass ratio (binder:sand) and a standardized consistency of 225 ± 5 mm. The Pozzolanic Activity Index (PAI) was calculated as the ratio between the compressive strength of the mortar containing CGP and that of the reference mortar, both after 28 days of curing. For the material to be considered pozzolanic, the PAI must be greater than 90%, indicating that the partial replacement of cement did not significantly compromise its mechanical strength.

X-ray fluorescence (XRF) and X-ray diffractometry (XRD) analysis

For mineralogical analysis by X-ray diffraction (XRD), an aliquot of approximately 3.0 grams of the sample was homogenized by quartering and then pulverized in a Retsch McCrone® mill, using agate elements to avoid contamination. Grinding was carried out for 20 minutes in a suspension with deionized water. After this process, the sample was oven-dried at 60°C and then mounted in a backload sample holder for analysis in the diffractometer. For determination of chemical composition by X-ray fluorescence (XRF), an aliquot of approximately 5.0 grams was subjected to quartering and grinding in a planetary ball mill with agate elements for 8 minutes. The sample was then dried at 105°C for 12 hours and calcined at 1000°C for 5 hours to determine the mass loss or gain on ignition (LOI/GOI). Subsequently, 1.0 gram of the calcined sample was fused with lithium tetraborate to obtain homogeneous pellets suitable for quantitative analysis.

XRD analyses were conducted on a Bruker D8 Discover diffractometer using copper (Cu-Kα1) radiation with a Bragg-Brentano (θ-2θ) configuration, angular scanning from 5° to 90° (2θ), 0.01° step, and sample rotation at 15 rpm to improve counting statistics. XRF was performed on a Bruker S8 Tiger spectrometer equipped with a rhodium (Rh) tube and wavelength-dispersive detectors (WDS), using the GeoQuant M® package and certified calibration standards. The results were expressed as a percentage by mass, on a wet basis, ensuring accurate quantification of the oxides present. These combined methods allowed for a detailed characterization of the mineralogical and chemical composition of the samples, essential for evaluating their potential as pozzolanic materials and their application in cementitious matrices.

Leaching and Solubility Test

The leaching and solubility methods described in Brazilian standards NBR 10005 and NBR 10006 (ABNT, 2004) are essential for characterizing the percolation potential of contaminants present in solid waste. NBR 10005 addresses the leaching test itself, simulating the conditions of contact between the waste and water over time. The procedure consists of subjecting a sample of the fragmented waste to a standardized aqueous extractor, at a defined liquid-to-solid ratio (20:1), under continuous agitation for 18 hours. The resulting extract is then separated by filtration and collected for analysis of heavy metals and other potentially hazardous chemical compounds, aiming to assess the mobility of these elements under conditions similar to those of the environment.

NBR 10006 evaluates the solubilization of contaminants in direct contact with water, without pH adjustment, simulating less aggressive conditions, such as exposure to rain or infiltration into water bodies. The procedure consists of stirring the residue with deionized water in a 10:1 ratio (liquid:solid) for 24 hours, followed by decantation, filtration, and analysis of the extract. While NBR 10005 is more suitable for prolonged leaching scenarios, NBR 10006 provides data on the immediately soluble fraction, complementing environmental risk assessment. Both standards are widely used in Brazil in accordance with NBR 10004, which establishes criteria for classifying solid waste according to its risks to the environment and public health.

III. Result

Particle Size Distribution of Raw Waste

Particle size analysis of raw waste reveals fundamental characteristics of particle distribution and its technical implications. The maximum diameter (MD) of 4.75 mm, determined according to NBR 17054 (ABNT, 2022), indicates that the material does not present significantly coarse particles, limited to a size range that can be classified as fine to medium. The fineness modulus (MF) of 2.83 indicates a balanced distribution among fine fractions. The data obtained corroborate the findings of [14] who identified a fineness modulus of 2.80 and a maximum characteristic dimension of 4.76 mm in equivalent analyses in their research. The curve presents a moderate slope, reflecting the presence of particles in various size ranges, without a marked dominance of fine fractions. The tests demonstrated that the quarry fines met the requirements of the standard for fine aggregate in concrete, considering: (i) the granulometric curve positioned within the optimal range; and (ii) the fineness modulus within the specified parameters.

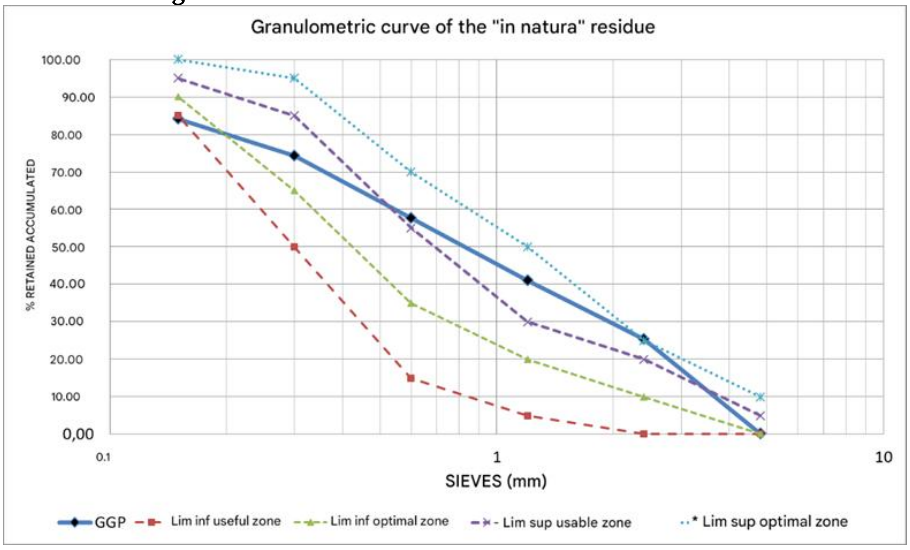
The granulometric analysis performed showed that only 9.18% of the material had particles smaller than 75 µm (200 mesh), indicating a relatively low amount of fines in the sample. This fraction is particularly relevant, as particles with this size approximate the typical granulometric range of Portland cement, which plays a fundamental role in the development of pozzolanic reactions. To ensure greater effectiveness in the reactions and, consequently, better utilization of the material's pozzolanic potential, it is necessary to reduce the particle size through controlled grinding, followed by sieving through a 200 mesh (75 µm), in accordance with the normative specifications. This step increases the proportion of particles in the target range, making it closer to the particle size distribution of industrial pozzolans, such as metakaolin and silica fume. Grinding promotes the rupture of larger grains, releasing reactive silica and alumina originally encapsulated in denser crystalline structures, while screening ensures precise separation of the optimized fraction. This procedure ensures a more appropriate particle size distribution, increasing the specific surface area and consequently improving chemical reactivity.

Table 2: Determination of the granulometric composition of the "in natura" residue.

Test	Sieve opening (mm)	Percentage retained		Passing Percentage (%)	Test Method
		Individual	Accumulated		
Granulometric Composition	9.5	0.00%	0.00%	100.00%	NBR 17054 (ABNT, 2022)
	6.3	0.00%	0.00%	100.00%	
	4.8	0.20%	0.20%	99.80%	
	2.4	25.20%	25.40%	74.60%	
	1.2	15.65%	41.05%	58.95%	
	0.6	16.65%	57.70%	42.30%	
	0.3	16.65%	74.35%	25.65%	
	0.15	9.82%	84.17%	15.83%	
	0.075	6.65%	90.82%	9.18%	
	< 0.075	9.18%	100.00%	0.00%	
Maximum characteristic dimension				4.8 mm	NBR 17054 (ABNT, 2022)
Fineness modulus				2.8 mm	NBR 17054 (ABNT, 2022)

Source: Author, 2025

Figure 4: Granulometric curve of the "in natura" residue.



Source: Author, 2025

Specific Gravity and Surface Area (Blaine)

The physical characteristics of the analyzed materials highlight properties that directly influence their behavior in cement applications. CP II-F-32 cement has the highest specific gravity (3.07 g/cm³), a value typical of Portland cements due to its dense composition of clinker and additives. In contrast, CGP has a specific gravity of 2.70 g/cm³, lower than cement but consistent with its rocky origin, rich in less dense silicates such as quartz and feldspars. Silica fume and metakaolin have even lower specific gravities (2.22 g/cm³ and 2.56 g/cm³, respectively), reflecting their more porous and lightweight structures. This difference is particularly relevant for concrete and mortar mixes, where less dense materials can alter mass-to-volume ratios. Regarding fineness, measured by the Blaine method, metakaolin stands out with the largest specific surface area (11.294,36 cm²/g), indicating extremely fine particles that favor pozzolanic reactivity. Silica fume, although also presenting a high fineness (7.336,76 cm²/g), lags behind metakaolin, while CGP presents an intermediate value (4.938,75 cm²/g), compatible with its grinding but inferior to industrial materials.

Cement, despite its high density, presents a moderate fineness (6.057,62 cm²/g), balancing packing properties and reactivity. These data suggest that CGP, although less fine than industrial pozzolanics, has physical characteristics suitable for use as a mineral admixture, and can contribute to the compaction of the cementitious matrix without excessively compromising workability. The combination of specific gravity and fineness observed in CGP reinforces its potential as a partial cement substitute, especially when seeking to reduce density without significant loss of reactivity.

Table 3: Crushed Granite Powder Specific Gravity and Blaine Results

Materials	Specific Gravity (g/cm³)	Blaine (cm²/g)
Portland cement	3.07	6.057,62
Crushed Granite Powder	2.70	4.938,75
Silica Fume	2.22	7.336,76
Metakaolin	2.56	11.294,36

Source: Author, 2025

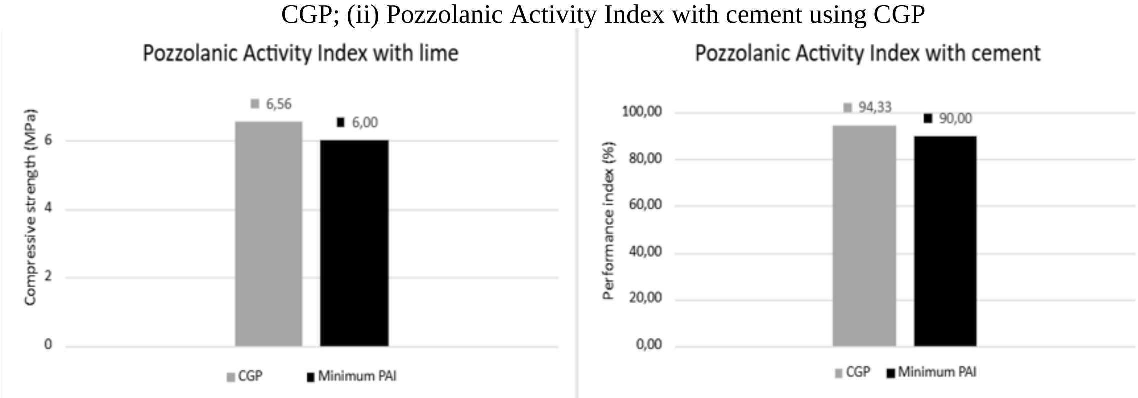
Pozzolanic Activity Index (PAI) – Calcium Hydroxide and Cement

The tests performed to determine the Pozzolanic Activity Index (PAI), both with lime and cement, allowed us to evaluate the reactivity of the analyzed material in the presence of calcium hydroxide and the cementitious medium. According to the results, in the test with lime, the compressive strength obtained for the mixture with the tested material was 6.56 MPa, higher than the minimum required by the standard, which is 6.00 MPa. This result indicates that the material exhibits satisfactory pozzolanic behavior, as its reactivity was sufficient to promote the formation of secondary cementing compounds, such as hydrated calcium silicates and aluminates, even though the value is close to the regulatory limit.

On the other hand, the test performed with cement showed even more impressive performance. The material achieved a 94.33% index, while the minimum value established by the standard is 90. This result demonstrates that the material has greater synergy with the cementitious matrix than with lime-based systems, which can be attributed to the more favorable conditions for the pozzolanic reaction present in the cementitious medium, such as greater alkalinity, calcium ion availability, and heat of hydration.

The comparison between the two tests confirms that the evaluated material can be classified as pozzolanic, meeting the requirements of ABNT NBR 12653 (2014), which regulates the criteria for pozzolanic materials in Brazil. Furthermore, the results obtained suggest that the use of this material in cementitious compositions, such as blended cements, mortars, and concretes, is technically feasible and can contribute to improving the mechanical performance and durability of the matrices, in addition to reducing clinker consumption, promoting environmental and economic benefits.

Figure 5: Graphs showing the results of pozzolanic activity tests: (i) Pozzolanic Activity Index with lime using CGP; (ii) Pozzolanic Activity Index with cement using CGP



(i) (ii)

Source: Author, 2025

X-ray Fluorescence (XRF) Analysis

X-ray fluorescence (XRF) analysis revealed the detailed chemical composition of the materials studied, with Crushed Granite Powder (CGP) standing out as the main focus. The results demonstrated that the CGP has a high silica (SiO_2) content, accounting for 71.1% of its composition, which is consistent with its origin as ground granite waste, a naturally silicate-rich rock. In addition to silica, the material also contained significant levels of aluminum oxide (Al_2O_3) and iron oxide (Fe_2O_3), at 15.51% and 1.52%, respectively. The sum of these three oxides (SiO_2, Al_2O_3, and Fe_2O_3) totaled 88.13%, exceeding the minimum requirement of 70% established by ABNT NBR 12653 to characterize a material as a pozzolanic additive. Another relevant aspect was the quantifiable absence of sulfur trioxide (SO_3), indicated in the table as "< LQ" (below the quantifiable limit).

This result is crucial, as the standard also requires that the SO_3 content not exceed 4% for the material to be classified as pozzolanic. The combination of these data—high presence of silica, aluminum, and iron, coupled with the low SO_3 concentration—confirms the viability of CGP as an effective pozzolanic material. Compared to other materials analyzed, such as metakaolin and silica fume, CGP showed an intermediate composition, with SiO_2 contents lower than those of silica fume (94.77%), but higher than those of metakaolin (51.71%). Furthermore, CGP presented significant amounts of alkaline oxides, such as Na_2O (3.75%) and K_2O (4.64%), which may influence its reactive properties in cementitious matrices.

Table 4: Chemical characterization of materials

Oxides analyzed (%)	CGP	Metakaolin	Silica Fume
SiO_2	71.10	51.71	94.77
TiO_2	0.16	<LQ	<LQ
Al_2O_3	15.51	41.51	0.19
Fe_2O_3	1.52	2.81	0.13
MnO	< LQ	< LQ	<LQ
MgO	0.33	0.12	0.45
CaO	1.12	0.22	0.40
Na_2O	3.75	0.09	0.20
K_2O	4.64	0.18	0.69
P_2O	0.37	< LQ	0.10
SO_3	< LQ	< LQ	0.10
LOI	1.06	1.33	1.99
SUM	99.56	97.97	99.02
(< LQ) = Below the quantifiable limit.			

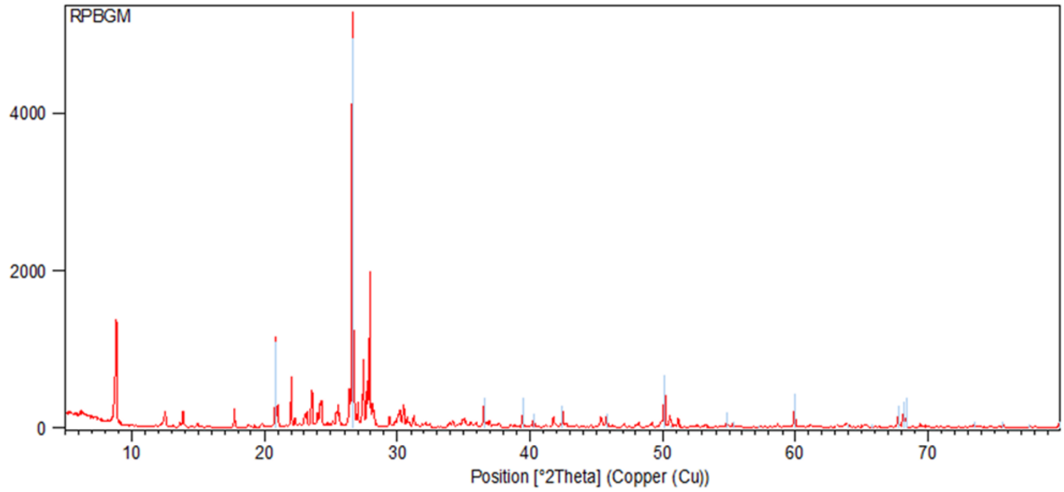
Source: Author, 2025

X-ray Diffractometry (XRD) Analysis

The diffractogram uses copper radiation (Cu-Kα) as the source. The standard selected for comparison was crystalline silica (Silicon Oxide 00-033-1161), which suggests the presence of quartz as one of the material's main mineral components. Qualitative analysis of the diffraction peaks allows us to infer the presence of typical granite minerals, such as feldspars (albite and microcline) and micas (muscovite and biotite), as confirmed by the quantitative analysis table using the Rietveld method, which indicated albite (35.17%), quartz (27.43%), microcline (22.64%), and muscovite (10.52%) as the predominant phases. The presence of quartz is corroborated by the proximity of the silica reference pattern, while the other minerals reflect the aluminosilicate nature of the material, consistent with its origin in granitic rocks.

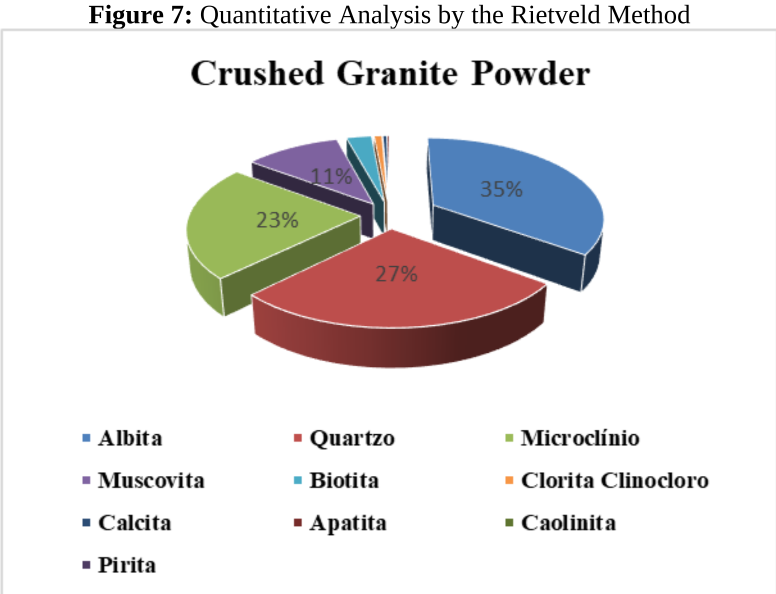
Furthermore, the absence of significant peaks of minerals such as calcite and pyrite is consistent with the low levels of CaO (1.12%) and Fe_2O_3 (1.52%) observed in the XRF analysis. The small amount of clinochlore chlorite (0.84%) and apatite (0.22%) is also consistent with the traces of MgO, P_2O_5, and other oxides detected. The XRF pattern confirms the nature of the CGP, with a predominance of silicate crystalline phases, reinforcing its potential as a pozzolanic material. The combination of these data with the XRF results (high levels of SiO_2, Al_2O_3 and Fe_2O_3) validates the compliance of the residue with the regulatory requirements for pozzolans, highlighting its viability as a partial substitute for Portland cement in sustainable applications in civil construction.

Figure 6: X-ray diffractogram (XRD) of crushed granite powder



Source: Author, 2025

Figure 7: Quantitative Analysis by the Rietveld Method



Source: Author, 2025

Leaching and Solubility Result

Table 5: Environmental Test – Leached and Solubilized Extract of CGP.

Crushed Granite Powder			
NBR 10.005 – Procedure for Obtaining Leachate Extract from Solid Waste			
Element	Permitted Concentration (mg/L) (According to Annex F of NBR 10.004)	Measured Concentration (mg/L)	Status
Cadmium	0.50	-0.0118	Concentration below the equipment detection limit
Copper	-	-0.0086	The element is not listed in the standard annex
Chromium	5.00	0.3249	Below Maximum Limit
Iron	-	-0.0675	The element is not listed in the standard annex
Manganese	-	0.7053	The element is not listed in the standard annex
Zinc	-	0.2788	The element is not listed in the standard annex
NBR 10.006 – Procedure for Obtaining Solubilized Extract from Solid Waste			
Elemento	Permitted Concentration (mg/L) (According to Annex G of NBR 10.004)	Measured Concentration (mg/L)	Status
Cadmium	0.005	-0.0154	Concentration below the equipment detection limit
Copper	2.00	-0.0115	Concentration below the equipment detection limit
Chromium	0.05	0.0098	Below Maximum Limit
Iron	0.30	-0.0894	Concentration below the equipment detection limit
Manganese	0.10	-0.0097	Concentration below the equipment detection limit
Zinc	5.00	0.0692	Below Maximum Limit

Source: Author, 2025

The leachate extraction test, conducted in compliance with NBR 10005 (ABNT, 2004), was carried out in the laboratory of a cement plant located in Currais Novos, Rio Grande do Norte, Brazil. This test aimed to evaluate the leaching potential of heavy metals and other toxic compounds from the analyzed waste material. The results, presented in Table 5, confirm full adherence to regulatory limits set by NBR 10004, with all measured concentrations falling below the permissible thresholds. Additionally, a solubilized extract test was performed following NBR 10006 (ABNT, 2004) guidelines in the same facility. This analysis assesses the release of soluble contaminants under conditions simulating material use or disposal. As shown in Table 5, the concentrations of all tested elements were well below the maximum limits defined by the standard. Collectively, the results from both tests indicate that the studied material poses no significant environmental risk from heavy metals or toxic substances, fully satisfying applicable regulatory criteria. This compliance ensures the material's safety for handling and disposal, with no identifiable threats to environmental or public health under the evaluated conditions.

IV. Discussion

The characterization of Tracuateua granite powder (CGP) confirmed its potential as a supplementary cementitious material, fully meeting the required technical and environmental criteria. The high concentration of reactive oxides (SiO_2 + Al_2O_3 + Fe_2O_3 = 88.13%) exceeds the limits of NBR 12653, being comparable to industrial pozzolans such as metakaolin and silica fume. Mechanical tests demonstrated satisfactory pozzolanic activity, with a compressive strength of 6.56 MPa with lime and an activity index of 94.33% with cement, demonstrating greater synergy with the cementitious medium.

From a physical perspective, the intermediate fineness (4,938.75 cm²/g) and density of 2.70 g/cm³ reinforce its viability in cementitious matrices, although they indicate the need for processing optimization. Regarding environmental aspects, leaching and solubility tests demonstrated the absence of contaminants above legal limits, ensuring safe use of the residue.

Compared to industrial pozzolans, CGP offers the advantage of local origin and lower energy costs, reducing its carbon footprint. However, its mineralogical variability and alkaline oxide content indicate the need for further studies on durability, reactivity, and mixing strategies. Therefore, CGP shows promise for sustainable use in granite regions, contributing to the reduction of clinker consumption and the recovery of waste.

V. Conclusion

The study conclusively demonstrates that Crushed Granite Powder (CGP) from Tracuateua, Pará, exhibits robust potential as a sustainable supplementary cementitious material (SCM), aligning with circular economy principles by valorizing industrial waste. Its high silica and alumina content (88.13% combined), compliance with pozzolanic activity indices (6.56 MPa with lime; 94.33% PAI with cement), and environmentally inert characteristics (non-leachable heavy metals) validate its technical and ecological viability for partial cement replacement. By reducing reliance on clinker, CGP directly addresses the construction sector's carbon footprint while offering a cost-effective solution for granite waste management.

However, to fully harness its potential, future research should prioritize: (1) processing optimization, including advanced grinding techniques to enhance fineness and reactivity without excessive energy input; (2) long-term durability studies to assess performance under real-world conditions, such as carbonation, chloride exposure, and freeze-thaw cycles; (3) blending strategies with other SCMs (e.g., metakaolin or fly ash) to tailor properties for specific applications, such as high-performance or self-compacting concrete; and (4) scalability assessments, including economic feasibility and supply chain logistics for industrial adoption. Additionally, investigations into CGP's role in alkali-activated binders or its impact on concrete rheology could open new avenues for sustainable material innovation. By addressing these gaps, CGP could transition from a regional byproduct to a mainstream sustainable material, contributing to global decarbonization goals in construction.

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