

Evaluation of CO₂ Emissions of Portland Cement and Geopolymers with Mineral Additions from Ecuador

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Abstract The cement industry represents one of the largest sources of carbon dioxide (CO₂) emissions worldwide, generating approximately 1 ton of CO₂ for every ton of cement produced. With this environmental challenge, geopolymeric materials have emerged as a sustainable alternative to Portland cement due to their lower carbon footprint and comparable mechanical properties. This study compares the CO₂ emissions associated with type General Use (GU) Portland cement with three alkali-activated geopolymeric matrices formulated with different concentrations of sodium hydroxide and mineral additions from Ecuador. The matrices were evaluated based on their chemical composition, activation process, and emission mitigation potential, considering the production phase and partial clinker substitution. The results indicate that although the production cost of the geopolymer is higher, it demonstrates superior durability against acid attacks and can achieve compressive strengths of up to 33.42 MPa. Additionally, it reduces CO₂ emissions by up to 11.8% compared to traditional cement. Mixtures with mineral additions allow optimizing the proportion of alkaline activators, achieving a better balance between technical performance and environmental sustainability. In particular, adding silica fume improves flexural strength in low-alkalinity systems. This study confirms that pumice geopolymers are a viable, low-impact alternative for the construction industry, aligning with global decarbonization goals.

Keywords CO₂, Portland Cement, Geopolymer, Pumice Stone, Silica Fume, Brick Dust

1. Introduction

According to Mehta [1], cement production produces significant CO₂ emissions, estimated at around 1 kg of CO₂ for each kg of cement produced. The International Energy Agency [2], which is responsible for ensuring energy security, supporting economic growth, and promoting environmental sustainability at the global level, has stated that the cement industry accounts for about 7% of global CO₂ emissions, becoming one of the most important industrial sources of greenhouse gases. For this reason, a strategy to mitigate this carbon footprint is the incorporation of pozzolans and other supplementary cementitious materials in the cement production process. According to Scrivener et al. [3] and Juenger et al. [4], substituting a portion of the clinker, which is emissions-intensive in production due to decarbonization and fossil fuel use, with pozzolans can reduce the amount of CO₂ released per kilogram of cement produced. This technique, permitted in cement such as type GU under regulations including ASTM C1157 [5] and NTE INEN 2380 [6], not only optimizes the material's durability but also represents an important step towards reducing the environmental impact of the cement industry.

Portland cement type GU, according to standards ASTM C1157 [5] and NTE INEN 2380-2 [6], is a general-purpose cement that can contain mineral additions such as pozzolans, slag, or limestone filler, as long as it meets the established performance requirements (strength, durability, setting). Unlike other types of cement, such as type IP (pozzolanic) or IL (with limestone), type GU does not have a fixed amount of pozzolan, with silicon, aluminum, and iron present, according to ASTM C618 [7].

The amount of pozzolan in a GU-type cement is usually between 10% and 20% by weight in practice when used as an addition to improve durability, reduce the alkali-aggregate reaction, or reduce the carbon footprint, according to Juenger et al. [4] and Scrivener et al. [3], who mention that 1 ton of Portland cement type GU generates approximately 850 to 950 kg of CO₂. According to several scientific and technical sources, this value may vary depending on the clinker content and the use of mineral additions (such as pozzolans or slag) because clinker is the component that contributes the most to emissions.

Geopolymers have emerged as an alternative due to their lower energy consumption and low CO₂ emissions. These materials present technical and mechanical properties similar to traditional cement, highlighting their compressive strength and lower environmental impact according to Sabando [8]. Pumice, a volcanic material rich in aluminosilicates, has been widely studied as a precursor in synthesizing geopolymers, a sustainable alternative to Portland cement, due to its lower carbon footprint, according to Davidovits [9]. Provis and Van Deventer [10] note that the material's amorphous structure and high content of silica (SiO₂) and alumina (Al₂O₃) render it well-suited for alkaline activation, enabling it to form matrices with mechanical properties comparable to those of conventional concrete.

The life cycle of construction materials encompasses stages ranging from raw material extraction, manufacturing, and transportation, to use, maintenance, recycling, final disposal, and potential reuse after demolition, with each stage involving resource consumption and associated environmental impacts. In this context, Maigulema [11] conducted a life cycle assessment (LCA) of the geopolymer studied, followed by an environmental evaluation using the Leopold Matrix. The results showed a total impact score of -457 units for the geopolymer, compared to -268 units for Type GU Portland cement. This significant difference supports the environmental viability of the geopolymer as a more sustainable alternative for the construction industry.

The high cost of alkaline activators, which can constitute up to 85% of the total production cost, is a primary limitation to the economic viability of geopolymers. However, incorporating aluminosilicate waste into the activator formulation can significantly reduce these costs, as confirmed by Martinez and Miller [12] and Firdous et al. [13]. In the production of this binder, sourcing local raw materials contributes to optimizing logistics and

minimizing transportation-related expenses, according to Matsimbe [14]. Moreover, the use of more affordable activators and the valorization of construction and demolition waste as precursor materials are key strategies to enhance economic feasibility and support the broader adoption of geopolymer technology.

This research evaluates the CO₂ emissions, costs, and durability of GU Portland cement compared to alkaline-activated geopolymer formulations, including three different alkali-activated versions, using different concentrations of sodium hydroxide and mineral additions of pumice, silica fume, and brick dust. The objective is to analyze the potential of these matrices as sustainable solutions to mitigate the environmental impact of the cement industry without compromising the technical performance of the material.

2. Materials and Methods

2.1. Materials

2.1.1. Portland Cement Type GU (PC)

It is a cement that meets the requirements of the Ecuadorian standard according to NTE INEN 2380 [6], which regulates performance cement for construction. This conglomerate is composed of clinker (calcium aluminosilicates derived from limestone and clay), calcium sulfate (setting regulator), and mineral additions (pozzolans, slag) to optimize durability and chemical resistance according to ASTM C150/C150M [15] and Adesanya et al. [16]. It is commonly used as it does not require special additives, according to Zahabi et al. [17], and Metha and Monteiro [18]. This material was selected as a reference to compare its performance with the developed geopolymer since its widespread use in conventional constructions makes it a suitable benchmark to evaluate cementitious alternatives. Its widespread application in the construction industry and its widely documented physical-mechanical properties support its choice as a comparative standard, reported by Papy and Timothe [19].

The potential for using geopolymers as an alternative to Portland cement is influenced by both economic considerations and the durability of the materials. Research conducted by Firdous et al. [13], and Martínez and Miller [12] suggests that geopolymer concrete can offer production costs that are competitive while also minimizing environmental impact in comparison to conventional cement. In terms of durability, geopolymers have shown commendable resistance to carbonation, corrosion, and chemical attack, frequently outperforming Portland cement according to Provis [20]. Additionally, studies by Marcillo [21], Martín [22], and Bernal and Provis [23] provide valuable insights, indicating that their effectiveness in challenging conditions positions them as a strong and sustainable long-term alternative.

2.1.2. Pumice Stone (PS)

The inter-Andean valley of South America is characterized by extensive deposits of natural pozzolans, including pumice, among the most extensive worldwide reports for Castro et al. [24] and Andrade et al. [25]. In Ecuador, these deposits are mainly concentrated in the Sierra region, in areas close to extinct volcanoes, facilitating their exploitation as raw materials for applications in supplementary cement and geopolymeric systems.

In this research, Ecuadorian PS was used as a geopolymeric precursor. According to the study conducted, this material presents an amorphous structure with a high content of silica (SiO_2) and alumina (Al_2O_3), key components for its reactivity in alkaline media. Activation of this pumice with alkaline solutions forms aluminosilicate gels that consolidate matrices with mechanical properties comparable to those of PC. These results agree with those reported by several authors, who have documented the high performance of amorphous aluminosilicate materials in the production of sustainable and high-performance geopolymers according to Provis and Van Deventer [10], Andrade et al. [26] and Fernandez et al. [27].

2.1.3. Silica Fume (SF)

Also known as microsilica, it is a by-product generated during the reduction of high-purity quartz to manufacture silicon and ferrosilicon alloys, according to Hamada et al. [28]. Due to its high fineness and high amorphous silica content, this material has been widely studied for its ability to improve the mechanical properties of geopolymeric matrices. Several studies have shown that incorporating small amounts of SF can significantly optimize compressive strength. For instance, the authors Smoleń et al. [29], Pan et al. [30], and Min et al. [31] reported that a 2 wt% addition significantly increases the mechanical strength of geopolymers; however, when increasing the proportion to 4 wt%, a decrease in this parameter was observed, suggesting the existence of an optimal dosage threshold.

In contrast, other authors have identified different effective ranges. Okoye et al. [32] argue that ratios up to 5 % can provide a favorable balance between the strength and workability of the material. More recently, Andrade et al. [26] demonstrated that a 10 % addition of SF significantly improves mechanical properties in geopolymers specifically formulated with PP as an aluminosilicate precursor, indicating that the effect of silica fume also depends on the type of precursor used.

2.1.4. Brick Dust (BD)

Traditional brick production is one of the most widely used construction practices for elaborating masonry in housing. This activity, mostly concentrated in the Andean region, has remained valid through the intergenerational transmission of empirical knowledge and manufacturing

techniques based on local clay, according to Tandazo et al. [33], Barreiro [34], and Zúñiga [35]. Despite its cultural and economic relevance, artisanal brick presents limitations regarding quality control and energy efficiency during firing, which motivates its reevaluation from a sustainable and technological approach.

The present study proposes using recycled brick powder as a partial substitute for pumice in the formulation of geopolymeric matrices. This strategy seeks to reduce the demand for virgin natural resources and recover ceramic wastes with a high content of silicon and aluminum oxides, thus contributing to the development of alternative cementitious materials with lower environmental impact according to Juenger et al. [4], and Duxson et al. [36].

2.1.5. Sodium Hydroxide (NaOH)

In Ecuador, sodium hydroxide (NaOH) is a controlled chemical substance because of its high reactivity, corrosive nature, and the risks associated with its handling, storage, and transportation. For this reason, its acquisition is subject to specific regulations under the supervision of competent government entities, such as the Ministry of Government of Ecuador [37]. Current regulations establish technical and legal requirements to guarantee the handling and safety of hazardous chemical compounds under several Latin American countries' chemical substance control policies.

As part of this research, the acquisition of sodium hydroxide was managed following the protocols established by the national authorities, complying with the requirements regarding permits, technical justification for use, and safety measures. Provis [20] and Shi et al. [38] demonstrated that this procedure ensured regulatory compliance and allowed the responsible use of the reagent as an essential component in the alkaline activation of geopolymer matrices, which had a material purity of 99.77%.

2.1.6. Sodium Silicate (Na_2SiO_3)

ProduQumic del Valle, based in Quito, Ecuador, supplied the sodium silicate used in this study. This compound, supplied in a liquid state, constitutes one of the primary sources of silicon in the alkaline activation of aluminosilicate materials for the synthesis of geopolymeric matrices as reported by Provis et al. [10], Bernal and Provis [23], and Shi et al. [39]. Proper handling and storage are essential to preserve their reactivity and avoid premature gelling or crystallization processes, as confirmed by Bernal and Provis [23] and Juenger et al. [4]. Following the manufacturer's recommendations of Produquimic del Valle [40] and technical guidelines such as those established by ASTM C1240 [41], the silicate was stored in a cool, dry, ventilated environment protected from direct sunlight conditions that ensure its physicochemical stability during the geopolymer formulation process.

2.2. Methodology

Figure 1 shows the methodological scheme of the present investigation. The mechanical behavior of geopolymer pastes was initially evaluated using compression and flexural tests to determine their technical feasibility compared to PC. This stage allowed comparisons in terms of mechanical performance and served as the basis for a subsequent evaluation of CO₂ emissions.

Compressive strength tests followed Ecuadorian standards NTE INEN 198 [42] and NTE INEN 488 [43], which regulate the procedures for preparing, curing, and testing hydraulic and non-hydraulic mortars. These standards offer technical guidelines that ensure the repeatability and validity of the results obtained in different curing stages, allowing a characterization of the progressive development of mechanical strength.

The flexural tensile strength was determined according to the European standard EN 196-1 [44], using prismatic specimens of dimensions 40 × 40 × 160 mm, tested in a three-point loading configuration. This standard is widely recognized in the scientific literature for its suitability in the mechanical characterization of alternative cementitious materials, including geopolymers, according to Provis and Van Deventer [10]. It provides relevant information on the toughness, internal cohesion, and structural behavior of the material under flexural stresses.

Subsequently, carbon dioxide (CO₂) emissions associated with producing PC paste and geopolymeric pastes were estimated. This assessment was conducted using the methodology proposed by the Intergovernmental Panel on Climate Change (IPCC), which is responsible for evaluating and synthesizing scientific, technical, and socioeconomic knowledge regarding climate change, its impacts, and options for mitigation and adaptation, as outlined in the Guidelines for National Greenhouse Gas Inventories [45]. This approach allowed for the quantification of emissions, a comparison of the environmental performance of both materials, and an evaluation of the potential of geopolymers as a sustainable alternative in the construction sector.

A comparative economic analysis was conducted between geopolymer formulations (GPS, GPS+SF, and GPS+BD) and Portland cement (PC). This analysis evaluated the costs of raw materials, energy, transportation, and labor to estimate the cost per kilogram of precursor material. Furthermore, to assess the long-term performance of the geopolymer, durability tests were performed under extreme conditions. Specifically, hardened samples were subjected to an acid attack using a nitric acid solution for 120 hours, during which mass loss and surface degradation were analyzed using scanning electron microscopy (SEM).

2.3. Experimental Design

2.3.1. Number of Specimens

For the mechanical analysis of the geopolymer and PC reference pastes, prismatic specimens were prepared according to the dimensional requirements established by European standards EN 196-1 [44], to evaluate their performance in compression and flexure. **Table 1** summarizes the dimensions and quantity of specimens manufactured for each type of test.

A total of 6 prismatic specimens were prepared for each type of paste, which were tested at different curing ages: 7 days (PC; GPS; GPS+SF), 14 days (GPS+BD), and 28 days for all the pastes. This distribution made it possible to follow the development of strength over time, following widely accepted practices in the characterization of cementitious materials according to Provis and Van Deventer [10], and EN 196-1 [44]. For geopolymers, 18 specimens per type of test were used to ensure the availability of sufficient samples for each curing age, complying with reproducibility criteria and statistical validity of the results.

This experimental design allowed a comparative evaluation of the evolution of the mechanical properties of geopolymer pastes versus PC pastes in terms of compressive strength and flexural toughness.

2.3.2. Mix Proportions Used in Pastes

Table 2 shows the materials required to prepare pastes based on PC, GPS, GPS+SF, and GPS+BD, standardized according to 1 kg of aluminosilicate source. This common basis allows a consistent comparison of the precursor material and activators used in each system. Standardization of the primary precursor facilitates comparative analysis of the environmental impacts generated.

For the elaboration of geopolymers, a constant amount of sodium hydroxide (NaOH) by mass was used; however, the concentration of the alkaline solution (molarity) was adjusted according to the chemical composition and reactivity of the precursor used to guarantee adequate alkaline activation and achieve mechanical strengths above 15 MPa. In the case of GPS, NaOH solutions with concentrations of 16 M and 20 M were used since this material, presenting a lower initial reactivity compared to other silica- and alumina-rich precursors, requires a more alkaline medium to induce an efficient formation of N-A-S-H gels, a fundamental amorphous reaction product in cementitious materials, particularly in alkali-activated geopolymers. Its acronym denotes its primary composition: Sodium (Na), Aluminum (Al), Silicon (Si), and Hydrates (H). This gel acts as the main binding phase that confers strength and durability to the final material, according to Davidovits [9].

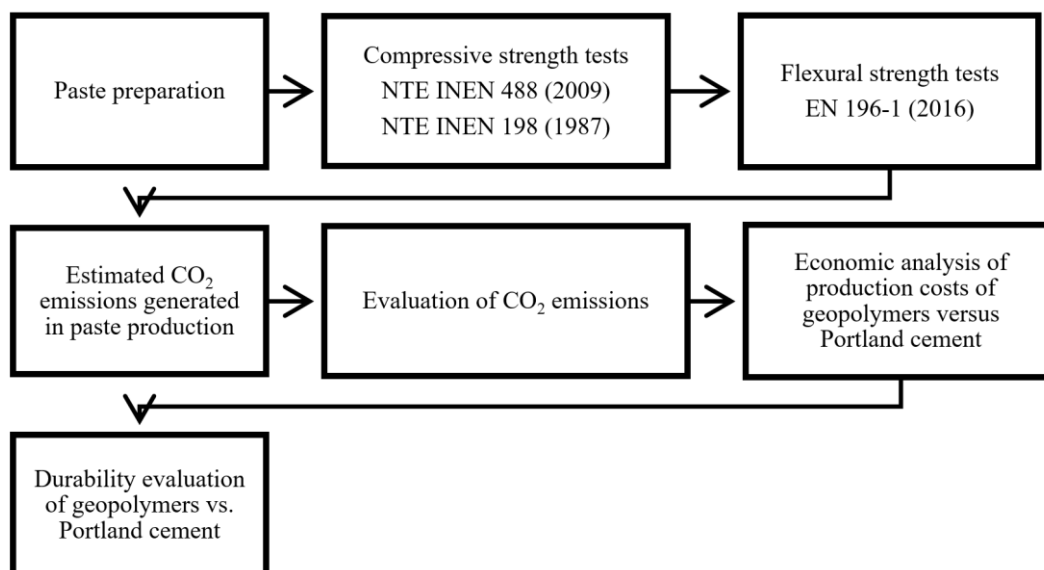


Figure 1. Methodological scheme

Table 1. Number of specimens

Test	Shape	Dimensions (mm)	PC Matrix Specimens	PS Matrix Specimens (3 types)
Compression	Prism	40x40x160	24	72
Flexure	Prism	40x40x160	12	36
Total	-	-	36	108

Table 2. Amount of material required for paste elaboration

	PC (kg)	PS (Kg)	SF (kg)	BD (kg)	NaOH (kg)	Na ₂ SiO ₃ (kg)	Water (kg)
PC (0,70)	1,00	-	-	-	-	-	0,7
GPS (0,65)	-	1,00	-	-	0,19	0,46	-
GPS+SF (0,35)	-	0,88	0,12	-	0,10	0,25	-
GPS+BD (0,70)	-	0,85	-	0,15	0,20	0,50	-

Moreover, for geopolymeric systems that included additions to the precursor as silica fume (GPS+SF) and brick dust (GPS+BD), a concentration of 10 M was used. This reduction in molarity was given by the synergistic effect of these supplementary materials, which, being additional sources of amorphous silica (silica fume) and calcined aluminosilicates (brick dust), increased the reactivity of the precursor system, allowing effective activation even with less concentrated solutions obtained in the researches of Zhang et al. [46] and Puertas et al., [47].

2.4. Paste Preparation

2.4.1. PC Paste with Water

A a/cm ratio of 0.4 and 0.7 was used to prepare the cement paste to establish a comparative basis from an environmental point of view compared to geopolymer pastes [48]. The procedure initially incorporated the

cement, followed by water, and a homogeneous mixture was obtained for 10 minutes with mechanical agitation. Subsequently, the paste was poured into molds with the dimensions previously specified based on ASTM C109 [49], EN 196-1 [44], NTE INEN 198 [50] and NTE INEN 488 [43], without requiring an intensive vibrating process, since its fluid consistency significantly reduces the presence of air bubbles. After an initial curing of 24 hours at room temperature, the formwork was removed, and the specimens were stored in water saturated with lime until the tests were performed to avoid premature carbonation processes due to exposure to atmospheric CO₂.

2.4.2. Geopolymer with Pumice (GPS)

For the preparation of the GPS, the dosage proposed by Andrade et al., [25] based on the Ecuadorian standards NTE INEN 488 [51] and NTE INEN 198 [52] adapted for experimental purposes, was followed. Alkaline activation was carried out using a combination of sodium hydroxide

(NaOH) and sodium silicate (Na₂SiO₃), following the guidelines of Provis and Van Deventer [10].

NaOH solution was prepared by dissolving the reagent in cold distilled water, with gradual addition and constant stirring, until a molar concentration of 10 M. This procedure was performed in an extractor cabinet to minimize hazards associated with the vapor release and to control the exothermic reaction according to Duxson et al. [36], and Holler et al. [53]. Subsequently, the solution was cooled and stored in amber bottles to preserve its chemical stability following the normative ASTM C114 [54].

After 24 hours of resting, this NaOH solution was mixed with Na₂SiO₃ at a molar ratio of 2.5 (NaOH/Na₂SiO₃), stirring for 10 minutes to ensure homogeneity. The final alkaline solution was also stored in amber bottles, protected from light to avoid evaporation and degradation.

The pumice stone was used as a solid precursor, previously dried in an oven at 110 °C for 24 hours and cooled to room temperature for 24 hours, according to ASTM C128 [55], to eliminate moisture and ensure the material's reactivity. For the preparation of the mixture, the alkaline activator was initially incorporated at a water/cementitious material (a/cm) ratio of 0.65, a value recommended by Safari et al., [56] to optimize the workability and strength of the system. The precursor was added, and the mixture was stirred for 10 minutes until a homogeneous consistency was reached Provis and Van Deventer [10].

Finally, the fresh material was poured into metal molds for cubes and beams, previously treated with a release agent. During pouring, gentle blows with a rubber hammer were applied around the mold to eliminate voids and improve compaction according to Duxson et al. [36]. The specimens were covered with plastic film and cured at room temperature for 24 hours.

2.4.3. Geopolymer with Pumice + Silica Fume (GPS+SF)

SF was incorporated as a mineral addition to optimize the mechanical properties, durability, and microstructural performance of the GPS developed in this research. SF is an ultrafine industrial by-product with a high amorphous silica content, known for its high pozzolanic reactivity and ability to densify the microstructure of cementitious matrices. It favors the development of more compact and resistant phases according to Vijaya and Kumar [57], Shi et al. [58], Liu et al. [59], Paya et al. [60], Rodriguez et al. [61], and Tobón et al. [62].

Several investigations have shown that adding SF in moderate proportions significantly improves the compressive strength of geopolymer matrices. For example, Shaikh and Hosan [63], Du et al. [64], and Li et al., [65] reported that a 2 wt.% incorporation of SF can significantly increase mechanical strength. However, when exceeding 4 wt.%, this positive trend tends to reverse, indicating an oversaturation of the system that negatively affects its structural properties.

Likewise, Abdi and Izadifard [66] suggest that a dosage

of up to 5-10 wt% allows achieving a balance between strength and workability of the fresh material. However, for this research, the dosage proposed by Andrade et al. [26] was adopted, who, through experimental tests with geopolymers made specifically with Ecuadorian pumice, concluded an addition of 10 wt.% SF is the most effective for improving compressive strength without compromising the workability and stability of the system.

The formulation adopted by Andrade et al. [26] has a NaOH/Na₂SiO₃ molar ratio of 2.5, a water/cementitious material (a/cm) ratio of 0.35, and an activating solution with sodium hydroxide at 10 M concentration. These conditions were replicated in the present study, allowing efficient alkaline activation and favoring the formation of geopolymer reaction products with improved mechanical and microstructural properties according to Provis [20], Provis and Bernal [23], and Duxson et al. [36].

2.4.4. Geopolymer with Pumice + Brick Dust (GPS+BD)

To the GPS used in this study, 15% by mass of BD was added as a partial substitute for the pumice stone. This modification aimed to improve the efficiency of alkaline activation and reduce the amount of NaOH required. Brick dust, being a secondary source rich in silica (SiO₂) and alumina (Al₂O₃), contributes to the development of N-A-S-H type geopolymer gels by increasing the reactivity of the mixture and facilitating polymerization according to Davidovits [9], Temuujin et al. [67], Pacheco-Torgal et al. [68], Sharmin et al. [69], and Zhang et al. [70]. This strategy was proposed by Cajamarca and Paullan [71], who identified that adding 15 % BD improves the cohesion of the geopolymer matrix without negatively affecting its strength.

For the preparation of mixtures, the following mix proportions were used: 15 % BD replacing pumice, a NaOH/sodium silicate (Na₂SiO₃) ratio of 2.5, and a water/cementitious material (a/cm) ratio of 0.70, with an activating solution composed of NaOH at a concentration of 10 M. The mixtures were poured into the molds and initially subjected to an environmental pre-curing of 24 hours to achieve a slight increase in surface strength that would facilitate handling. Subsequently, the samples were thermally cured in an oven at 60 °C for 14 days. This curing time extension to the standard protocol (7 days) responded to preliminary observations: specimens cured for only 7 days presented a soft and spongy consistency, which made the formwork removal difficult and generated premature fractures in the specimens, according to Habert [72] and Turner and Collins [73].

After thermal curing, the specimens were carefully stripped and coated with polyethylene plastic film to prevent moisture loss and allow progressive stabilization of their microstructure at room temperature. This process is key to minimizing shrinkage cracks and favoring an adequate evolution of the geopolymeric before its mechanical evaluation, according to Provis and Van Deventer [10].

2.5. Calculation of Emissions in kg of CO₂/kg of Aluminosilicate Source (Precursor)

The Intergovernmental Panel on Climate Change [45] guidelines for National Greenhouse Gas Inventories were followed to calculate CO₂ emissions generated by preparing cement pastes and geopolymers. The general methodology used to estimate the emissions associated with a particular process involves the product of activity level data, e.g., the amount of material processed, or the amount of energy consumed, and an associated emission factor per unit of consumption/production, according to:

$$E_i = A_i \times EF \quad (1)$$

Where:

E_i = CO₂ emission from the process (kg) of each ingredient or operation 'i';

A_i = Amount of activity or material processed 'i'; and

EF_i = Emission factor associated with CO₂ emission per unit of activity or process material 'i'.

Four types of binder mixtures were evaluated to estimate their CO₂ emissions: Portland cement paste (PC), pumice-based geopolymer paste (GPS), pumice geopolymer paste with the addition of silica fume (GPS+SF), and pumice geopolymer paste with the addition of brick dust (GPS+BD). The emissions calculation was performed using a simplified methodology that considers only the emissions associated with the constituent materials of the binder, excluding the processes of mixing, curing, and transporting the raw material from its point of origin to the laboratory. This approach aligns with standard practices in simplified life cycle analyses for cement and alternative materials in line with Scrivener et al. [3] and Habert et al. [72], where the impact of clinker or activated precursors is prioritized as the primary source of emissions.

According to Mellado et al. [74] PC generates approximately 1 kg of CO₂ per kilogram. Similarly, Scrivener et al. [3] and Habert et al. [72] report that the production of one ton of GU-type cement emits between 0.85 and 0.95 kg of CO₂ per kilogram, depending on factors such as clinker content and energy efficiency of the process.

Within the framework of this research, an average value of 0.93 kg CO₂ per kilogram of GU cement has been adopted as a reference for estimating emissions, considering both the technical literature and the typical industrial context.

The emission associated with the use of 1 kg of cement was calculated with (1) to obtain the CO₂ emission per unit mass of aluminosilicate source (kg of CO₂/kg of aluminosilicate source).

The GPS, GPS+SF, and the GPS+BD have a solution consisting of a mixture of NaOH and Na₂SiO₃. Since the paste is obtained from mixing the binder with PS, SF, and BD (material of mineral from Ecuador) for calculating CO₂ emissions, the manufacture of NaOH and Na₂SiO₃ (without emissions associated with water supply) was

considered. According to Mellado [74], both emission factors, corresponding to NaOH and Na₂SiO₃, were obtained from the SimaPro 7.1 program database [75]. The emission factors are 1.12 kg of CO₂ per kg of NaOH and 1.2 kg of CO₂ per kg of Na₂SiO₃ solution. The emission associated with the use of 1kg of aluminosilicate source was calculated to obtain the CO₂ emission per unit mass of paste.

Additionally, CO₂ emissions associated with the preparation of 1 liter of the different molar concentrations used throughout the development of the research were estimated, considering a molar weight of sodium hydroxide (NaOH) of 39.997 g/mol and a NaOH/Na₂SiO₃ ratio of 2.5. Similarly, emission factors reported in the literature were used for this calculation: 1.12 kg of CO₂ for each kg of NaOH and 1.20 kg of CO₂ for each kg of sodium silicate solution (Na₂SiO₃). This information made it possible to quantify the environmental impact of the alkaline activators used in the geopolymeric mixtures.

2.6. Economic Analysis of Production Costs of Geopolymers versus CP

To conduct a comparative economic analysis between geopolymers (GPS, GPS+SF, and GPS+BD) and PC, several components were taken into account: raw materials, transportation, and production costs, which include energy consumption and labor. Maigulema [11] performed a life cycle assessment (LCA) of the materials utilized in this research. The process begins with the extraction of pumice stone from the PROFUTURO quarry, located in Cotopaxi Province, followed by transport to the processing plant in Chimborazo, approximately 96 kilometers away. The estimated fuel consumption for the extraction process is 0.312 gallons of diesel per 8 cubic meters of pumice, while transportation to the Riobamba plant requires about 6.67 gallons of diesel per 8 cubic meters. A diesel price of \$1.80 per gallon is considered for the Global Petrol Prices [76]. To convert these values into mass, an average bulk density of 2084.23 kg/m³ is used for pumice.

The acquisition of alkaline activators will take place through authorized distributors, with transportation costs included. Sodium silicate in solution is priced at approximately 65 USD per 25 gallons and has a density of 2.4 g/cm³. This density is used to convert volume to mass according to Ferrekret [77]. Sodium hydroxide flakes are estimated to cost 2 USD per kilogram, as reported by AGRIPAC [78] and Ferrekret [79]. For mixtures that include silica fume, the estimated cost is approximately 3 USD per kilogram.

The geopolymer production process consists of several key unit operations. First, pumice is processed through a crusher with a capacity of 50 tons per hour, which consumes 7.93 gallons of diesel fuel each hour. Next, the pumice is sieved, with an estimated energy consumption of 0.5 kWh per ton, costing around \$0.10 per kWh for

electricity. Finally, the materials are mixed, with an approximate cost of \$0.05 per kilogram, based on operational requirements like those used in Portland cement mixing, according to Mendez [80] and HOLCIM [81].

Regarding Portland cement in Ecuador, according to studies by Mendez [80] and HOLCIM [81], the approximate cost per ton is broken down into three main components: raw materials at 66.25 USD/ton, corresponding to the typical blend of clinker, pozzolan, and gypsum; labor at approximately 5.11 USD/ton, associated with factory labor per ton; and energy costs estimated at 2.85 USD/ton, based on an average electricity consumption of 40.8 kWh per ton at a rate of 0.07 USD/kWh.

2.7. Durability Evaluation of Geopolymers vs. Portland Cement

Resistance to acid attack was assessed using a mass loss assay, which is a commonly employed method for quantifying the degradation of geopolymeric matrices when exposed to harsh environments, according to Marcillo [21], Bernal et al. [82], and Provis and Bernal [83]. To do this, prismatic specimens were molded, cured for 24 hours at 60 °C and then stored for 28 days at room temperature, following validated methodologies for slag and ash-based geopolymers. Under moderately aggressive conditions (pH 2), the samples were immersed in a diluted nitric acid solution with controlled pH for 120 hours. They were extracted at regular intervals, drained for three minutes, and weighed in order to calculate the accumulated mass loss (%). This protocol was based on previous studies by Bernal and Provis [23] and served as the basis for the studies conducted by Mart ın [22] and Marcillo [21] for mixtures activated with biomass ash, which allowed for the evaluation of degradation kinetics and the estimation of the relative durability between pastes.

The microstructural characterization of the material was performed using scanning electron microscopy (SEM). This technique utilizes a focused beam of electrons to scan the sample's surface and produce high-resolution images. It allows for the observation of morphology, texture, and structure at the micro- and nanometric scales according to Goldstein et al. [84]. The analysis was conducted in accordance with the guidelines established by ISO 16700 [85], which provides directives for the processing and analysis of SEM images, and ASTM E766 [86], which outlines practices for evaluating SEM images in the fractographic analysis of materials. In addition, ASTM E1588 [87] and the method reported by Ukrainczyk et al. [88] were used to determine the elemental composition before and after acid attack, with the aim of evaluating the leaching percentage and the stability of the gel, normalizing the results with respect to the contents of silicon, aluminum, sodium and potassium.

3. Results and Discussion

3.1. Mechanical Properties of Pastes

Table 3 shows the compressive strength at 28 days of age of the specimens, considering the average characteristic strength of the material, as established in various standards and studies on alternative cementitious materials according to ASTM C109 [49] and Zhang et al. [70]. The choice of this age resulted from the fact that the samples with brick dust incorporation were stripped at 14 days due to their slower setting, which makes a homogeneous comparison with other earlier curing ages difficult. However, this difference in setting and stripping times does not influence the analysis of CO₂ emissions, since it is determined by the quantities and types of materials used in the manufacture of the specimens, rather than by the age at which their mechanical properties are evaluated. This finding is consistent with the studies conducted by Habert et al. [72], and Turner et al. [73].

Table 3. Average strength of pastes

Type of mixture	a/cm	Molarity	Compressive strength	Flexural strength
			MPa	MPa
PC	0,4	-	52,22	8,22
PC	0,7	-	9,56	3,52
GPS	0,65	20 M	33,42	7,67
GPS	0,65	16 M	22,12	4,91
GPS+SF	0,35	12 M	16,26	8,22
GPS+BD	0,70	10 M	18,77	3,05

The results show a clear difference in the mechanical behavior of PC pastes versus geopolymers, with and without mineral additions. The highest compressive strength corresponds to the PC mix with a/cm ratio of 0.4 (52.22 MPa), which agrees with the literature, indicating that a lower water/cementitious material ratio favors a denser and stronger structure according to Mehta and Moreiro [18]. The same PC with an a/cm ratio of 0.7 presents a drastically lower strength (9.56 MPa), confirming the sensitivity of this material to its a/cm ratio, coinciding with Papy and Timoth ́e [19]. This decrease is also reflected in the flexural strength.

For the geopolymer mixes, the strength improves considerably compared to PC-0.7. The GPS mix with 20M NaOH reaches 33.42 MPa, which is consistent with studies indicating that high alkali concentrations enhance the dissolution of aluminosilicates and, thus, the formation of denser and stronger N-A-S-H gels consistent with research of Provis [20], Temuujin [67], and Bernal and Provis [23]. However, when reducing the concentration to 16M, the strength decreases to 22.12 MPa, supporting the direct influence of the alkaline concentration on the reactivity and strength of the system.

The incorporation of silica fume (SF) into the GPS+SF mix (12M, a/cm 0.35) demonstrates a significantly high flexural strength (8.22 MPa), comparable to the PC-0.4 mix. This can be attributed to the pozzolanic effect of silica fume, which improves the matrix by filling voids and promoting a more homogeneous structure consistent with previous studies of Paya et al. [60], Shaikh and Hosan [63], Du et al. [64], and Li et al. [65].

The GPS+BD mix presents a moderate compressive strength (18.77 MPa) and the lowest flexural strength (3.05 MPa) among the geopolymeric mixes. This may be due to the lower reactivity of brick dust compared to silica fume and the low alkali concentration, which limits the formation of dense geopolymer gels, according to Pacheco et al. [68].

3.2. Evaluation of Emissions in kg of CO₂/kg of Aluminosilicate Source (Precursor)

Figure 2 presents the calculation of CO₂ emissions associated with using 1 kg of precursor in the production of PC and geopolymer pastes. The result is expressed as kilograms of CO₂ per kilogram; for cement paste, 0.92 kg of CO₂ emission per kilogram produced is used to calculate that of geopolymer paste produced in each system (kg CO₂/kg paste). (1) was applied, incorporating the specific emission factors of alkaline activators: 1.12 kg CO₂ per kg NaOH and 1.20 kg CO₂ per kg Na₂SiO₃ solution. This methodology made it possible to compare the direct environmental impact of the different mix designs as a function.

In the case of PC, emissions of 0.93 kg of CO₂ per kg of precursor are attributable exclusively to the cement content, the manufacture of which involves high energy consumption and emissions due to clinker decarbonization. Whereas the mixture with GPS does not contain PC but

variations made among its source of aluminosilicates, its total emissions are 0.82 kg of CO₂ per kg of the mixture, distributed between 0.60 kg from the use of Na₂SiO₃ and 0.22 kg from sodium hydroxide NaOH. Although alkaline activators also generate significant emissions, GPS achieves a net reduction of approximately 11.8% compared to traditional cement.

This result demonstrates that GPS is environmentally friendly by partially replacing high-carbon-footprint materials with locally available natural resources, such as pumice. Applying geopolymers represents a viable strategy for decarbonizing the construction sector, coinciding with what was stated by Scrivener et al. [3], Habert et al. [72], and Turner and Collins [73].

Evaluating the CO₂ emissions associated with the different concentrations of NaOH employed in the alkaline activation of the geopolymers in the present study is essential for a conscious environmental assessment. Maintaining a constant NaOH/Na₂SiO₃ ratio of 2.5 for all mixes, **Figure 3** presents the specific emissions generated in kg/kg required per liter of solution at different molar concentrations of NaOH, calculated with a molar weight of 40 g/mol.

The results in **Figure 2** indicate a net reduction in CO₂ emissions for GPS compared to PC. However, this analysis shows the key role of the concentration of alkaline activators, as a linear increase in emissions with molar concentration indicates that using lower concentrations of alkaline activators is a strategy to minimize the carbon footprint of geopolymers.

Figure 4 shows the CO₂ emissions for producing 1 liter of solution, varying the amount of NaOH as a function of the molar concentration required in the study. The ratio between the sodium silicate and sodium hydroxide was kept constant at 2.5.

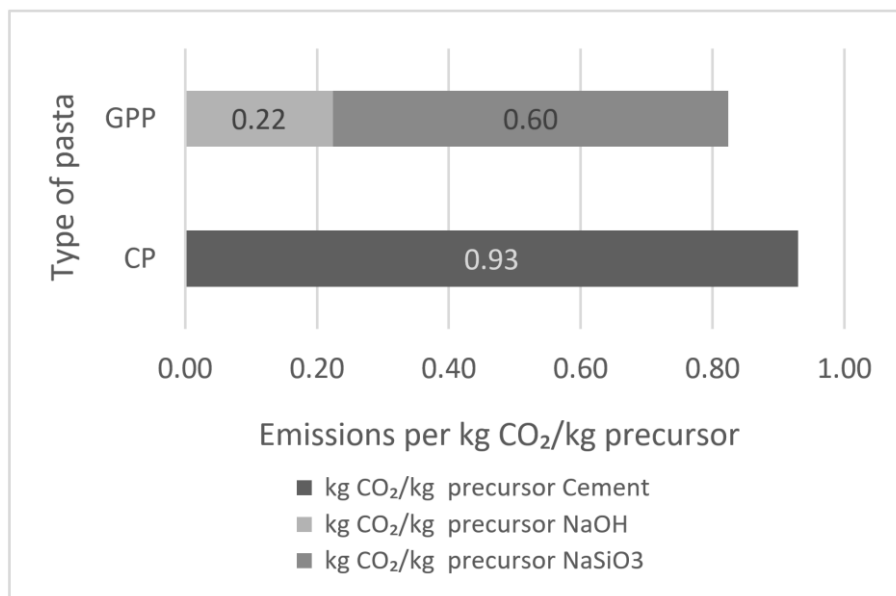


Figure 2. CO₂ emissions per kilogram of precursor

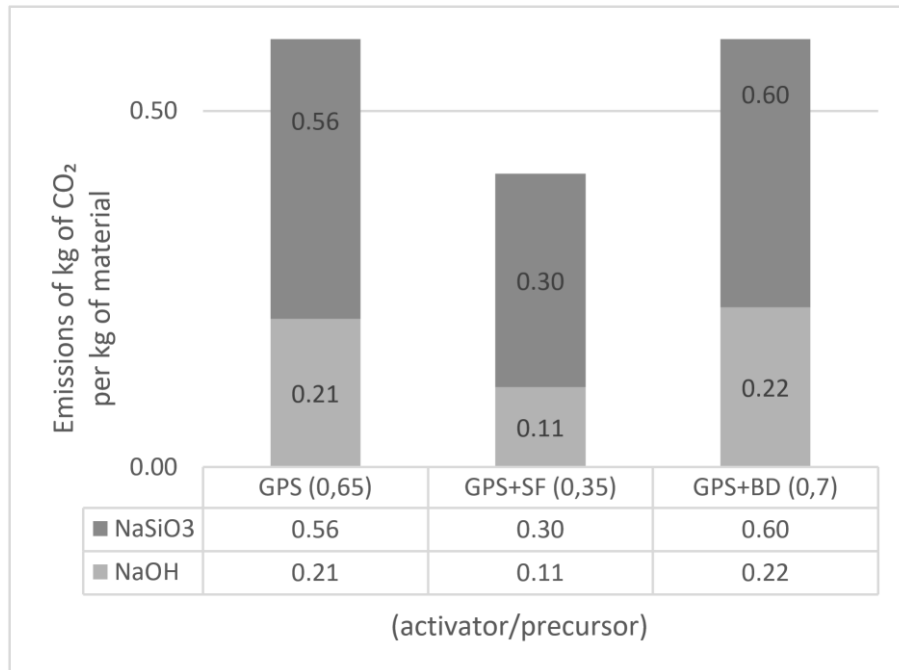


Figure 3. CO₂ emissions per kg of material per liter of dissolution

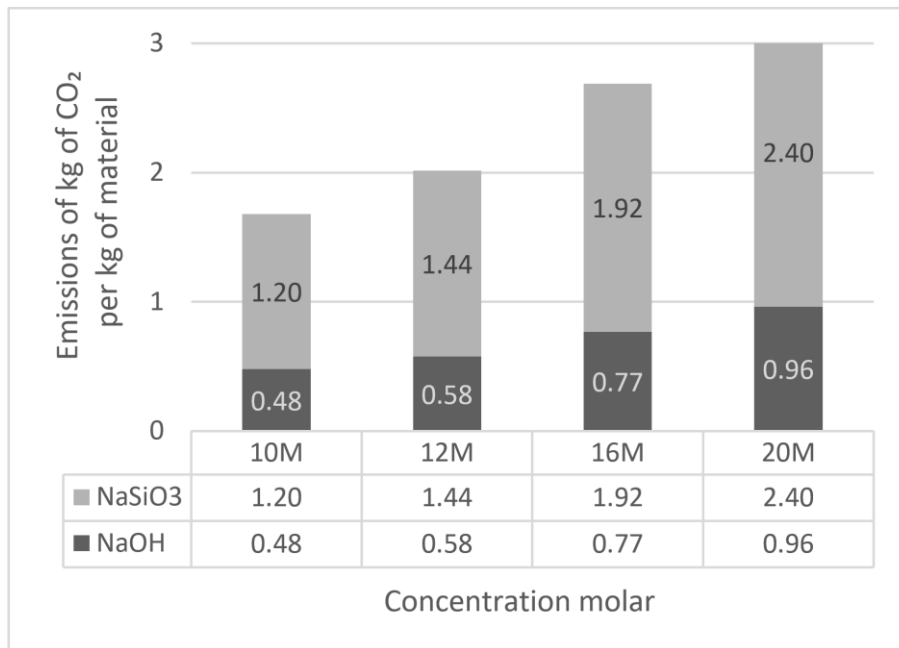


Figure 4. CO₂ emissions per kg of material per liter of dissolution

In **Table 4**, it can be appreciated how reducing activators or incorporating industrial by-products (such as silica fume or brick dust) is recommended to further improve geopolymers' sustainability, according to IEA [2] and Juenger [4]. Considering the different strategies to reduce the carbon footprint of geopolymer mixes, it is essential to ensure that these optimizations do not compromise the mechanical properties and durability required for their specific application in construction.

The trend of the design of geopolymeric materials is that

the higher the NaOH concentration, the higher the mechanical strength and the higher the CO₂ emissions. The GPS mixture with 20 M NaOH achieves high strength (33.42 MPa) but with a high environmental load: 0.96 kg CO₂ per kg NaOH and 2.40 kg CO₂ per kg Na₂SiO₃, representing a considerable carbon footprint. This high strength is due to the higher availability of OH⁻ ions, which intensify the dissolution of aluminosilicates and favor the formation of the N-A-S-H gel responsible for mechanical performance, following the research of Bernal and Provis

[23], Duxson et al. [36], and Zhang et al. [70]. However, by decreasing the NaOH concentration to 16 M, a reduction in strength (22.12 MPa) and a decrease in emissions (0.77 and 1.92 kg CO₂ per kg of NaOH and per kg of Na₂SiO₃, respectively) are observed, indicating the relationship between mechanical performance and environmental sustainability.

Mixtures with mineral additions, such as silica fume (GPS+SF) and brick dust (GPS+BD), allow for the reduction of the amount of activator required. In GPS+SF with 10 M NaOH, 16.26 MPa is achieved with significantly lower emissions (0.58 and 1.44 kg CO₂ per kg of material). This improvement in efficiency is due to the high reactivity of silica fume, which promotes geopolymerization with lower alkali requirements, coinciding with Liu et al. [59]. On the other hand, the GPS+BD mixture, although with a strength of 18.77 MPa, also exhibits reduced emissions (0.48 and 1.20 kg CO₂), showing that residual materials such as brick dust can contribute to sustainability without excessively compromising its performance.

Figure 5 shows an analysis of CO₂ emission sensitivity and compressive strength in geopolymer mixtures with different formulation types and activator molarity. The stacked bars represent the CO₂ emissions per kilogram of

precursor, differentiating the contributions of NaOH and Na₂SiO₃, while the superimposed line indicates the compressive strength in MPa. It is observed that with lower molarity and with the use of additives such as SF or BD, total emissions decrease significantly, although with a moderate reduction in mechanical strength.

The findings align with the studies of Habert et al. [72], and Scrivener et al. [3], which emphasize that the environmental impact of geopolymers is significantly affected by the type and quantity of alkaline activators used, especially sodium silicate (Na₂SiO₃), whose production is very energy intensive. While geopolymers exhibit superior structural performance compared to Portland cement, their economic and environmental viability is limited by the substantial impact and cost associated with these activators.

However, using local raw materials, such as Ecuadorian pumice and recycled brick powder from construction waste, helps optimize logistics and reduce emissions related to transportation. This aligns with Sing et al. [89] who highlight the urgent need to decrease emissions in the cement sector. Therefore, it is essential to optimize geopolymer formulations to strike a balance between technical performance, costs, and environmental sustainability.

Table 4. CO₂ emissions generated as a function of the molar concentration required to activate the alkaline solution

Type of mixture	Molarity	Compressive strength	Emissions (kg CO ₂ /kg material)		
		MPa	NaOH	Na ₂ SiO ₃	Total
GPS	20 M	33,42	0,96	2,40	3,36
GPS	16 M	22,12	0,77	1,92	2,69
GPS+SF	12 M	16,26	0,58	1,44	2,02
GPS+BD	10 M	18,77	0,48	1,20	1,68

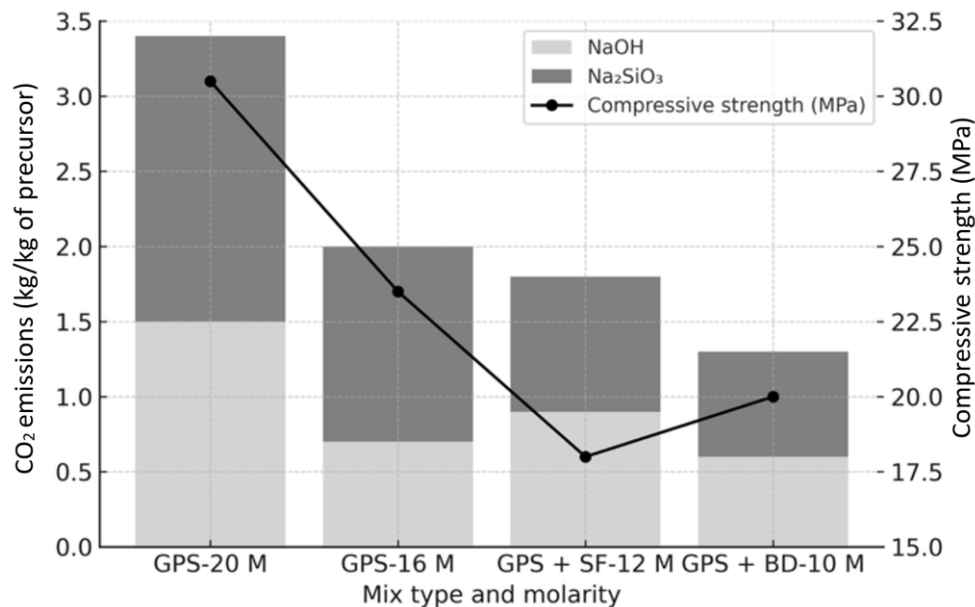


Figure 5. Emission sensitivity by mix type and molarity

This study validates the potential of Ecuadorian pumice-based geopolymer as a sustainable alternative for construction. However, its global implementation requires methodological and formulation adjustments, particularly when adapting the approach to regions with different types of natural aluminosilicates or waste materials, aligned with the principles of a circular economy. Optimizing the activator concentration and curing conditions is essential not only due to variations in the chemical composition and reactivity of locally available raw materials, but also to reduce the environmental impact of the activator, which currently represents the main source of emissions and cost in the mixture. This adaptability is crucial for the large-scale technical, economic, and environmental feasibility of the material.

3.3. Economic Analysis to Produce 1 kg of Geopolymer (Precursor) and 1 kg CP

Table 5 and **Table 6** show the production costs per kilogram of geopolymer (GPS, GPS+SF, and GPS+BD mixtures) and CP, respectively.

Although the production cost of Portland cement (0.074 USD/kg) is significantly lower than that of the geopolymer (ranging from 0.29 to 0.46 USD/kg depending on the formulation), the latter offers strategic,

technical, and environmental benefits that justify its consideration as a sustainable alternative. Among the geopolymers analyzed, the GPS+SF mix is the most cost-effective, owing to the efficient use of activators and the incorporation of silica fume, which enhances mechanical performance without substantially increasing cost. Furthermore, the use of industrial by-products such as silica fume or brick dust supports the circular economy. From an environmental standpoint, studies such as those by Maigualema [11] and Martínez and Miller [12] report significant CO₂ emission reductions up to 70% compared to conventional cement. Technically, geopolymers exhibit greater resistance to aggressive environments, which can translate into lower long-term maintenance costs according to Firdous et al. [13]. Although their initial cost is higher, life-cycle cost analysis (LCC) and global decarbonization goals supported by the IPCC [45], Maigualema [11], and the IEA [2], position geopolymers as a viable and strategic alternative for a more sustainable future.

3.4. Evaluation of Geopolymer and CP Durability

Figures 6 and **7** show the percentage mass loss of the CP and geopolymer specimens, respectively, compared to the volume of acid added over a period of 120 hours.

Table 5. Production costs per kilogram of geopolymer

Concept and commercial unit	Unit of analysis	Cost in unit value of analysis	Material cost for 1kg of precursor (GPS)	Material cost for 1kg of precursor (GPS+SF)	Material cost for 1kg of precursor (GPS+BD)
PS Extraction (USD/gallon fuel) /m ³	m ³	0,07	0,00002	0,00002	0,00002
PS Transport (USD/gallon fuel) /m ³	m ³	1,50	0,0004	0,0004	0,0004
PS Milling and sieving energy (USD/kWh) /ton	kg	0,01	0,0050	0,01	0,01
Sodium hydroxide, includes transport (USD/kg)	kg	1,00	0,19	0,10	0,20
Sodium silicate, includes transport (USD/gallon)	kg	0,49	0,23	0,12	0,25
Silica fume (USD/kg)	kg	3,00	-	0,06	-
Labor (USD/kg mixture)	kg	0,005	0,01	0,01	0,01
Estimated total cost (USD/kg of geopolymer precursor)			0,43	0,29	0,46

Table 6. Production costs per kilogram of CP

Concept and commercial unit	Unit of analysis	Cost in unit value of analysis
Raw material, includes transport (USD/ton)	kg	0,066
Milling and sieving energy (USD/kWh)/ton	kg	0,003
Labor (USD/ton mixture)	kg	0,005
Estimated total cost (USD/kg cement)		0,074

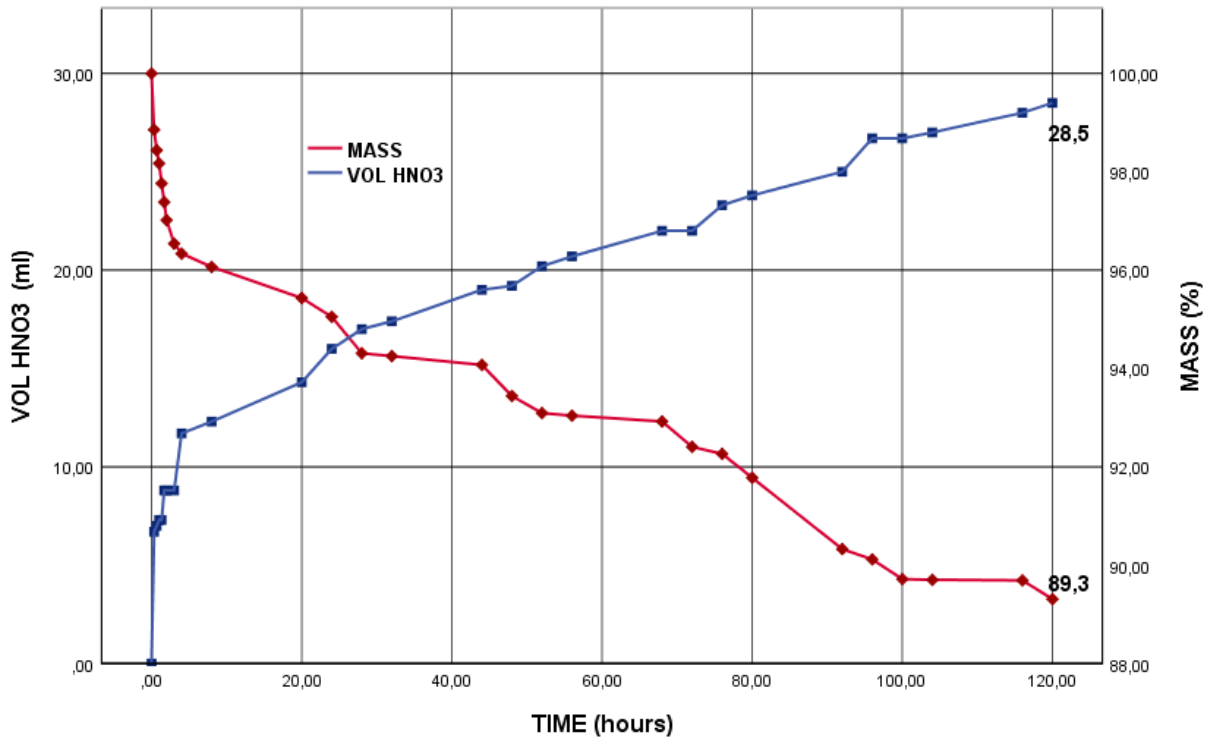


Figure 6. Added acid and residual mass after 120 hours of attack in a CP specimen

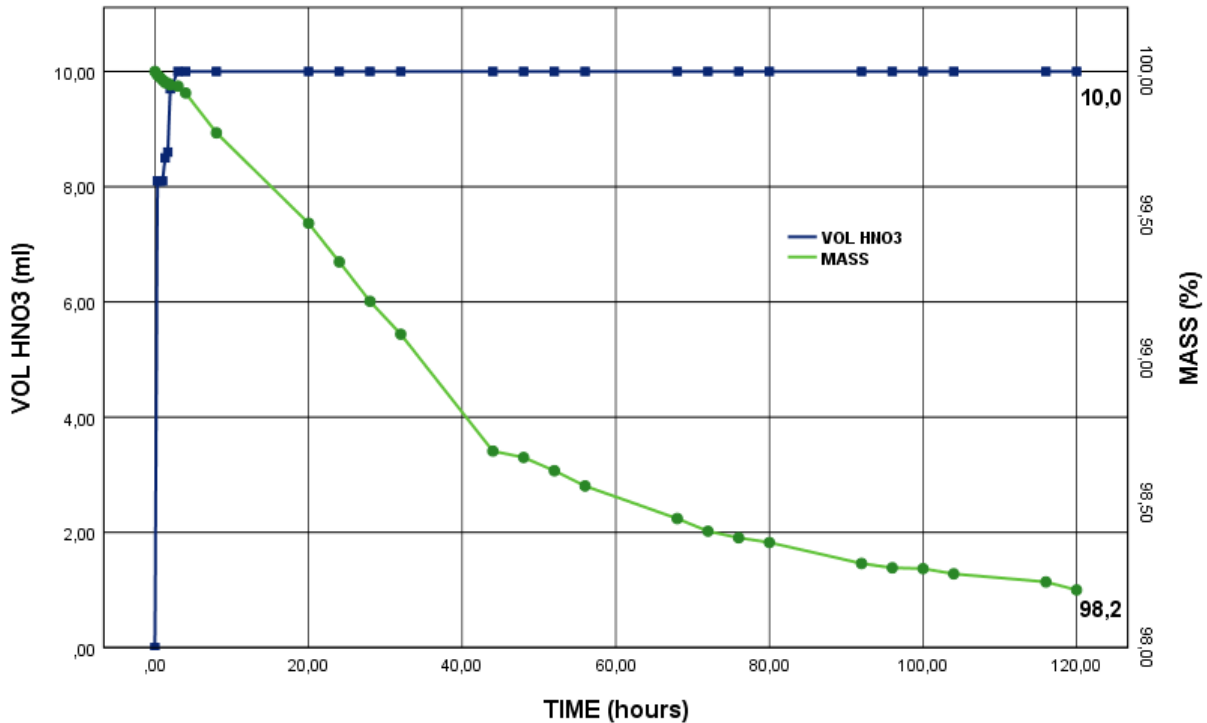


Figure 7. Added acid and residual mass after 120 hours of attack in a geopolymer specimen

An inverse relationship is observed between the volume of HNO₃ added and the mass of the material over time. Initially, the mass loss occurs at an accelerated rate, showing an intense chemical reaction with the acid. However, as the test progresses, the decrease in mass slows down, indicating a possible reduction in the

dissolution rate. The mass of the specimens experienced a progressive loss, decreasing from an initial 100% to 89.3% at the end of the test, which represents a total loss of 10.7% and required an acid volume of 28.5 ml. This indicates that the CP has low resistance to acidic environments, which is consistent with observations made

by Marcillo [21] and Mart ın [22] who reported similar behavior in alkali-activated matrices when exposed to acid attacks.

The volume of HNO₃ was kept constant up to approximately 8 ml of acid, which indicates adequate control of the aggressive environment. In contrast, the mass of the specimens experienced a progressive loss, decreasing from an initial 100% to 98.2% at the end of the test, which represents a total loss of 1.8%. This moderate mass loss under aggressive conditions suggests high chemical resistance of the material, attributable to the formation of N-A-S-H gels, characteristic of alkali-activated geopolymers according to Firdous et al. [13], and Marcillo [21]. Furthermore, Bernal and Provis [23] in their study have highlighted that chemical resistance depends significantly on the composition and type of activator used.

The SEM analysis of the specimens without and with acid attack is presented in **Figure 8**.

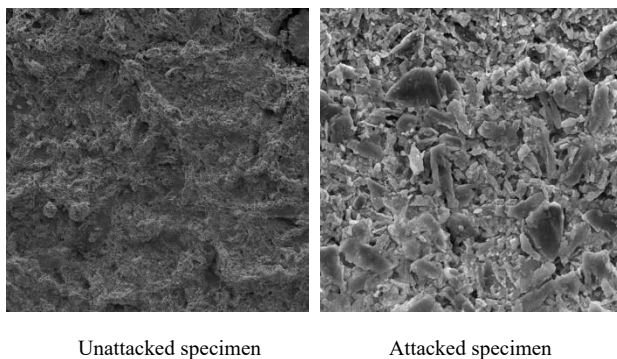


Figure 8. Morphology of the material before and after the acid attack

The pumice geopolymer specimen without exposure to the acid agent presented a dense microstructure, with a compact bond between particles, homogeneous packing, and low porosity. However, some incompletely activated particles were observed, which is consistent with the findings of Bernal et al. [82], and Provis et al. [83], who highlight that incomplete activation can be due to insufficient curing conditions or heterogeneity in the raw materials. In contrast, the specimen exposed for 120 hours to an acidic medium showed significant microstructural degradation, with a loss of cohesion between particles and an increase in voids, factors that favor the penetration of aggressive solutions and accelerate the leaching of cations such as Ca²⁺, Na⁺, or Al³⁺, as also pointed out by Marcillo [21] and Mart ın [22].

In **Figure 9**, the EDS of the material can be observed, which shows that silicon (Si) exhibited high chemical resistance to acid attack, while aluminum (Al), sodium (Na), and potassium (K) showed greater susceptibility to leaching according to Bernal and Provis [23] and Duxson et al. [36]. The Al had an initial increase followed by a slight reduction, associated with partial dissolution and reprecipitation. Na progressively decreased, confirming its high solubility in acidic media, while K showed minimal

variations.

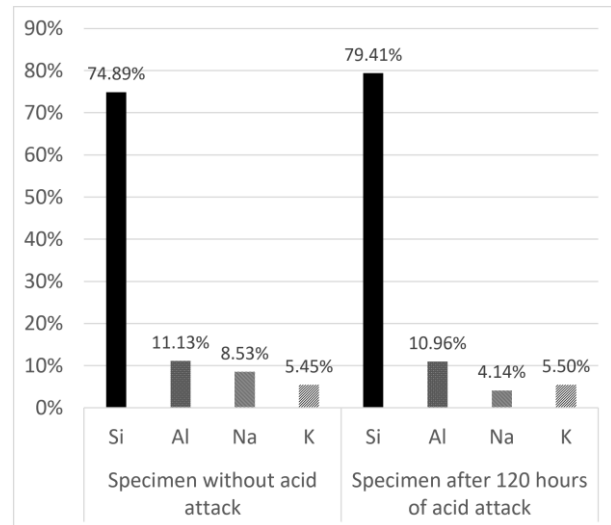


Figure 9. Elemental composition before and after acid attack

These results are consistent with previous research on the chemical stability of geopolymers and aluminosilicate materials in aggressive environments, in which Si retains greater structural integrity due to the strength of Si–O bonds compared to Al–O bonds or the mobility of alkali cations according to Marcillo [21], Mart ın [22] and Ukrainczyk et al. [88].

4. Conclusions

The results obtained in this research demonstrate that geopolymers formulated with pumice represent a feasible and more environmentally sustainable alternative compared to PC. In particular, an 11.8% reduction in CO₂ emissions per kilogram of material produced was evidenced, attributed to the lower energy demand of the alkaline activation process and the absence of emissions derived from clinker decarbonization, typical of conventional cement. This finding agrees with previous studies on the carbon footprint of alternative cementitious materials.

Regarding mechanical behavior, a higher concentration of NaOH favors the development of compressive and flexural strength by increasing the dissolution and reactivity of the aluminosilicates in the pumice. However, this increase in structural performance is associated with a significant increase in emissions from the production of the alkaline activator, which challenges the balance between technical performance and environmental sustainability.

Incorporating mineral additions, such as silica fume and brick dust, is an effective strategy to optimize both the mechanical performance and environmental impact of the system. In particular, silica fume improved flexural strength under low alkali concentration conditions, while brick dust acted as a supplementary material in the matrix,

although with lower reactivity. These additions allow reducing the activator dosage without significantly compromising the material properties, favoring a more sustainable geopolymer design.

Although geopolymers have a higher production cost than Portland cement (between USD 0.29 and USD 0.46/kg compared to USD 0.074/kg), they offer significant advantages in terms of sustainability, durability, and technical performance. The GPP+SF formulation stands out as the most cost-effective option, as it optimizes the use of activators and industrial by-products such as SF. Additionally, the pumice-based geopolymer demonstrated remarkable resistance to acid attack, with only a 1.8% mass loss compared to the 10.7% recorded for Portland cement. This high stability of the geopolymer, confirmed through SEM and EDS, is attributed to its dense microstructure and the formation of N-A-S-H gels, consolidating it as a solid, durable, and resistant alternative for applications in aggressive environments.

This study validates the potential of geopolymers made from Ecuadorian pumice as a sustainable alternative for construction. However, its global implementation requires methodological and formulation adjustments, especially when adapting the approach to regions with different types of natural aluminosilicates or waste materials, in line with the principles of the circular economy. The optimization of the activator concentration and curing conditions is fundamental, not only because of the variability in the chemical composition and reactivity of local raw materials, but also to mitigate the environmental impact of the activator, which currently represents the main factor of pollution and cost in the mix. This ability to adapt is key to large-scale technical, economic, and environmental viability.

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