Geomechanical Characterization of Volcanic Rock Samples from the Camilo Ponce Enríquez Mining Field, Ecuador

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Abstract

This study investigates the geomechanical properties of volcanic rocks from the Camilo Ponce Enríquez mining field in Ecuador. The research aims to understand the physical and mechanical features of these rocks to enhance the safety of mining operations in the area. Laboratory tests were conducted following ISRM and ASTM methodologies to provide relevant information for these purposes. The results revealed a significant correlation (R 0.802) between uniaxial compressive strength (UCS) and point load strength (PLT), as well as (R 0.703) between UCS and indirect tensile strength index (IDT). Additionally, a new equation was developed to estimate compressive strength from the Schmidt hammer, facilitating rapid assessment of rock masses in the field. These findings have significant implications for decision-making in the mining industry and civil engineering in the region.

Highlights

- Geomechanical characterization of volcanic rocks in the Camilo Ponce Enríquez mining field.
- Strong correlation between parameters such as uniaxial compressive strength and abrasion resistance.
- Development of an equation to estimate compressive strength from the number of rebounds of the Schmidt hammer.
- Contribution to geotechnical knowledge for future explorations and constructions in the Ecuadorian mining region of the Sierra.

Keywords: geomechanical properties, volcanic rocks, laboratory tests, compressive strength, mining.

1 Introduction

The mining industry, being a cornerstone in the global economy and particularly in the Andean region, constantly faces the challenge of ensuring the safety of mining operations and maximizing resource extraction efficiency (RMI 2005). To achieve these goals, it is essential to thoroughly understand the geomechanical properties of rocks present in mining deposits (Coduto et al. 2020). In this context, the present research focuses on the geomechanical characterization of volcanic rocks samples from the Camilo Ponce Enríquez mining field in Ecuador.

Geomechanics plays a critical role in understanding the behavior of rocks and soils under various loading and stress conditions (Dehghan and Yazdi 2023; dos Santos Lemos et al. 2023). This knowledge is essential for ensuring the stability of mining structures, preventing accidents, and optimizing extraction processes (Cuervas-Mon et al. 2017; Brousset et al. 2023; Dehghan and Yazdi 2023). However, the lack of detailed information on the specific geomechanical properties of some volcanic rocks poses a significant challenge for the mining industry in the region (Escobar-Segovia et al. 2020).

The mining concession of Camilo Ponce Enríquez in Ecuador is located in volcanic units. Despite its geological and economic significance, there is a notable lack of information regarding specific geomechanical features (Török and Czinder 2017). This lack of information hampers proper planning of mining operations, increasing the risk of accidents and affect resource extraction efficiency. Therefore, there arises a need to conduct research to characterize the geomechanical properties of the volcanic rocks of this area.

The importance of this research lies in its contribution to practical and low-cost scientific knowledge and its impact on the mining industry. Understanding the geomechanical properties of the rock deposits will not only enhance the safety of mining operations but also enable the optimization of extraction processes and more effective planning of mining structure (Adamcová et al., 2014; Czinder & Török, 2021; Dinçer et al., 2004). Additionally, from an environmental and sustainability perspective, precise knowledge of these properties will help implement more responsible mining practices and reduce negative impacts on the natural environment (Török and Czinder 2017; Czinder and Török 2021).

The goal of this study is to evaluate the geomechanical properties of volcanic rocks samples through a series of mechanical tests. The tests are destructive in nature to determine uniaxial compressive strength (UCS), indirect tensile strength (IDT), point load strength, and partially non-destructive in the case of the sclerometer, as it leaves a slight imprint. These results will not only provide a better understanding of the behavior of volcanic rocks under different loading conditions but also offer practical recommendations to enhance the safety and efficiency of mining operations.

It is crucial to establish correlations that allow estimating the value of one parameter from the measurement of others. This is a practical application in mining and underground works, where often only a sclerometer and geological hammer are available on a day-to-day basis. The results obtained from this work will serve as a basis for future geotechnical stability studies in this region of the country.

2 Geographical and geological framework

The Camilo Ponce Enríquez Mining Field is located in Azuay Province, southern Ecuador, on the western flank of the Western Cordillera. This region is characterized by significant geological formations, including the Pallatanga Formation (Duque et al. 2018; Escobar-Segovia et al. 2020).

The Pallatanga Formation, originating from the Cretaceous period, represents an ophiolitic association comprising various rock types, including oceanic basalts, pillow lavas, hyaloclastites, and massive dolerites (Fulignati et al. 2023). These rocks exhibit a range of textures, from aphanitic to variolitic, and may contain localized gabbroid bodies. Geochemically, they are classified as basaltic rocks with tholeiitic affinity.

The majority of rocks within the Pallatanga Formation are aphanitic, although some sections contain phenocrysts of pyroxene and plagioclase. These rocks are predominantly basaltic in composition, with minor variations in texture and mineralogy across different localities (Codigem 1997). The formation's lithological composition and geochemical characteristics make it a significant target for geological and geomechanical studies, particularly concerning mining operations and infrastructure development.

The structural setting of the Camilo Ponce Enríquez Mining Field is influenced by various fault systems, with orientations including N-S, NW-SE, or WNW-ESE (Prodeminca 2000). These fault structures play a crucial role in controlling the distribution of mineralization within the region, affecting the overall geomechanical behavior of the volcanic rocks of the Pallatanga Formation.

Samples for this study were specifically obtained at UTM coordinates 642475 m E and 9663916 m N in the WGS84 system, providing a precise location for the geomechanical characterization of the volcanic rocks from the area. Fig1 presents a map showing the location of the study area.

Fig1.

3 Materials and Methods

For our current investigation, laboratory tests were conducted in accordance with methodologies outlined by the International Society for Rock Mechanics (ISRM) and the American Society for Testing and Materials (ASTM). Sample preparation involved extracting rock core specimens to meet the Length/Diameter (L/D) as specified for the different methodologies applied. For UCS and IDT tests the cores were cut to meet the L/D ratio of 2 according to ASTM D 4543-01 (2001) and D/L ratio of 2 for ISRM (Alejano et al. 2018), respectively. The remaining fragments that did not meet the mentioned ratios were used for the dry density and point load tests (PLT). The tests were divided into 3 categories: (1) physical characterization, (2) non-destructive tests, and (3) destructive tests.

3.1 Physical Characterization

Dry Density

The dry density test was developed following the ISRM lineaments according with the method of Ulusaym and Hudson (2007) which utilizes saturation and buoyancy techniques. Ten irregular fragments weighing more than 50 grams were used. The fragments were saturated in a vacuum capsule for one hour. After this time, the samples were weighed on the hydrostatic balance to obtain the value of the submerged mass, and subsequently dried with a damp cloth to weigh them on a digital balance and obtain the value of the surface-saturated dry mass. The apparent volume of each sample was obtained using the density of water that was defined according to the temperature it had during the test (29.1°C). To determine the value of the dry mass, the samples were placed in an oven at a temperature of 105°C for a duration of 18 hours. Finally, the dry density was calculated using these values. Additionally, the apparent density of a rock core was calculated by measuring its dimensions.

3.2 Non-destructive test

Uniaxial Compressive Strength - Schmidt Hammer

To determine the UCS of the rock, a Schmidt hammer was used recording the number of rebounds (N). The impact energy of the hammer is 2207 N·m. Twenty impacts were executed on the faces of the blocks that were flat and without major roughness as suggested by ISRM (Aydin 2008).

Depending on the orientation of the face, impacts were made vertically downwards or at 45° to the horizontal. The calculation of UCS values was carried out according to the equipment specifications based on the rebound number.

Tilt Test

The method suggested by ISRM was employed to determine the basic friction angle of Flat Rock Surfaces (Alejano et al. 2018). A configuration of series of 3 cylindrical cores was used as shown in Fig2. The inclination angle corresponds to the measured angle at which the upper core begins to slide relative to the base cores. The basic friction angle was calculated from specific equation mentioned in this suggested method. The loading rate for this test was controlled and maintained at 10°/s or its equivalent 60 mm/min. The cores were tested with their natural moisture.

Fig2.

3.3 Destructive test

Indirect Tensile Test (IDT)

The IDT was conducted using the method suggested by ISRM (Ulusaym and Hudson 2007). Steel couplings according to the method were used and tested in a compression press, recording force and displacement data. The tensile strength value of the samples was calculated using this force and the specimen dimensions, the diameter and thickness specifically. Fig3 shows the result of the test application on one of the samples.

Fig3.

Point Load Test (PLT)

The method suggested by ISRM for PLT states that cylindrical specimens, well-formed blocks, and irregular rock pieces can be used (Ulusaym and Hudson 2007). For this study, irregular fragments that met the dimensions established by the method were used. The loading rate for this test was 500 N/s, this value was set for the failure occur within a range of 10 to 60 seconds according to the method.

Uniaxial Compressive Strength (UCS)

Rock cores with an approximate L/D ratio of 2 were used to according with ASTM D 4543-01 (2001). Subsequently, they were placed on the central axis of the equipment between two platens that compressed the core. Axial load was applied at a rate of 0.25 MPa/s until failure occurred in the core. The load was recorded on the compression machine, and the area of each core was measured with a Vernier caliper. From these values, the uniaxial compressive strength of the volcanic rocks samples was obtained.

3.4 Statistical analysis

The SPSS (Statistical Package for the Social Sciences) software package was used to perform statistical analysis. Bivariate Pearson correlation analysis was conducted to examine the relationship between the results of uniaxial compressive strength (UCS), point load strength (PLT), indirect tensile strength (IDT), and the rebound number of the Schmidt hammer (N) in the volcanic rocks samples from the Ponce Enriquez area. Subsequently, regression analysis was performed to estimate the curve and determine which equation best fit the established model.

4 Results

In this section, the results of a series of geomechanical tests conducted on volcanic rocks samples are presented. Table 1 shows the apparent volume and dry density of the samples. The average value of dry density is 2.93 g/cm3, a typical value for a more basic and competent rock. To verify this data, direct measurement of a rock core with known geometry was conducted, yielding a value of 2.98 g/cm^3, confirming the consistency of the measurements. Additionally, the basic friction angle was calculated for different core configurations, showing a range of values between 23 and 27 degrees.

Table1.

Table 2 shows the results of uniaxial compression, point load, indirect tensile, and Schmidt hammer tests conducted on 18 samples of volcanic rocks. Significant variations in mechanical properties are observed among the samples, likely caused by mineralization and veins found in the internal structure of the tested samples (Fulignati et al. 2023).

Table2.

The minimum, maximum, average, and standard deviation values of the conducted tests are summarized in Table 3. An average UCS of 167.52 MPa is shown; the average for PLT is 15.43 MPa; the average for IDT is 24.32 MPa; and an average of 51.6 rebounds per Schmidt hammer measurement.

Table3.

Correlation of Laboratory Findings

In this section, statistical analysis was applied using the SPSS software package to correlate the results of UCS, PLT, IDT, and N. The results of this correlation are presented in Table 4.

For the andesite samples, the proposed equation relating PLT and UCS showed the highest multiple correlation coefficient (0.895**). Similarly, the correlation between UCS and IDT resulted in a correlation coefficient of 0.839**, and the correlation between UCS and N showed a correlation coefficient of 0.913**. The significance of these correlations is confirmed with a confidence level of 0.01 (bilateral).

Table4.

The fitting models found for the relationship between UCS and PLT, as well as between UCS and IDT, showed that the best fit was achieved with linear and quadratic equations. The analysis of Table 5 revealed determination coefficients (R-squared) of 0.802 and 0.703 respectively for the linear equation, and R-squared of 0.841; 0.704 for the quadratic equation. Figure 4 illustrates the various equipment used for laboratory tests as well as the specimens after the test application.

Fig4.

Additionally, Figures 5-7 visually present the relationships between UCS vs PLT, IDT, and N, supporting the statistical findings. This study has found significant and consistent relationships among the evaluated geomechanical properties of the volcanic rocks.

Table5.

Fig4.
Fig5.
Fig6.

5 Discussion

The results of the tests show significant variability in the mechanical properties of the analyzed volcanic rock samples. Uniaxial compressive strength (UCS) ranged from 131.56 MPa to 225.57 MPa, with an average of 167.52 MPa and a standard deviation of 27.16 MPa. These variations could be attributed to differences in mineralogy, internal structure, and the presence of mineralization and veins in the tested samples.

When correlating the results of UCS with PLT, IDT, and Schmidt rebound number N, significant correlations were found, supported by Pearson correlation coefficients of 0.895, 0.839, and 0.913 respectively, all with a significance level of 0.01 bilateral.

The fitting models revealed that the relationships between UCS and PLT, as well as between UCS and IDT, showed the best fit with linear and quadratic equations. These findings suggest that these properties are closely related to each other and can be predicted with some precision using relatively simple laboratory tests.

Comparing these results with previous studies conducted in different parts of the world (see Table 6), similarities are observed regarding the importance of understanding the variability in the mechanical properties of rocks and their relationship with factors such as mineralogy, internal structure, and degree of alteration. However, each study also presents its own particularities and methodological approaches.

Table6.

When comparing the results obtained in this study with previous research on other volcanic rocks, similarities and differences are observed that reflect the complexity of these materials in different geological contexts. For instance, considering the UCS values, it is found that the minimum, maximum, and average UCS values for andesite in this study fall within similar ranges as those reported for other volcanic rocks, such as basalt and tuff, in previous studies. However, variations in UCS values among different types of volcanic rocks suggest the influence of factors such as mineralogy, internal structure, and degree of alteration. Similarly, when comparing the values of the Schmidt hammer rebound number (N), considerable variability is observed among the different rocks, emphasizing the importance of evaluating geomechanical properties specifically for each type of material.

Regarding the practical implications of this study, the obtained results can be valuable for the mining and construction industry, offering valuable information for material selection, structural design, and geotechnical project planning in the region and geologically similar areas.

6 Conclusions

In conclusion, the results of this study provide a detailed geomechanical characterization of volcanic rock samples from the Camilo Ponce Enríquez mining field, Ecuador. Despite conducting the tests following the methodology suggested by ISRM and ASTM, a considerable variation was obtained among the results of the same parameter.

It was identified that one of the reasons for this variation was the orientation of the fault planes in the destructive tests, which were guided by the veins or fissures with oxidation characteristic of the mineralization present in the rock composition. In certain specimens, these elements were more pronounced, which in a way weakened the resistance that the rock could present. However, the results obtained in the destructive tests do reflect high values of resistance, which makes sense considering that it is a hard and competent volcanic rock.

The comparison with other types of volcanic rocks highlights the variability in geomechanical properties. Remarkably, these rocks exhibit characteristics akin to basalts, aligning with findings from previous studies. Although similarities are observed in UCS and N, the differences underscore the importance of considering the mineralogy and internal structure of each type of rock.

The information provided by this study serves to understand the type of rock present in the study area. In future work, certain strength parameters can be estimated using field tests such as rebound number with a Schmidt hammer with equipment similar to that used in this study. Likewise, in design and stability issues, the values of basic friction angle can be used for a preliminary analysis of the rock mass.

The correlation among different geomechanical parameters, such as uniaxial compressive strength, point load, indirect tensile strength, and Schmidt hammer rebound number, showed significant and consistent relationships. These relationships provide a deeper understanding of the mechanical response of volcanic rocks in the study region. The development of tests according to international standards and the consistent results obtained in the statistical analysis are factors that demonstrate the reliability and accuracy of the information presented in this study.

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Data Availability The datasets used and analyzed during the current study are available from the corresponding author upon reasonable request.

Statements

Conflict of Interest The authors declare no relevant financial or non-financial interests.

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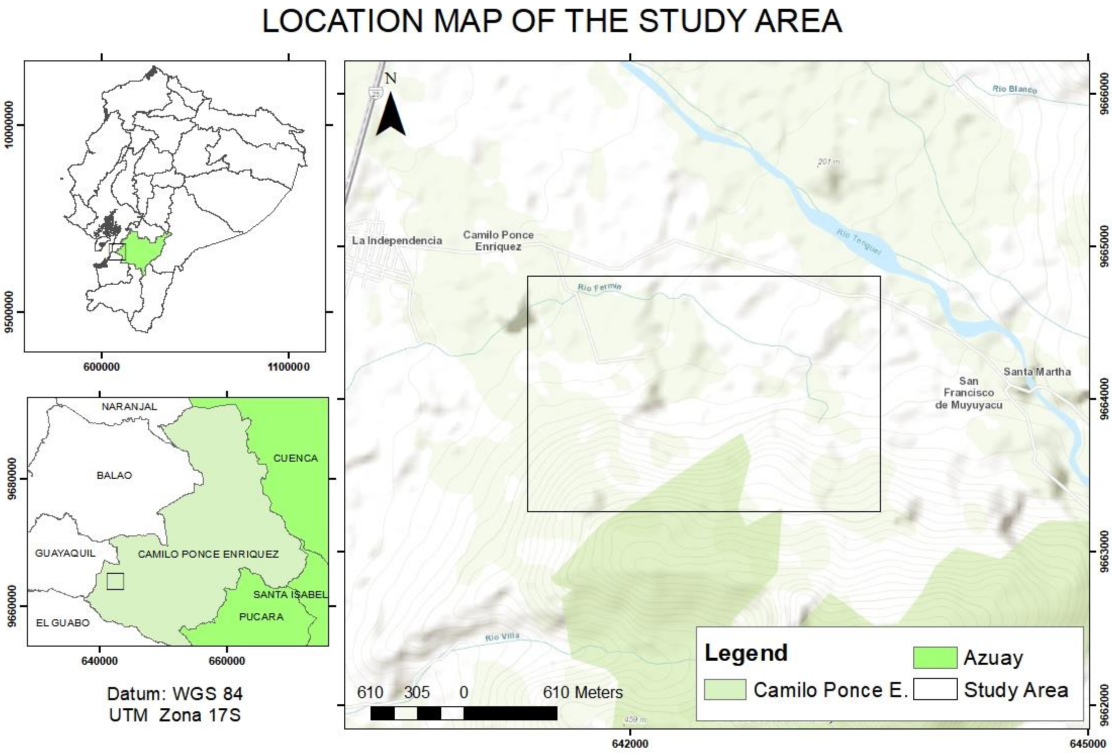

Fig1. Location Map of the Study Area in the Camilo Ponce Enríquez Mining Field, Ecuador.

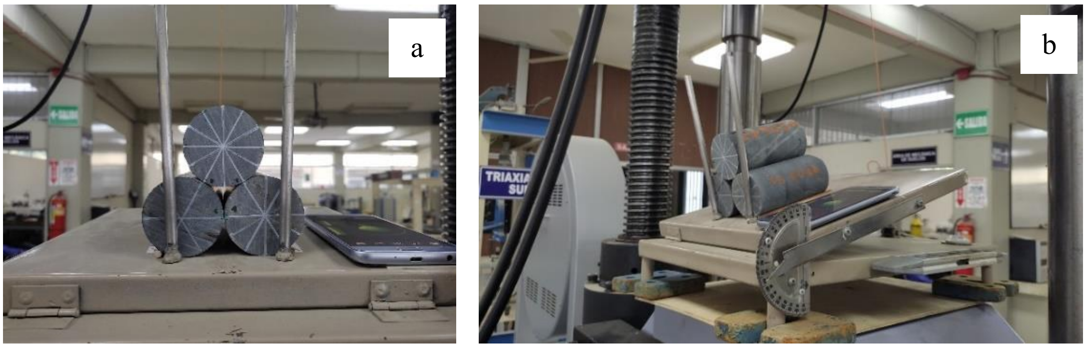

Fig2. Tilt Test. a) Core configuration for the test; b) equipment used to maintain the loading rate.

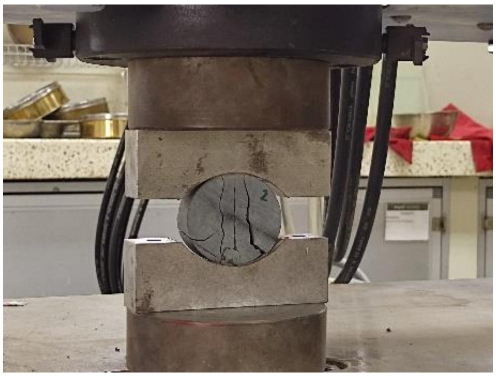

Fig3. Indirect Tensile Test with the method suggested by ISRM.

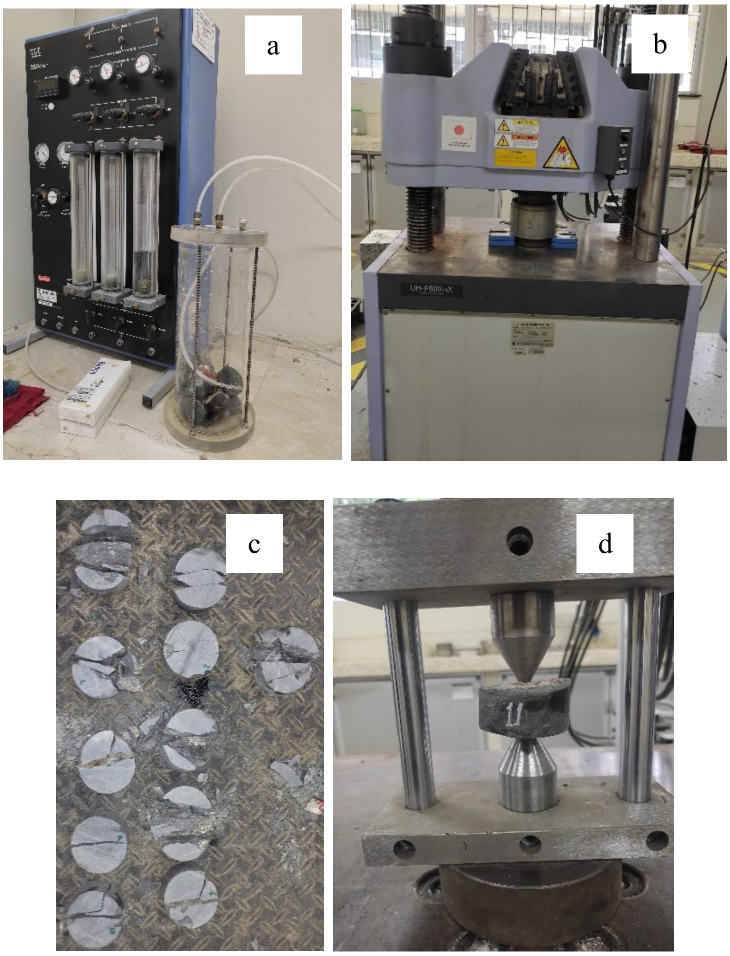

Fig4. Geomechanical characterization tests of the samples. a) Vacuum chamber for density determination; b) Compression machine for uniaxial compression tests; c) Specimens after indirect tensile test application; d) Couplings used for PLT test.

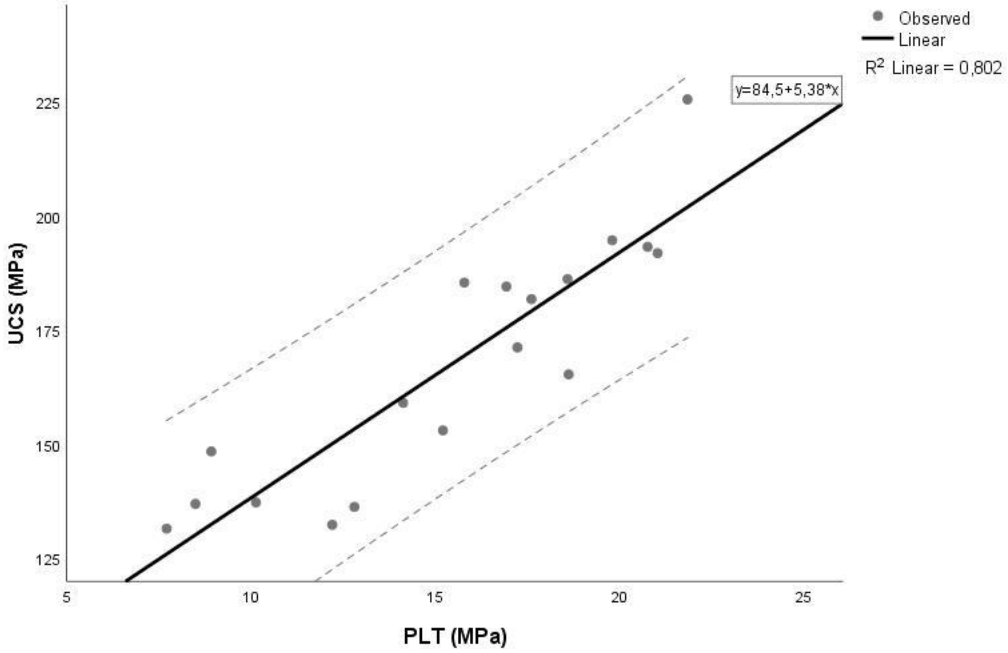

Fig5. Linear relationship between UCS and PLT of the volcanic rock samples.

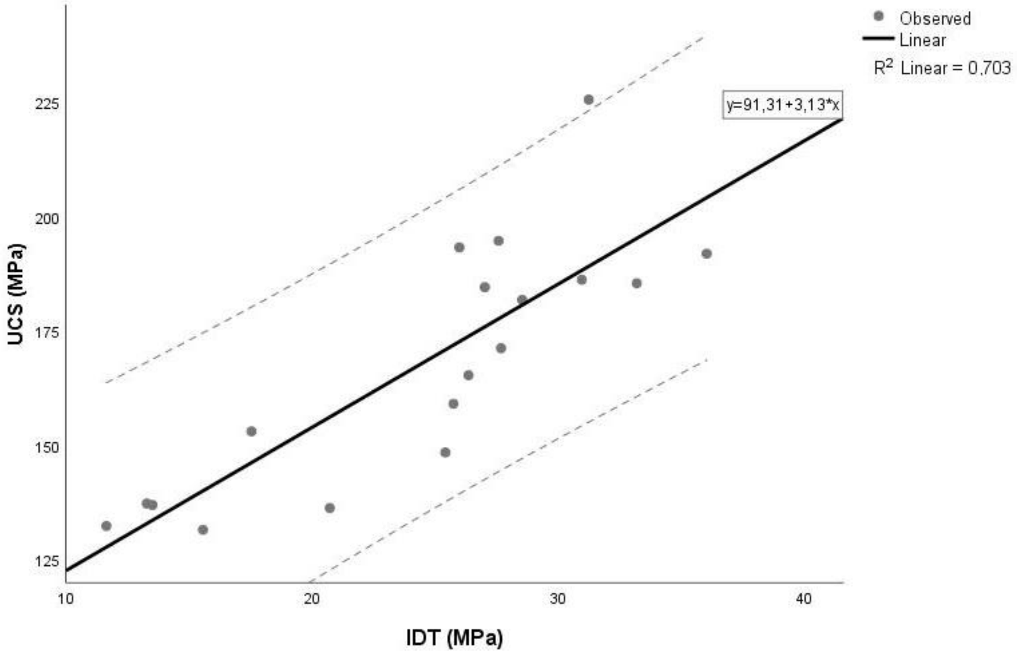

Fig6. Linear relationship between UCS and IDT of the volcanic rock samples.

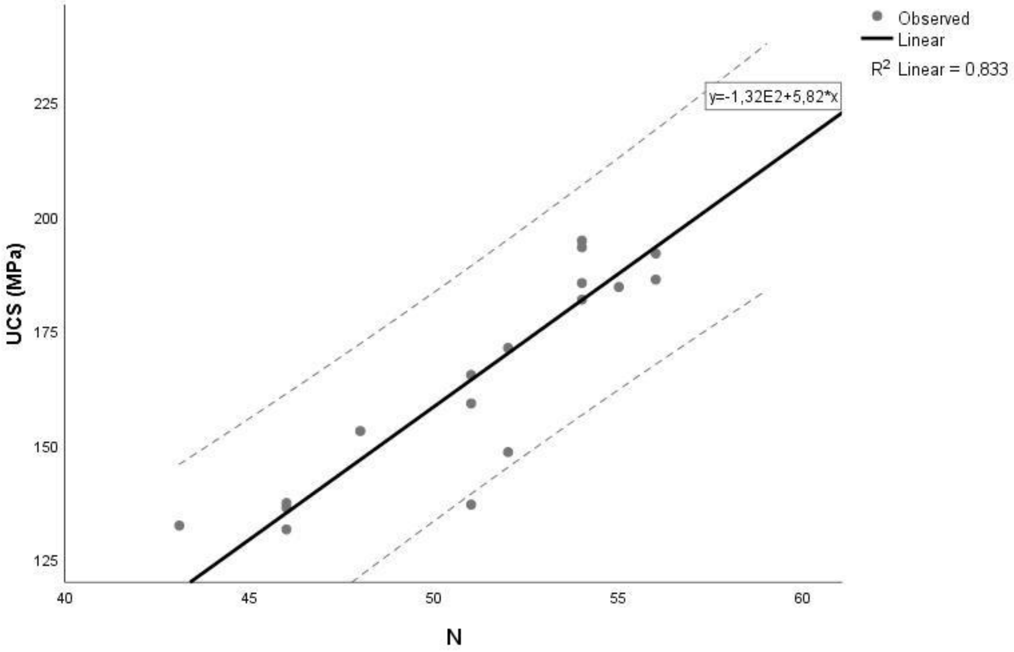

Fig7. Linear relationship between UCS and the number of rebounds of the Schmidt hammer of the volcanic rock samples.

Table 1. Apparent Volume and Dry Density of Volcanic Rock Samples.

Sample No.	**M_{sub} (g)**	**M_{sat} (g)**	**M_s (g)**	**V (cm^3)**	**ρ_d (g/cm^3)**
1	41.42	63.35	63.09	22.02	2.87
2	230.67	352.10	351.44	121.92	2.88
3	206.33	311.57	311.16	105.66	2.94
4	196.52	297.92	297.24	101.81	2.92
5	169.56	255.25	254.73	86.04	2.96
6	68.03	102.66	102.46	34.77	2.95
7	179.93	271.51	271.05	91.95	2.95
8	73.22	110.42	110.22	37.35	2.95
9	123.80	186.04	185.77	62.49	2.97
10	147.50	223.80	223.48	76.61	2.92

Table 2. Results of tests conducted on volcanic rock samples.

Sample No.	UCS (MPa)	PLT (MPa)	IDT (MPa)	N
1	181.81	17.60	28.52	54.00
2	131.56	7.71	15.56	46.00
3	186.21	18.58	30.94	56.00
4	193.27	20.75	25.97	54.00
5	132.40	12.20	11.64	43.10
6	153.06	15.20	17.53	48.00
7	165.34	18.61	26.34	51.00
8	159.11	14.12	25.73	51.00
9	184.58	16.92	27.00	55.00
10	185.44	15.78	33.17	54.00
11	225.57	21.83	31.22	59.00
12	194.71	19.79	27.56	54.00
13	136.98	8.49	13.51	51.00
14	148.46	8.92	25.40	52.00
15	171.24	17.22	27.66	52.00
16	136.32	12.80	20.71	46.00
17	137.31	10.13	13.28	46.00
18	191.91	21.02	36.01	56.00

Table 3. Statistical results obtained from the tests.

	Minimum	Maximum	Average	STD
UCS (MPa)	131.56	225.57	167.52	27.16
PLT (MPa)	7.71	21.83	15.43	4.52
IDT (MPa)	11.64	36.01	24.32	7.27
N	43.10	59.00	51.56	4.26

Table 4. Correlation Matrix between Laboratory Tests.

		PLT (MPa)	IDT(MPa)	N
UCS (MPa)	**Pearson's Correlation**	.895**	.839**	.913**
	Sig. (bilateral)	0,000	0,000	0,000

(** denotes significance at the 0.01 level)

Table 5. Summary of model and parameter estimates.

Dependent variable: UCS Independent variable: PLT.								
Equation	**Model Summary**					**Parameter Estimates**		
	R-squared	**F**	**gl1**	**gl2**	**Sig.**	**Constant**	**b1**	**b2**
Linear	0.802	64.728	1	16	0	84.498	5.382	
Logarithmic	0.739	45.227	1	16	0	-22.904	70.819	
Quadratic	0.841	39.611	2	15	0	144.526	-3.624	0.307
Compound	0.817	71.31	1	16	0	100.313	1.033	
Exponential	0.817	71.31	1	16	0	100.313	0.032	
Logistic	0.817	71.31	1	16	0	0.01	0.968	
Dependent variable: UCS Independent variable: IDT.								
Linear	0.703	37.938	1	16	0	91.309	3.134	
Logarithmic	0.677	33.568	1	16	0	-37.341	65.224	
Quadratic	0.704	17.815	2	15	0	96.375	2.642	0.011
Compound	0.74	45.514	1	16	0	103.741	1.019	
Exponential	0.74	45.514	1	16	0	103.741	0.019	
Logistic	0.74	45.514	1	16	0	0.01	0.981	
Dependent variable: UCS Independent variable: N								
Linear	0.833	79.832	1	16	0	-132.401	5.817	
Logarithmic	0.815	70.347	1	16	0	-976.483	290.395	
Quadratic	0.877	53.392	2	15	0	628.037	-24.341	0.297
Compound	0.844	86.689	1	16	0	27.265	1.036	
Exponential	0.844	86.689	1	16	0	27.265	0.035	
Logistic	0.844	86.689	1	16	0	0.037	0.966	

Table 6. Comparison of Geomechanical Parameters in Volcanic Rocks.

Reference	**Rock Type**	**Parameter**	**Minimum**	**Maximum**	**Average**	**STD**
Dinçer et al. (2004)	Basalt	UCS	65.00	108.00	86.48	20.94
		N	35.00	53.40	44.32	8.38
	Andesite	UCS	38.48	112.70	82.52	23.30
		N	27.90	52.40	43.13	8.14
	Tuff	UCS	32.93	52.00	41.90	7.88
		N	24.80	35.20	29.40	4.05
Aggistalis et al. (1996)	Basalt	UCS	17.11	91.21	46.65	19.11
		PLT	0.67	3.43	3.10	0.82
		N	21.75	54.98	42.37	6.81
	Gabbro	UCS	6.30	107.50	43.12	22.76
		PLT	0.34	4.54	1.36	0.95
		N	19.50	57.20	32.19	8.04
This study	Volcanic rock	UCS	131.56	225.57	167.52	27.16
		PLT	7.71	21.83	15.43	4.52
		N	43.10	59.00	51.56	4.26

CERTIFICACIÓN DE REVISIÓN DE PROYECTO DE TITULACIÓN

Por medio de la presente, Yo Davide Besenzon Venegas, Coordinador del Programa de Maestría en Geotecnia de la Escuela Superior Politécnica del Litoral (ESPOL), certifico que:

Con fecha 26 de enero de 2024, los estudiantes Johnny Arián Briones Escalante y Daniela Margarita Paz Barzola con números de identificación 1104269244 y 1104257975, respectivamente, de la Cohorte 5, presentaron la propuesta de su tema de titulación al Comité Académico del programa. Posteriormente, con fecha 22 de abril de 2024, el Comité revisó y aprobó la propuesta mediante la resolución FICT-CA-GEOTEC-005-2024, cumpliendo con los requisitos establecidos para la aprobación del tema.

A partir de dicha aprobación, los estudiantes mantuvieron reuniones periódicas con el tutor designado, Luis Jordá Bordehore, para la elaboración y desarrollo de su proyecto de titulación, siguiendo los lineamientos establecidos por el programa. Con fecha 08 de mayo de 2024, los estudiantes presentaron y sustentaron su proyecto de titulación ante el tribunal evaluador asignado, cumpliendo con el proceso formal de evaluación académica.

Por lo tanto, en calidad de Coordinador del Programa de Maestría en Geotecnia, certifico que el trabajo de titulación denominado **"Caracterización geomecánica de muestras de roca volcánica del campo minero Camilo Ponce Enríquez, Ecuador"**, realizado por los estudiantes Santiago Vicente Rengel Román y Freddy Santiago Vargas Pesantez con números de identificación 1104269244 y 1104257975, respectivamente, ha sido revisado y evaluado conforme a los lineamientos y estándares establecidos por el programa.

Debido a circunstancias externas, no ha sido posible obtener las firmas de los involucrados (estudiante, tutor(es) y/o evaluadores). No obstante, en calidad de Coordinador del Programa, certifico que el proyecto cumple con los requisitos académicos y ha sido revisado para su presentación y archivo institucional.

Atentamente,

Firmado electrónicamente por:
DAVIDE BESENZON VENEGAS

M. Sc. Davide Besenzon Venegas
Coordinador de la Maestría en Geotecnia