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Geopolymer Designed with Pumice Stone from Ecuador

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Abstract The present investigation focuses on the creation of a geopolymer, using pumice stone from Ecuador as a precursor material. The chemical composition of the pumice and the alkaline activation of the geopolymer with NaOH and Na_2SiO_3 were validated through a multi-criteria analysis that was used to identify the best mine among the ones located in Cotopaxi, Chimborazo, and Tungurahua states. Through laboratory tests, it was obtained that the best pumice stone had the presence of aluminum oxide and silicon in its composition, as well as amorphous particles, with a size of 40 to 50µm. The percentage of aluminum that was found in the mines of Cotopaxi, Imbabura, and Tungurahua states was 0.60%, 0.68%, and 1.50% respectively. In the fineness modulus tests, it stands out that more than 80% passes the 75µm sieve. In regards to the activation of the geopolymer, the average resistance of the deposits was Cotopaxi 22.60 MPa, Imbabura 23.03 MPa, and Tungurahua 23.03 MPa. In the geopolymer concrete, the average resistance values of each of the deposits were: Cotopaxi 4.21 MPa, Imbabura 8.05 MPa, and Tungurahua 8.67 MPa. The multicriteria analysis showed that the best option to create geopolymer concrete comes from the mine located in Tungurahua. It should be noted that the increase in NaOH concentration, maintaining the ratio of 2.4 in geopolymer cubes between Na_2SiO_3/NaOH as an activating solution, induces an increase in compressive strength. The concrete made from the Tungurahua mine, made up of 50% geopolymer and 50% aggregates. It is the one that showed the best properties with a compressive strength of 16.16 MPa, cured in an oven for 24 hours and at a temperature of 80°C. The design of geopolymer concrete that replaces the use of portland cement is the first step to reduce the pollution produced by hydraulic cement.

Keywords Geopolymer, Pumice, Solution, Concrete, Resistance

1. Introduction

Ecuador is the sixth economy in the region that generates the most carbon dioxide (CO_2) per habitant -around 2.31 tons annually [1][2]. According to a study conducted by the World Bank, of the 107 countries considered, Ecuador ranks as the sixth most polluting economy in South America and the ninth in Latin America [3].

The high emissions of (CO_2) are a worrisome environmental problem, for both government bodies and the citizenry in general. The present research proposes an ecological construction material that can replace concrete, as it has similar mechanical characteristics, using less quantity of (CO_2) in its production [4][5].

The study of geopolymers as cementitious materials was first investigated by Khul in the 1930s and later in the 1950s by V. D. Glukhovskii. The first application appeared in 1958 and was formally patented in 1974. Many Eastern European countries and China undertook many projects with road slabs, airstrips, and precast in the 1970s and 1980s with excellent durability. In the 1980s, the term geopolymer was introduced by Davidovits [6][7], who first mixed alkali with a calcined mixture of kaolinite, limestone, and dolomite. In the 1990s, interest in geopolymers increased because these materials have the potential to reduce CO_2 emissions. They are considered a great alternative to reduce environmental pollution in the construction field [8].

Ecuador has several mines of pumice stone, mainly located in the states of Cotopaxi, Imbabura and Tungurahua [9][10]. Based on research conducted globally on the design of geopolymers, pumice stone is incorporated as a precursor material to create a more environmentally friendly alternative that meets similar mechanical characteristics of traditional concrete.

The objective of this research is to establish a dosage of a geopolymer using pumice stone from the mines located in the states of Cotopaxi, Imbabura and Tungurahua as a solution to the growing demand for sustainable materials in Ecuador. In this research, geopolymer cubes, with a size of 5cm per side, were created to activate the geopolymer, and concrete cylinders were used to determine its resistance.

2. Materials and Methods

This research was developed in 4 stages: the characterization of the pumice stone, the design of a geopolymer through laboratory tests, the application according to the dosage of concrete, and finally the analysis of the data through a multicriteria analysis. This final study allowed the identification of the best alternative among the 3 mines studied.

To collect the results of the composition of the pumice stone, the following tests were carried out:

- X-ray diffractometry test.
- Particle size measurement test
- Atomic absorption test
- Determination of fineness modulus by dry sieving

Currently, there is not a norm that clearly explains a methodology for alkaline activation, manufacturing, and applications in geopolymers. Despite the studies that have been carried out, through the years, each author presents a different approach to the development of their research.

In this study, the alkaline activation of the geopolymer with pumice stone was determined following the ASTM C109 (2016^{a}) “Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 50-mm or 2-inch Cubic Specimens)” and the standard NTE INEN 488:2009 “Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 50-mm or 2-in. Cubic Specimens).” Compression tests on the specimens were conducted to compare the resistance of the geopolymer with the concrete specimens made with Portland cement.

Once the results of the activation of the geopolymer were obtained, the cylindrical concrete specimens were made applying the regulations NTE INEN 1 573:2010 “Hydraulic cement concrete. Determination of the compressive strength of cylindrical specimens of hydraulic cement concrete”. Applying these norms, cylindrical concrete specimens with dimensions of 75 mm in diameter and 150 mm high were introduced into the study. Beginning with the performance of tests on aggregates with the granulometric analysis of sand and gravel applying the standard NTE INEN 696:2011 "Granulometric analysis in fine and coarse aggregates", the determination of the density of aggregates with the standard NTE INEN 856:2010 "Determination of density, relative density (specific gravity) and absorption of fine aggregate" and the standard NTE INEN 857:2010 “Determination of density, relative density (specific gravity) and absorption of coarse aggregate”.

Finally, the multicriteria analysis was carried out to determine the most effective mine. The criteria considered will be further explained in the results section.

2.1. Study Population

The population taken as the universe are the three main deposits of pumice stone in Ecuador. Tables 1, 2 and 3 show the location and coordinates; Figures 1, 2 and 3 show photographs of each of the mines in the states of Cotopaxi, Imbabura and Tungurahua. Cubes with a 50 mm edge were created to carry out the alkaline activation of the geopolymer. In addition, when alkaline activation took place, cylinders with the dimensions mentioned above were manufactured to measure the compressive strength of geopolymer concrete specimens. With the results obtained from the tests of the cubes and cylinders, a multicriteria analysis was applied to find the best alternative.

Table 1. Cotopaxi mine coordinates

Coordinates of the Cotopaxi pumice mine		
Nort	East	Altitude
9893289 m	764720 m	2752 m.s.n.m

Source: Google Earth Pro

Figure 1. Mine location PROFUTURO – Cotopaxi

Table 2. Imbabura deposit coordinates

Coordinates of the Imbabura pumice deposit		
Nort	East	Altitude
9893289 m	764720 m	2752 m.s.n.m

Source: Google Earth Pro

Figure 2. Mine location Gualsaqui – Imbabura

Table 3. Imbabura site coordinates

Coordinates of the pumice stone mine of Tungurahua		
Nort	East	Altitude
9868012m	769961m	2508m.s.n.m

Source: Google Earth Pro

Figure 3. MIne location "Los Pinos"– Tungurahua

2.2. Alkaline Activation of the Geopolymer

The alkaline activation of the geopolymer began with the preparation of the sodium hydroxide solution and distilled water. The bibliography used as a reference for this study considered a concentration already established in their analysis for pumice stone activation. However, in this case, this concentration did not exist, which caused several solutions with different concentrations that required improvement. Table 3 present the different concentrations used in this research project.

Table 3. Molar concentration of sodium hydroxide in 100 ml of solution

Molar concentration (mol)	Weight NaOH (g)
8	32
12	48
16	64
20	80

2.3. Geopolymer Dosage

Before describing the dosage of the geopolymer, it is important to define the following:

$$Aggregates\ [AR] = (Coarse\ Aggregate\ [AG] + Fine\ Aggregate\ [AF])$$

$$[AR] = [AG + AF] \qquad (1)$$

$$Alkaline\ solution\ [SA] = (Sodium\ hydroxide\ [NaOH] + Sodium\ silicate\ [Na_2SiO_3])$$

$$[SA] = [NaOH + Na_2SiO_3] \qquad (2)$$

$$Pumice\ stone\ =\ Source\ of\ aluminosilicates\ [FA] \qquad (3)$$

The dosage of the geopolymer was administered according to several points that will be detailed below.

The geopolymer concrete was made [HGP], according to the raw material density. In this case, the specific weight of conventional concrete was taken as a starting point: 2200 kg/m^3. When multiplied by the percentage of aggregates to be occupied in the concrete, this becomes the AR density.

(1) Relationship between [SA/FA]

It was established under a ratio of "SA / FA" that was a range of 0.3 to 0.65. This depends on the type of mixture to be used. For the purpose of this research, it was necessary to carry out several doses until finding the most suitable to be adapted to the properties of the raw material. This corresponds to the quality and composition of the precursor material and the alkaline solution obtained anywhere in the world.

(2) Quantity of [FA] and [SA]

The geopolymer [GEO] is called the sum of [SA] and [FA] and the geopolymeric concrete [HGP] is the sum of [AR] and [GEO], thus having these two equations:

$$[HGP] = [AR] + [GEO] \qquad (4)$$

$$[GEO] = [SA] + [FA] \qquad (5)$$

By equating coefficients of variables 4, 5 and knowing the relationship "[SA]/[FA]" we obtain the respective densities of [SA] and [FA].

Identify amounts of [NaOH] and [Na_2SiO_3]

Subsequently, to obtain the respective densities of the [Na_2SiO_3] and [NaOH] to create the alkaline solution, which is responsible for activating the geopolymer, the following relationship was used:

$$\frac{NaOH}{Na_2SiO_3} = (0.4 - 2.5) \qquad (6)$$

(3) Equating coefficients of variables 1 and 5, it was possible to obtain the densities occupied in the geopolymer. After previously obtaining the volume of the test tubes and adding 5% waste, it was multiplied by each of its densities and the necessary amounts in grams are obtained.

2.4. Geopolymeric Concrete

With the dosage and alkaline activation of the geopolymer, the geopolymeric concrete (HGP) was made. First, the percentage of aggregate and geopolymer was determined within the investigation to discover its behavior when there is a large amount of aggregates and vice versa. Table 4 shows the ratio of percentages used to make the cylinders.

Table 4. Percentages regarding the required volume of GEO and AR

Geopolymer Quantity (GEO)	Quantity of Aggregates (AR)
10%	90%
20%	80%
30%	70%
40%	60%
50%	50%
60%	40%
70%	30%
80%	20%
90%	10%
100%	0%

In addition, the amount of fine and coarse aggregate of the total weight of aggregates (AR) was taken into account; these figures are presented as percentages in table 5.

Table 5. Percentage of aggregates with respect to the weight of AR and percentage of additives

Sand	Gravel
40%	60%

Once the weight of fine and coarse aggregate was obtained, the alkaline activation process of the geopolymer was repeated with the only difference being that the volume of the aggregates was considered in the dosage of the concrete.

Figure 4 shows a scheme of the mentioned methodology.

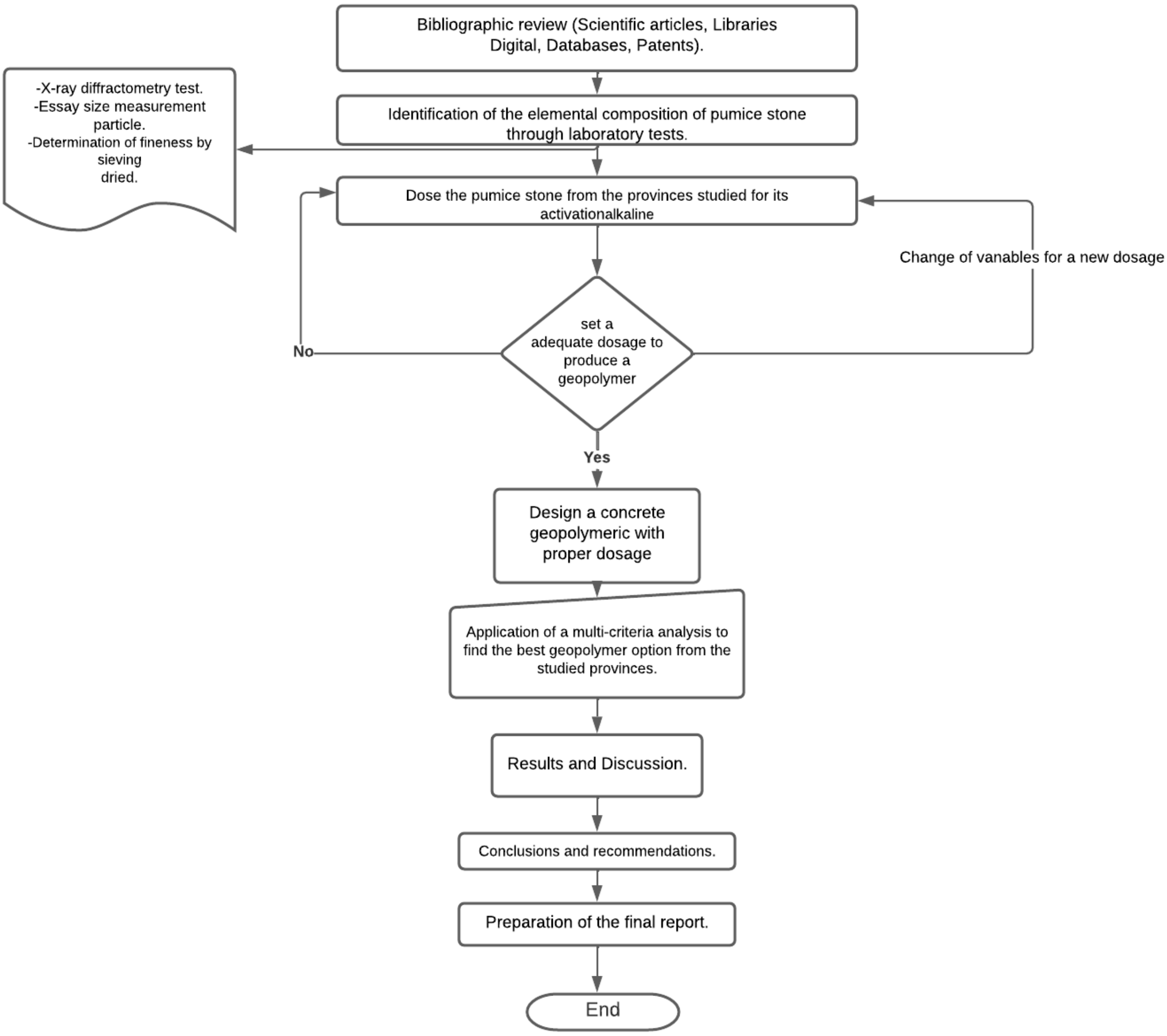

Figure 4. Methodological scheme

3. Results

Composition of Pumice Stone X-ray Diffraction

Figures 5, 6 and 7 show the graphs of the diffraction tests, the pie chart represents the percentage of the composition of the tested samples. We can highlight that there is the presence of ordered anorthite in each sample. Aluminum and silicon appear as fundamental elements for the geopolymerization process.

Table 6. Imbabura X-ray diffractometry assay results

Compound word	Chemical formula	Percentage
Quartz	SiO_2	4.7%
Anorthite, ordered	$Ca\ Al_2Si_2O_8$	5.8%
Magnesiohornblende ferroan	$Ca_2(Mg,Fe)_5(Si,Al)_8O$	8.8%
Albite, calcian, ordered	$(Na,Ca)Al(Si,Al)_3O_8$	4.4%
Amorphous particles	-	76.4%

Table 7. Tungurahua X-ray diffractometry test results

Compound word	Chemical formula	Percentage
Anorthite, ordered	$Ca\ Al_2Si_2O_8$	9.7%
Albite, calcian, ordered	$(Na,Ca)Al(Si,Al)_3O$	5.7%
Illite – 2\ITM#1\RG	$(K,H_3O)Al_2\ Si_3\ Al\ O$	7.6%
Gismondine	$Ca\ Al_2Si_2O_8\ .4H_2O$	11.2%
Amorphous particles	-	65.9%

Table 8. Cotopaxi X-ray diffractometry assay results

Compound word	Chemical formula	Percentage
Cristobalite , syn	SiO_2	1.9%
Anorthite, ordered	$Ca\ Al_2Si_2O_8$	3.8%
Albite, calcian, ordered	$(Na,Ca)Al(Si,Al)_3$	6.7%
Potassium Aluminum Silicate	$K\ Al\ Si\ O_4$	4.3%
Amorphous particles	-	83.4%

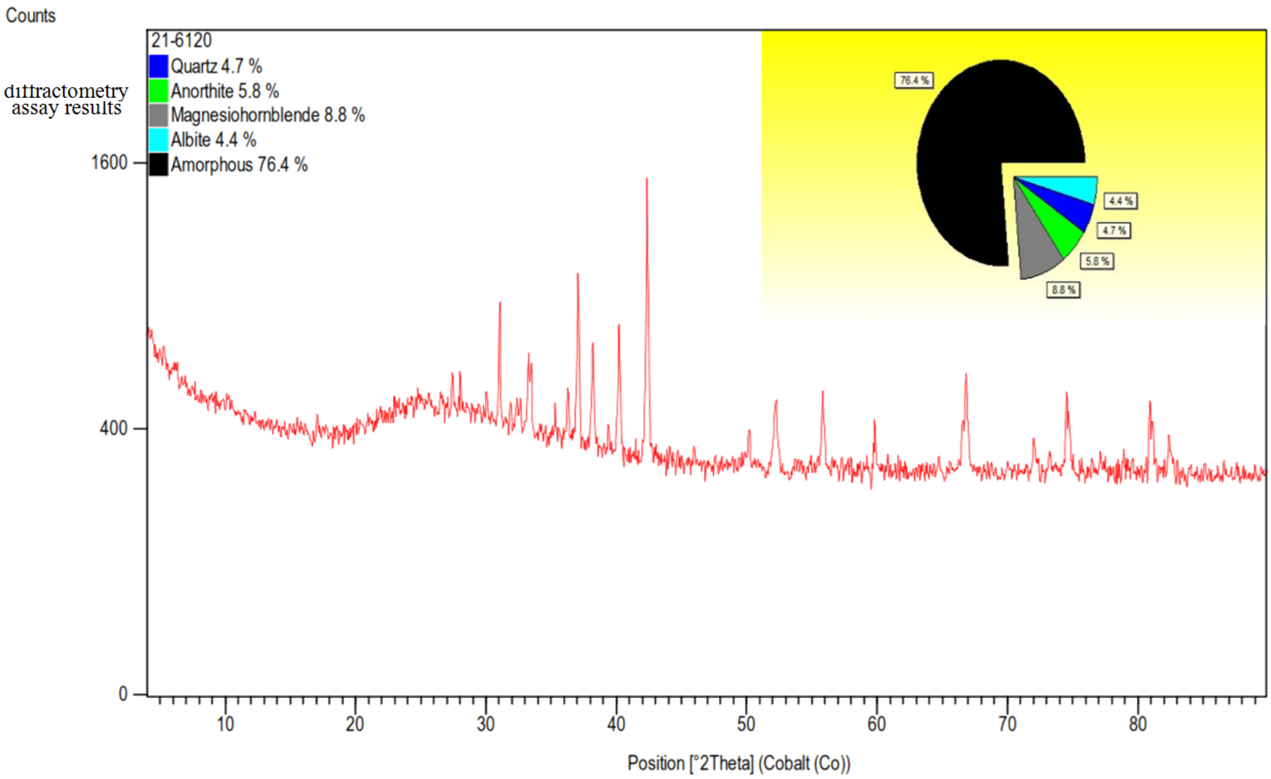

Figure 5. Imbabura X-ray diffractometry test results

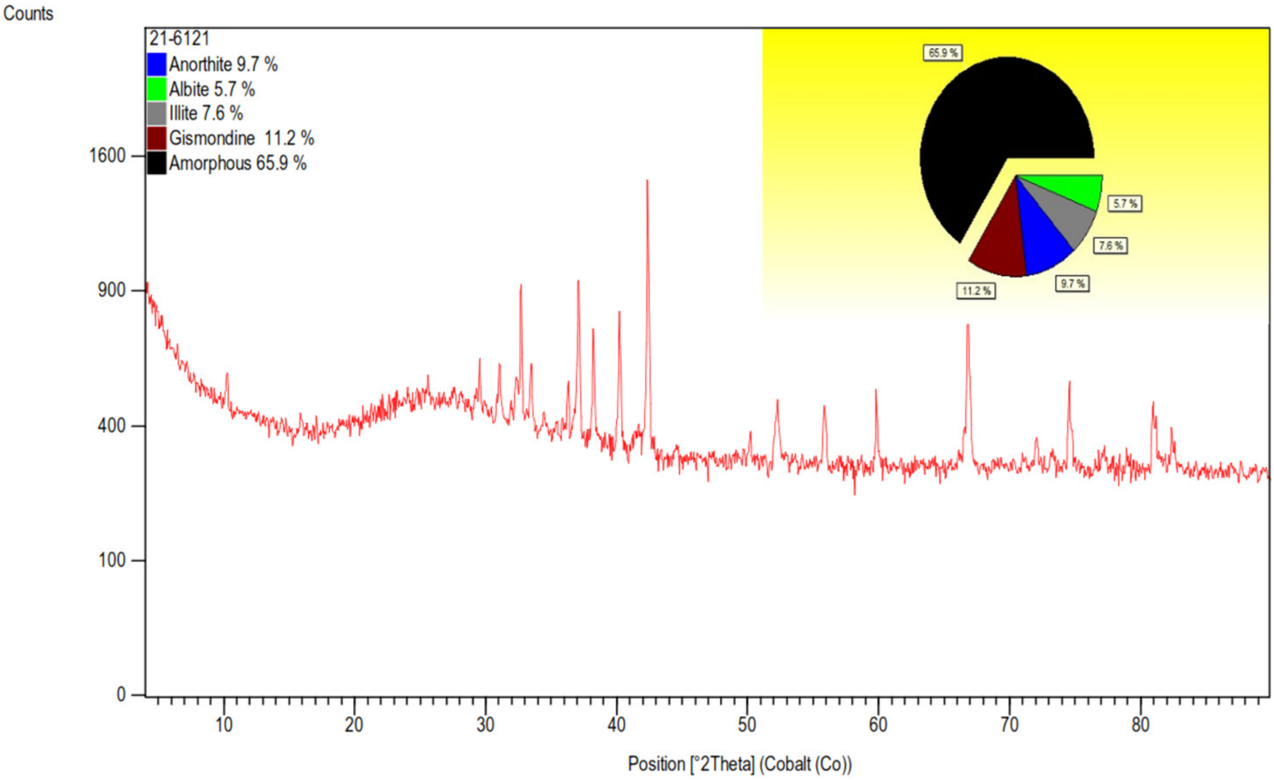

Figure 6. Tungurahua X-ray diffractometry test results

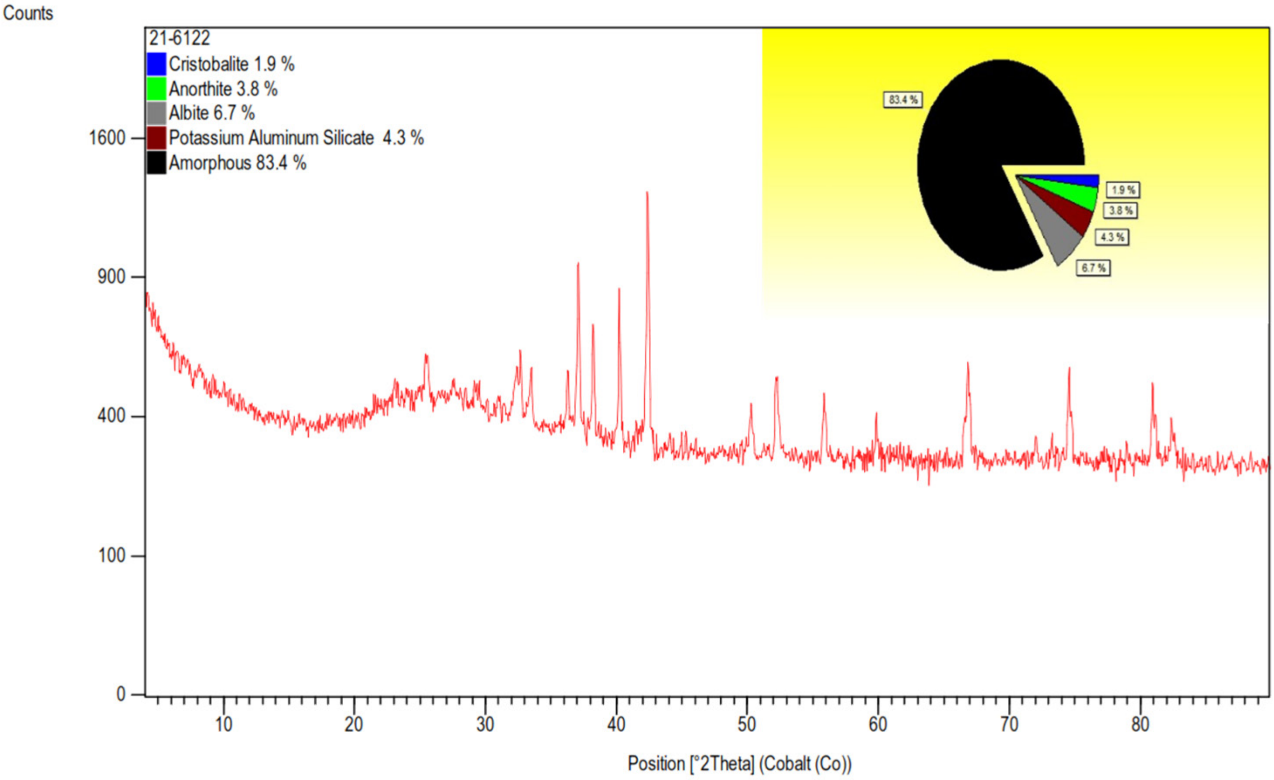

Figure 7. Cotopaxi X-ray diffractometry test results

Table 6, 7 and 8 show the percentages within the tested sample. It should be noted that for the aluminosilicate source to be considered a precursor material, it must comply with several recommendations established in the theoretical framework. Mainly they must have the presence of aluminum and silica in their composition and have amorphous particles. With these results, we are certain that each of the samples can be considered a source of aluminosilicates. This makes feasible to continue with the research.

Particle size measurement

Taking into consideration the previous results, the particle size of each of the samples was determined. Using a particle size analyzer, the test was carried out and the results were obtained as shown in figures 8, 9 and 10.

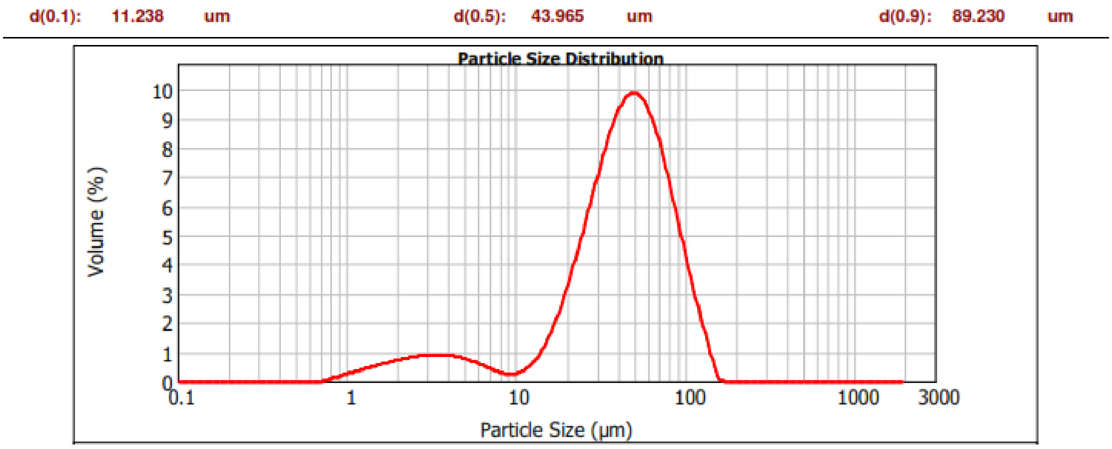

Figure 8. Granulometry of the pumice stone sample from Imbabura

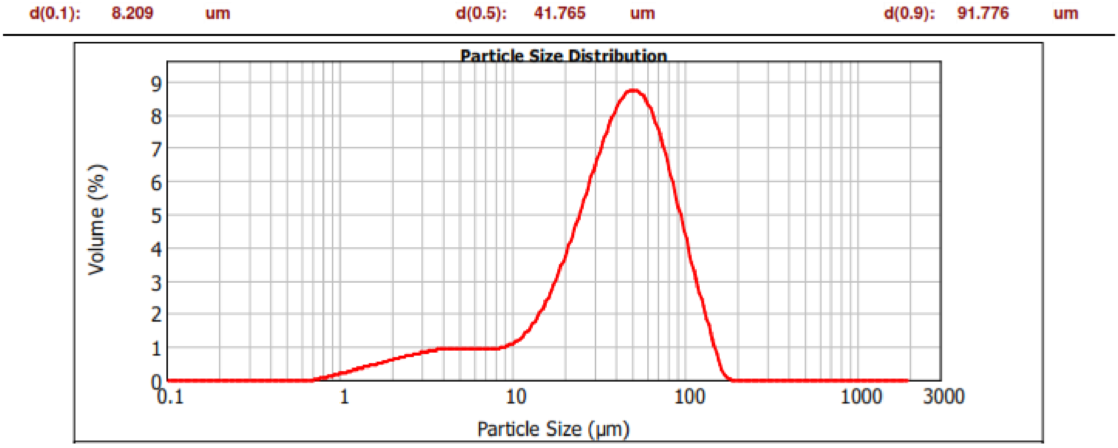

Figure 9. Granulometry of the pumice stone sample from Tungurahua

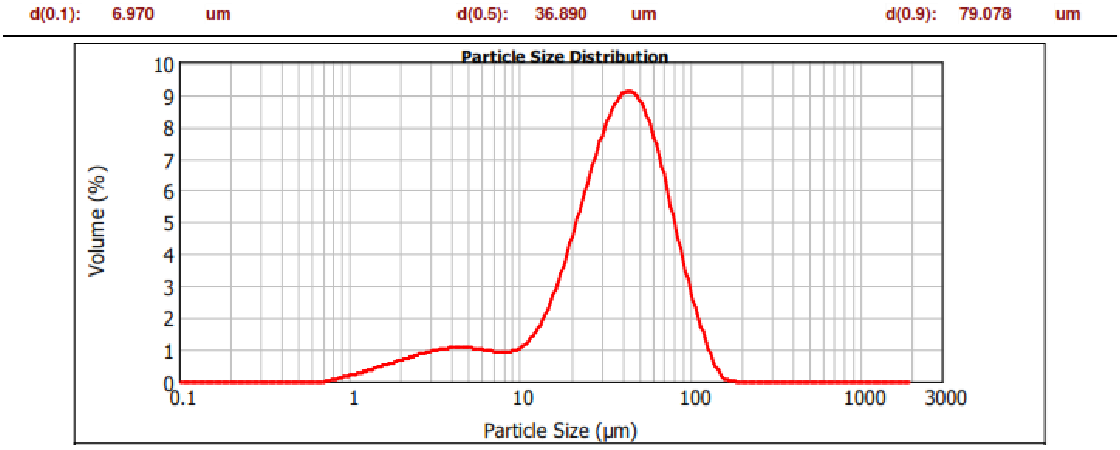

Figure 10. Granulometry of the pumice stone sample from Cotopaxi

Atomic Absorption Test

With the previous results from the x-ray diffractometry, it was evidenced the presence of aluminum within each of the samples. However, it was not possible to know the percentage of aluminum in each sample. For this reason, it was imperative to conduct an atomic absorption test. In order to determine the percentage of aluminum, three results were taken into account to establish an average and then calculate the percentage of Aluminum in the sample.

In Figure 11, X-axis represents the concentration of the aluminum standard, and the Y-axis identifies the values of the different concentrations analyzed. Table 9 shows the value of the aluminum concentration of each sample. It is worth mentioning that the results from the mine in Imbabura had to be corrected because the values obtained were not in the range of 0 mg/L - 50 mg/L. This suggested the concentration should be reduced by increasing distilled water to the previously tested sample to identify the accurate value.

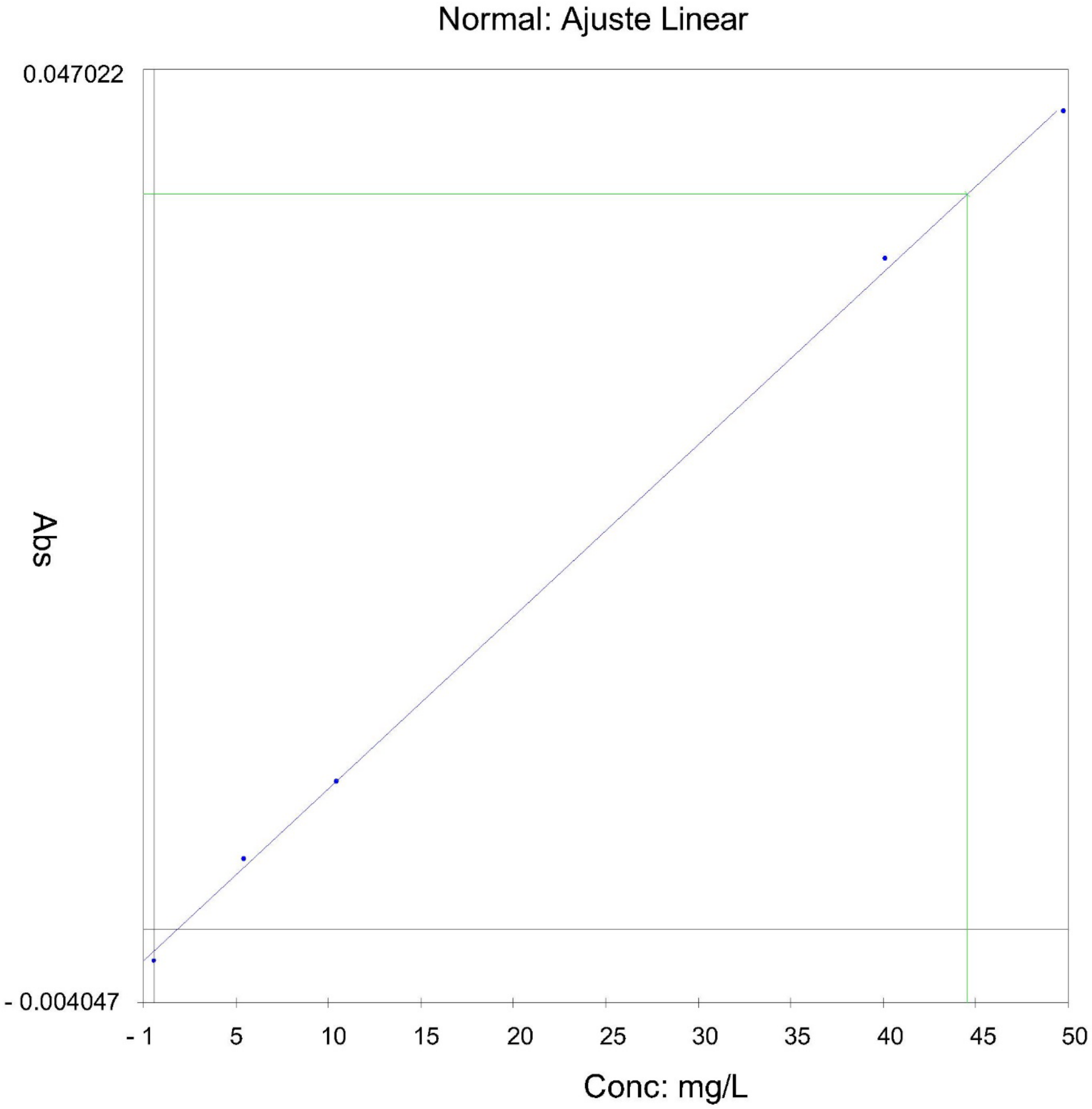

Figure 11. **A**tomic absorption of the material

Table 9. Aluminum Atomic Absorption Test Sample Results

Aluminum dissolution results			
Sample	**Conc. mg/L**	**Conc. mg/L corrected**	**Final concentration**
Cotopaxi L1	28.8681	28.8681	30.1518
Cotopaxi L2	30.6612	30.6612	
Cotopaxi L3	30.9261	30.9261	
Tungurahua L1	35.1384	35.1384	34.2882
Tungurahua L2	34.0354	34.0354	
Tungurahua L3	33.6910	33.6910	
Imbabura L1	36.8246*	73.6493**	74.8347
Imbabura L2	39.5164*	79.0327**	
Imbabura L3	35.9111*	71.8222**	

* Values obtained by reducing the concentration of the sample.
** Values of the corrected concentration of the sample.

Table 10. Aluminum percentage results

Aluminum percentage	
Sample	**% Aluminum**
Cotopaxi	0.6030
Tungurahua	0.6857
Imbabura	1.4966

Table 11. Fineness modulus test results

Deposit	Sieves µm	Test 1 (%)	Test 2 (%)	Mean of each test (%)
Imbabura	75	80.38	79.68	80.03
	150	93.16	92.28	92.72
Cotopaxi	75	76.04	77.12	76.58
	150	96.96	97.72	97.34
Tungurahua	75	80.02	79.86	79.94
	150	93.62	93.60	93.61
Cement Traditional	75	95.22	95.10	95.16
	150	96.92	96.68	96.80

Based on the value of the concentration, the percentage of aluminum was calculated, obtaining the results displayed on table 10.

Determination of fineness modulus by dry sieving

Table 11 presents the results from the comparison established to measure the fineness modulus from each mine. This process was conducted with the fineness modulus of traditional Portland cement.

Values are expressed in percentages, to facilitate the interpretation process fromthe results obtained.

The percentage retained in the 75 µm sieve was much higher than the one tradionally retained in traditional cement. In addition, the percentage that filters through the 150 µm sieve has values similar to those obtained in traditional cement. This gives us an idea that the pumice stone powder obtained by manual and mechanical grinding is close to the values of traditional cement.

Geopolymer Activation

The mixture design was simple, with the expected density of 2200 kg/m^3 in the mixture. The sodium silicate/sodium hydroxide ratio, was established with a value of 2 to later increase to 2.5; the molarity of the hydroxide of sodium was experimented with values from 8 mol to 20 mol.

Several buckets were made for each mine, varying the molar concentration of the sodium hydroxide solution in each one of them. Each specimen was evaluated by the compressive stress that it resisted after curing for 24 hours at a curing temperature indicated in Table 12. As can be seen in figure 12, an example of a geopolymer cube is presented.

Figure 12. Geopolymer cube sample

Table 12. Results of compressive strength f'c of the geopolymer

Date of elaboration	Sample	Ratio $NaOH/Na_2SiO_3$	NaOH mol	curing temp °C	f’c MPa
17/10/2021	Tungurahua	2	12	80	18.31
17/10/2021	Cotopaxi	2	12	80	11.98
22/11/2021	Cotopaxi	2	12	60	13.82
22/11/2021	Imbabura	2	12	60	11.94
22/11/2021	Tungurahua	2	12	60	15.34
30/11/2021	Cotopaxi	2.5	16	60	19.17
30/11/2021	Imbabura	2.5	16	60	15.25
30/11/2021	Tungurahua	2.5	16	60	18.01
30/11/2021	Cotopaxi	2.5	8	60	9.03
30/11/2021	Imbabura	2.5	8	60	8.14
30/11/2021	Tungurahua	2.5	8	60	9.15
06/12/2021	Cotopaxi	2.5	16*	80	33.49
06/12/2021	Imbabura	2.5	16*	80	28.13
06/12/2021	Tungurahua	2.5	16*	80	19.45
06/12/2021	Cotopaxi	2.5	16*	80	28.26
06/12/2021	Tungurahua	2.5	16*	80	27.88
06/12/2021	Tungurahua	2.5	16*	80	26.28
08/12/2021	Cotopaxi	2.5	20	80	37.53
08/12/2021	Imbabura	2.5	20	80	32.72
08/12/2021	Tungurahua	2.5	20	80	32.23
08/12/2021	Cotopaxi	2.5	20*	80	33.30
08/12/2021	Imbabura	2.5	20*	80	22.66
08/12/2021	Tungurahua	2.5	20*	80	32.46
16/12/2021	Cotopaxi	2.5	16	80	16.78
16/12/2021	Imbabura	2.5	16	80	15.46
16/12/2021	Tungurahua	2.5	16	80	17.25
16/12/2021	Imbabura	2.5	20	80	41.71
16/12/2021	Imbabura	2.5	20	80	31.23
16/12/2021	Tungurahua	2.5	20	80	36.96

Results detailed in table 12, explain the analysis of the data obtained from the compressive strength test of the geopolymer cubes. The data processing and analysis was developed with the IBM SPSS Statistics software. Figure 13 represents the values of the average resistance of each of the mines. We highlight Cotopaxi 22.5956 MPa, Imbabura 23.0267 MPa, Tungurahua 23.0291 MPa.

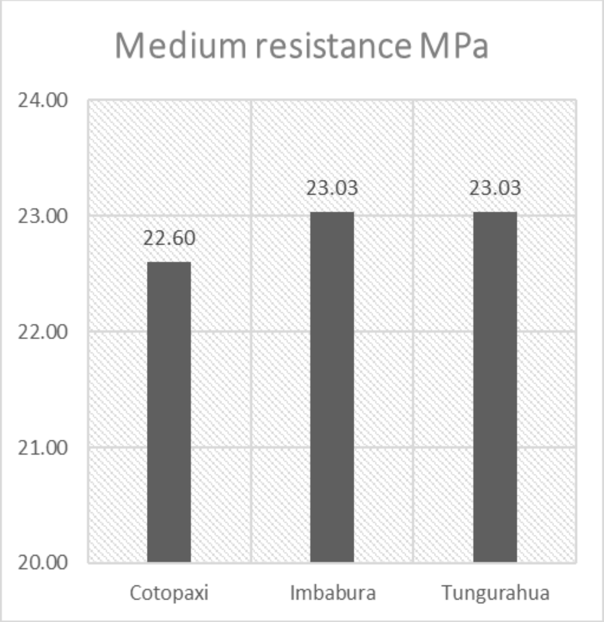

Figure 13. Bar chart of the average resistance of each reservoir

Continuing with the analysis, we proceed to discuss the results obtained from the data analysis between the ratio of sodium hydroxide and sodium silicate $NaOH/Na_2SiO_3$. The ratio was 2.5, however, at the time of data analysis, an average of 2.3889 was obtained for Cotopaxi, 2.444 for Imbabura, and 2.4091 for Tungurahua, but due to facilities for handling within the laboratory, it was considered to work with a ratio of 2.4.

Figure 14 exhibits a descriptive analysis of the curing temperature. An average of 75.56 for Cotopaxi, 76 for Imbabura and 76.36 for Tungurahua. To simplify the laboratory tests, the temperature started at 80 °C, as it is the oven starting temperature.

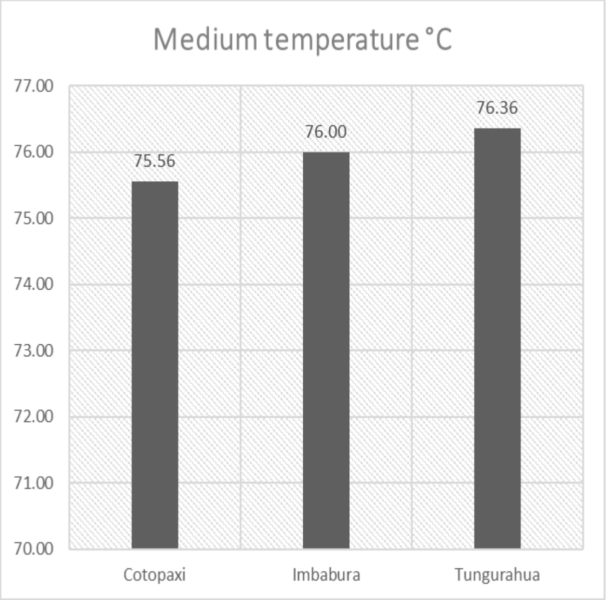

Figure 14. Bar chart of the average temperature of each reservoir

Finally, figure 15 of dispersion of points explains the resistance as a function of the molar concentration. We highlight that in the mines of Cotopaxi and Tungurahua the concentration was maintained and it tends to grow as the concentration increases. In the mines of Imbabura resistance is low, but when working with a concentration of 20 mol its resistance increases considerably.

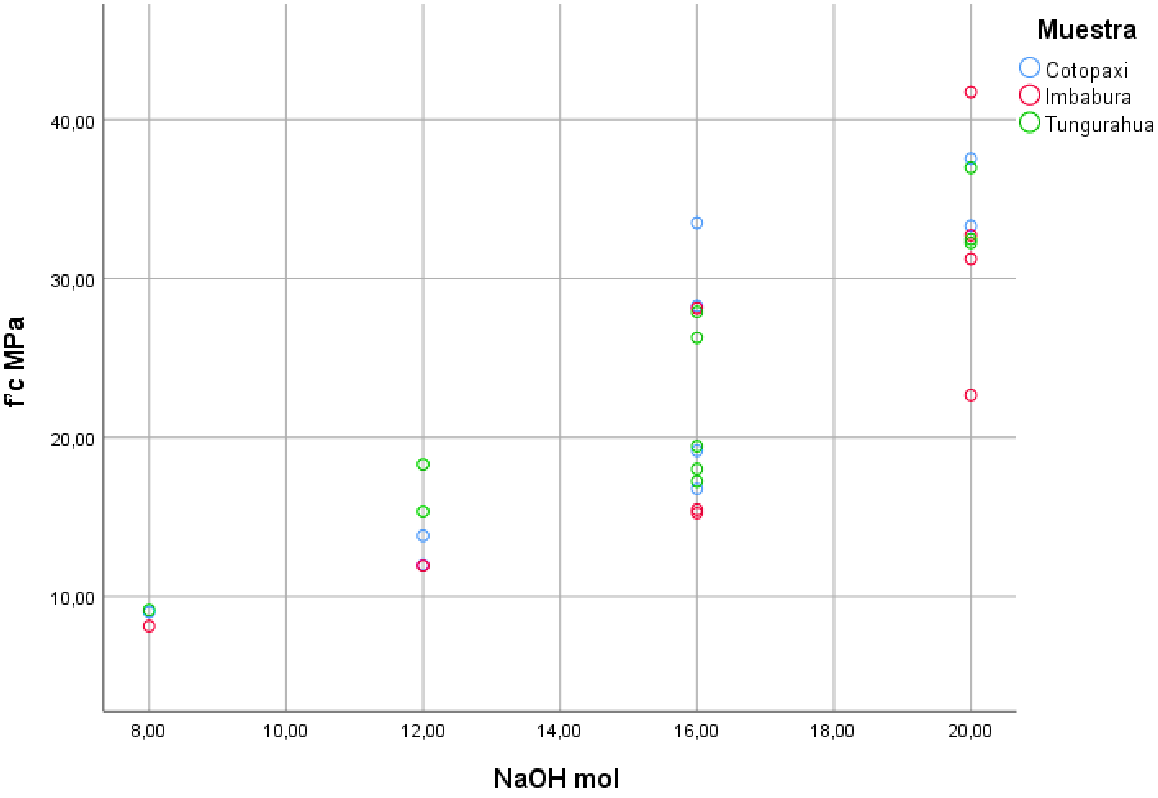

Figure 15. Point scatter as a function of resistance and molar concentration of NaOH.

Design of Geopolymeric Concrete

The previous results give us the guideline to create the geopolymeric concrete. The values of the molar concentration, the relationship between sodium hydroxide and sodium silicate are essential to outline the dosage of the concrete.

Table 13 shows the summary of the values that will be considered within the dosage and Table 14 shows the dosage for geopolymeric concrete specimens.

For the dosage, we worked with the one used for the activation of the geopolymer with some modifications. We decided to work with sand values of 40%, and gravel of 60% as it is detailed in Table 15.

Table 13. Geopolymer Activation Results

Sample	Sodium hydroxide molar concentration.	Sodium hydroxide / sodium silicate ratio.	Curing temperature.
Cotopaxi	16 mol	2.4	80°C
Imbabura	20 mol	2.4	80°C
Tungurahua	16 mol	2.4	80°C

Table 14. Dosage for geopolymeric concrete specimens

Dosage of geopolymeric concrete.		
Diameter	7.5	cm
Height	15	cm
Volume	0.000663	m3
Number of cylinders	1	u
Waste	1	%
AR quantity	1758	g
FA quantity	710	g
Na_2SiO_3 quantity	326	g
NaOH quantity	136	g

Table 15. Amount of aggregates for the concrete specimens

Amount of aggregates for the dosage of geopolymeric concrete.			
Sand	40%	703	g
Gravel	60%	1055	g

Below, table 16 details the values used for the preparation of the geopolymeric concrete specimens. These values are composed with a percentage starting from 10% geopolymer and 90% aggregate to 100% geopolymer and 0% aggregate.

Table 16. Quantities for the preparation of concrete specimens varying the percentage of aggregate and geopolymer

Geopolymer	Aggregate	Pumice	Sodium silicate	Sodium hydroxide	Total aggregate	Sand	Gravel
%	%	(g)	(g)	(g)	(g)	(g)	(g)
10	90	178	81	34	2637	1055	1582
20	80	355	163	68	2344	938	1407
30	70	533	244	102	2051	821	1231
40	60	710	326	136	1758	703	1055
50	50	888	407	170	1465	586	879
60	40	1066	489	204	1172	469	703
70	30	1243	570	238	879	352	527
80	20	1421	652	272	586	234	352
90	10	1598	733	306	293	117	176
100	0	1776	815	340	-	-	-

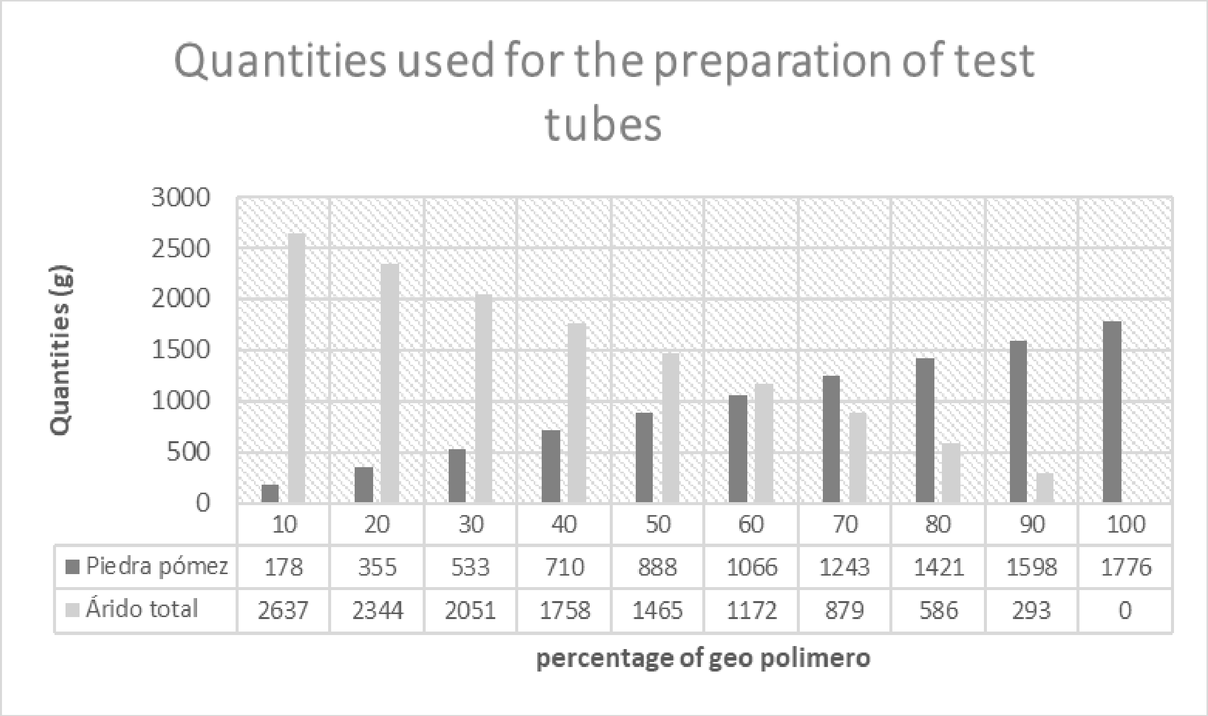

Figure 16. Quantities used for the preparation of test tubes.

Figure 16 shows a graphic representation of the values used for the geopolymeric concrete specimens. Forty five concrete cylinders were created, 15 from each mine. In this research project, the amount of aggregate is considerably greater than the amount of geopolymer.

The data processing and analysis was obtained using the IBM SPSS Statistics software. In the first place, the analysis was carried out based on the resistance results, followed by the analysis of the relationship between sodium hydroxide and sodium silicate NaOH/Na_2SiO_3, then the analysis of the curing temperature to finally select the best dosage for geopolymeric concrete.

Figure 17 shows the values of the average resistance of each of the deposits, we highlight Cotopaxi 4.21 MPa, Imbabura 8.05 MPa, Tungurahua 8.67 MPa.

Table 17 explains the optimal percentages of pumice stone and aggregates, for the samples coming from the 3 mines studied.

With the results for each dosage, 12 cylinders were created again, now modifying the granulometry and making them work in the upper and lower limits. The aggregates used were acquired thanks to the help of Moreno and Covipal, both companies located in the state of Chimborazo. The following results were obtained. (Table 18)

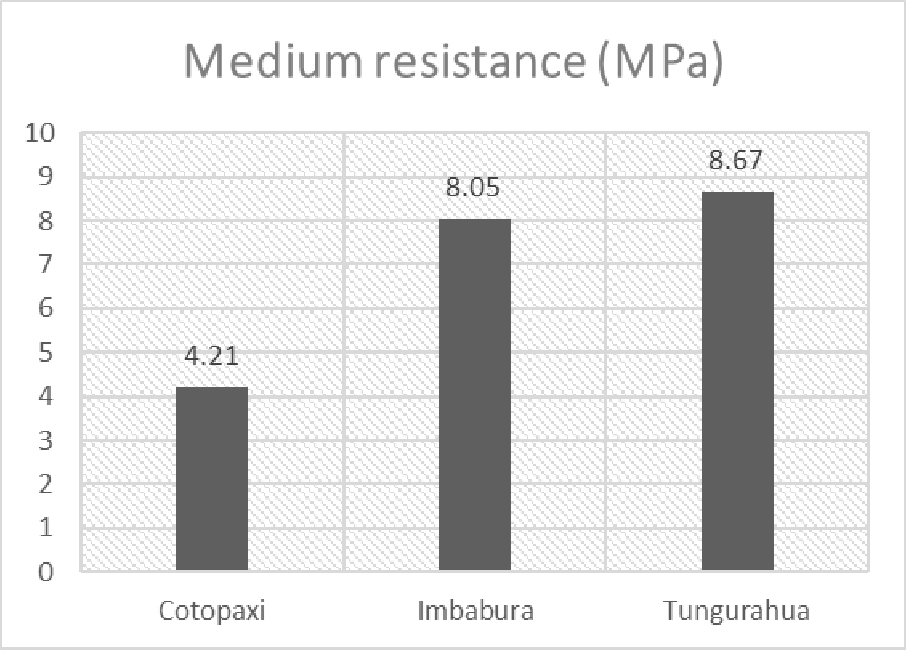

Figure 17. Bar chart of the average resistance of each reservoir

Table 17. Optimal percentages of pumice and aggregate

Sample	Pumice/Aggregates
Cotopaxi	50/50
Imbabura	40/60
Tungurahua	50/50

Table 18. Results of compressive strength f'c of the geopolymer

Item	Sample	Pumice/ Aggregates	Resistance MPa	Observations
1	Cotopaxi Lim Sup Hormigones Moreno	50/50	5.37	23/2/2022 Good surface finish, shows swelling.
2	Cotopaxi Lim Sup Covipal	50/50	5.40	23/2/2022 Good surface finish, shows swelling
3	Cotopaxi Lim Inf Hormigones Moreno	50/50	4.41	24/2/2022 Good surface finish, shows swelling
4	Cotopaxi Lim Inf Covipal	50/50	5.16	24/2/2022 Good surface finish, shows swelling
5	Imbabura Lim Sup Hormigones Moreno	40/60	12.09	23/2/2022 Good surface finish, no swelling, but cracks at the top
6	Imbabura Lim Sup Covipal	40/60	11.72	23/2/2022 Good surface finish, no swelling, but cracks at the top
7	Imbabura Lim Inf Hormigones Moreno	40/60	13.83	24/2/2022 Good surface finish, no swelling, but cracks at the top
8	Imbabura Lim Inf Covipal	40/60	7.11	24/2/2022 Good surface finish, no swelling, but cracks at the top
9	Tungurahua Lim Sup Hormigones Moreno	50/50	4.42	23/2/2022 Good surface finish, no swelling or cracks on top.
10	Tungurahua Lim Sup Covipal	50/50	12.31	23/2/2022 Good surface finish, no swelling or cracks on top.
11	Tungurahua Lim Inf Hormigones Moreno	50/50	11.34	24/2/2022 Good surface finish, no swelling or cracks on top.
12	Tungurahua Lim Inf Covipal	50/50	11.05	24/2/2022 Good surface finish, no swelling or cracks on top.

Multicriteria Analysis

After conducting an interview with six experts on construction materials, specialized in geopolymers and materials testing, we considered the following criteria in the analysis: resistance obtained (MPa), temperature, $NaOH/Na_2SiO_3$ ratio, molar concentration of sodium hydroxide, workability and porosity. In the next section we explain how we identified the best alternative from the results obtained in the test, contrasted with the advise from the professionals interviewed.

Table 19, 20 and Figure 18 show the results and percentages that each expert considers to be the best alternative. Five out of the six experts interviewed agree that the production of geopolymeric concrete should use pumice stones from the mine located in Tungurahua. At the time of this interview, we found the following results.

Table 19. Results to be considered for multicriteria analysis

	Resistencia (MPa)	Gained	Temperature (°C)	Relation	Molar concentration of sodium hydroxide	Workability	Porosity
	Max	**Min**					
Imbabura	1331	0.97	75.56	2.388	20	Liquid	Good surface
Cotopaxi	634	0.95	75.56	2.44	16	Dried	Smooth surface
Tungurahua	16.16	0.96	75.56	24.091	16	Normal	Smooth surface finish

Table 20. Results of the Multicriteria Analysis

Interviewees	Imbabura	Cotopaxi	Tungurahua
Expert 1	46,36%	20,55%	33,09%
Expert 2	30,57%	21,67%	47,76%
Expert 3	20,33%	25,25%	54,42%
Expert 4	31,44%	20,01%	48,55%
Expert 5	32,77%	22,71%	44,52%
Expert 6	32,17%	23,62%	44,21%

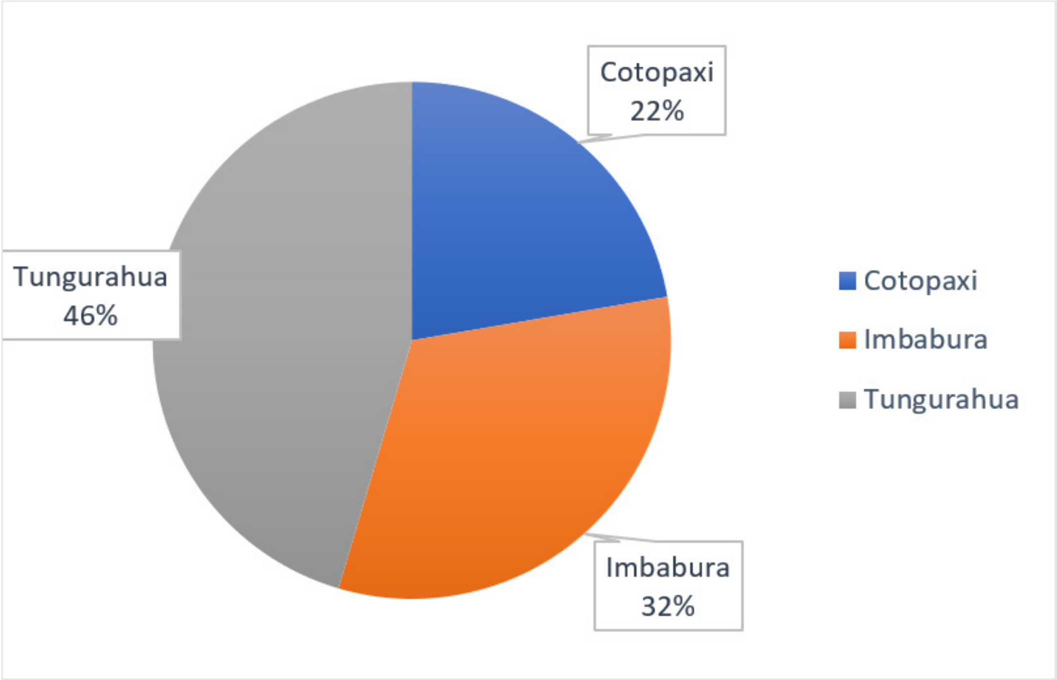

Figure 18. AHP results – Geopolymeric concretes

Even though in the alkaline activation of the geopolymer each one of the deposits meets the requirements of mechanical resistance to compression, when adding aggregates to the mixture we can see that the mechanical behavior changes.

4. Discussions

The results of this study indicate that pumice stones from the 3 mines studied can be used in the creation of geopolymers. They show acceptable results based on their resistance and excellent mechanical properties compared to Portland cement. This can be an innovative ecological alternative to reduce the production of CO_2 in Ecuador in the construction field.

Pumice stone can replace accementing agent due to the alkaline activation of geopolymers because the majority of its components are amorphous particles of silicon (Si) and aluminum (Al) oxides [11]. Each of the mines studied show that there is more than 65% of amorphous particles within its composition, in addition to the presence of silicon and aluminum, which makes them ideal for the alkaline activation of the geopolymer. According to [12] in order to the geopolymerization process to occur adequately, it is required to have certain criteria, such as the Si/Al ratios, the NaOH molar concentration, the temperature, and the previous curing. This research complies with all the aforementioned criteria.

The findings in this research are also supported with additional studies, based on microscopy tests, that allowed us to determine that the particles are amorphous due to grinding processes to reach granulometric with a diameter of less than 75 mm; in their chemical composition, there are mostly silicon oxides and of aluminum [13][14]. The purpose of grinding is to reduce the particle size to facilitate the dissolution of silicon and aluminum and thus increase the chemical activity of the source of aluminosilicates with the activating solution in the geopolymerization process. With the particle size tests carried out in the three mines, it was possible to determine that the pumice powder obtained by manual and mechanical grinding had values close to 75 mm. This allowed achieving the alkaline activation of the geopolymer, with the fineness modulus. More than 80% of the three deposits passed through the 75 mm sieve.

A variable considered for the activation of the geopolymer is the concentration of NaOH. As the concentration decreases, the compressive strength is also affected [8]. In changing the concentration of the cubes created for this study, we verified that when the concentration decreases, the resistance also decreases.

Geopolymers represent an opportunity to replace traditional products in the construction industry, including concrete, mortar, bricks, panels, pavements and ceramics [15]. The versatility of the material guarantees its application in multiple sectors and areas within civil engineering. In this research, the mechanical behavior was analyzed under the compressive strength test of geopolymeric concrete and through the multicriteria analysis carried out with the help of six experts in the field of material testing. The variables considered within the analysis are: resistance, curing temperature, $NaOH/Na_2SiO_3$ ratio, molar concentration of NaOH, workability and porosity within the concrete specimens produced.

5. Conclusions

Pumice stones from the three mines studied have amorphous particles in their elemental composition, and the presence of silicon oxide and aluminum oxide, which are essential for the alkaline activation process to be carried out in the creation of geopolymers.

The increase in NaOH concentration, maintaining the ratio of 2.4 in geopolymer cubes between $Na_2SiO_3/NaOH$ as activating solution, induces an increase in compressive strength.

The addition of water to the mixture considerably reduces the compressive strength of the geopolymer. For this reason, when preparing the geopolymeric concrete, dry aggregates were used for 24 hours in the oven to guarantee that water and humidity from the aggregates do not affect the relationships and concentrations previously established.

The concrete made from the Tungurahua mine, made up of 50% geopolymer and 50% aggregates. It is the one that presented the best properties with a compressive strength of 16.16 MPa, cured in an oven for 24 hours and at a temperature of 80°C.

Through the multicriteria analysis, it was possible to identify that the Tungurahua deposit is the one with the best characteristics in terms of resistance variables, curing temperature, $NaOH/Na_2SiO_3$ ratio, molar concentration of NaOH, workability and porosity within the specimens made of concrete. According to experts, the resistance variable is the one that most influences the creation of geopolymeric concrete. The mine that exhibits the highest values of resistance throughout this investigation is also the one located in Tungurahua.

We suggest that the design of geopolymeric concrete that replaces the use of portland cement is the first step to reduce the pollution produced by hydraulic cement. Transitioning to the use of ecological materials can open the way to the use of alternative technologies that can optimize the construction processes currently used in Ecuador.

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